U.S. Department of Energy
Hydrogen Program

2021 Annual Merit Review and Peer Evaluation Report

June 7–11, 2021

U.S. DEPARTMENT OF
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NOTICE

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Prologue

Dear Colleague:

This document summarizes peer review comments and scores for the fiscal year (FY) 2021 U.S. Department of Energy (DOE) Hydrogen Program Annual Merit Review and Peer Evaluation Meeting (AMR), held virtually June 7–11, 2021. In response to direction from various stakeholders, including the National Academies, this review process provides project- and program-level evaluations of DOE-funded research, development, demonstration, and analysis of hydrogen and fuel cell technologies.

This year's AMR kicked off with opening remarks from Energy Secretary Jennifer M. Granholm, who announced the launch of Hydrogen Shot—DOE's first Energy Earthshot. Hydrogen Shot seeks to reduce the cost of clean hydrogen to $1 per kilogram—an 80% decrease—in one decade, setting an ambitious yet achievable cost target for the DOE Hydrogen Program going forward. The opening plenary also included a panel discussion on H2@Scale opportunities and activities among leadership from DOE's Offices of Energy Efficiency and Renewable Energy (EERE), Fossil Energy and Carbon Management (FECM), Nuclear Energy (NE), and Science (SC), as well as program and subprogram overview presentations. The AMR technical session included a dedicated two-day track on DOE intra-agency activities, including project updates from FECM, NE, SC, and the Advanced Research Projects Agency–Energy (ARPA-E), and a one-day session on interagency- and state-level activities. The AMR was attended by more than 1,800 people, including more than 150 reviewers who reviewed 125 projects funded by EERE's Hydrogen and Fuel Cell Technologies Office and more than 50 reviewers who were asked to provide feedback on the overall R&D program and subprograms.

DOE values the transparent public process of soliciting technical input on its projects and programs from relevant experts with depth and breadth of knowledge across a wide range of areas. The reviewers' recommendations are taken into consideration by DOE technology managers in generating future work plans. The summary table that follows lists the projects presented at the review and the overall evaluation score for each project, and Appendix A provides the scores and comments from the program reviewers. The individual reports present the reviewer comments to be considered during the upcoming fiscal year (October 1, 2021–September 30, 2022). The projects have been grouped according to subprogram and reviewed according to the appropriate evaluation criteria. To furnish principal investigators (PIs) with direct feedback, all of the evaluations and comments are provided to each presenter; however, the authors of the individual comments remain anonymous. DOE instructs the PIs to consider these summary evaluation comments fully, along with any other comments by DOE managers, in the PIs' FY 2022 plans.

One behalf of the DOE Hydrogen Program, I would like to express my sincere appreciation to all the 2021 AMR participants and the reviewers, researchers, and presenters for your strong commitment, expertise, and dedication to advancing hydrogen and fuel cell technologies. You make this report possible, and we rely on your comments, along with other management processes, to help make project decisions for the new fiscal year. We look forward to your participation in the 2022 AMR, which is scheduled for the week of June 6, 2022.

Sincerely,

Dr. Sunita Satyapal
Director
Hydrogen and Fuel Cell Technologies Office, and
DOE Hydrogen Program Coordinator
U.S. Department of Energy

Hydrogen Technologies

Hydrogen Production

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
P-148	HydroGEN Overview: A Consortium on Advanced Water-Splitting Materials *Huyen Dinh, National Renewable Energy Laboratory*	3.7	X		
P-179	BioHydrogen (BioH2) Consortium to Advance Fermentative Hydrogen Production *Katherine Chou, National Renewable Energy Laboratory*	3.3	X		
P-182	Binary Chloride Salts as Catalysts for Methane to Hydrogen and Graphitic Powder *Eric McFarland, C-Zero, LLC*	3.1	X		
P-183	Extremely Durable Concrete Using Methane Decarbonization Nanofiber Co-Products with Hydrogen *Alan W. Weimer, University of Colorado, Boulder*	3.3	X		
P-184	Scalable and Highly Efficient Microbial Electrochemical Reactor for Hydrogen Generation from Lignocellulosic Biomass and Waste *Hong Liu, Oregon State University*	2.9	X		
P-196	H2NEW Consortium: Hydrogen from Next-Generation Electrolyzers of Water *Bryan Pivovar, National Renewable Energy Laboratory, and Richard Boardman, Idaho National Laboratory*	3.4	X		

Hydrogen Production—HydroGEN Seedling[1]

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
P-185	High-Performance Alkaline Electrolyte Membrane Low-Temperature Electrolysis with Advanced Membranes, Ionomers, and Platinum-Group-Metal-Free Electrodes *Paul A. Kohl, Georgia Institute of Technology*	3.0	X		
P-186	Performance and Durability Investigation of Thin, Low-Crossover Proton Exchange Membranes for Water Electrolyzers *Andrew Park, The Chemours Company FC, LLC*	3.3	X		
P-187	Pure Hydrogen Production through Precious-Metal-Free Membrane Electrolysis of Dirty Water *Shannon Boettcher, University of Oregon*	2.9	X		
P-188	Advanced Coatings to Enhance the Durability of Solid Oxide Electrolysis Cell Stacks *Neil Kidner, Nexceris, LLC*	3.4	X		
P-189	Scalable High-Hydrogen-Flux, Robust Thin Film Solid Oxide Electrolyzer *Colin Gore, Redox Power Systems, LLC*	3.4	X		
P-190	A Multifunctional Isostructural Bilayer Oxygen Evolution Electrode for Durable Intermediate-Temperature Electrochemical Water Splitting *Kevin Huang, University of South Carolina*	3.2	X		
P-191	Perovskite–Perovskite Tandem Photoelectrodes for Low-Cost Unassisted Photoelectrochemical Water Splitting *Yanfa Yan, The University of Toledo*	3.2	X		
P-192	Development of Composite Photocatalyst Materials That Are Highly Selective for Solar Hydrogen Production and Their Evaluation in Z-Scheme Reactor Designs *Shane Ardo, University of California, Irvine*	3.7	X		
P-193	Highly Efficient Solar Water Splitting Using Three-Dimensional/Two-Dimensional Hydrophobic Perovskites with Corrosion-Resistant Barriers *Aditya D. Mohite, William Marsh Rice University*	3.3	X		

[1] HydroGEN seedling projects marked "Continue" are on track, but project continuation is contingent on passing a go/no-go decision.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
P-194	New High-Entropy Perovskite Oxides with Increased Reducibility and Stability for Thermochemical Hydrogen Generation *Jian Luo, University of California, San Diego*	3.1	X		
P-195	A New Paradigm for Materials Discovery and Development for Lower-Temperature and Isothermal Thermochemical Hydrogen Production *Jonathan Scheffe, University of Florida*	3.1	X		

Hydrogen Infrastructure

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
H2-061	Innovating Hydrogen Stations: Heavy-Duty Fueling *Michael Peters, National Renewable Energy Laboratory*	3.8	X		
IN-001a	Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Metals *Chris San Marchi, Sandia National Laboratories*	3.1	X		
IN-001b	Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Polymers *Kevin Simmons, Pacific Northwest National Laboratory*	3.0	X		
IN-004	Magnetocaloric Hydrogen Liquefaction *John Barclay, Pacific Northwest National Laboratory*	2.4	X		
IN-015	Optimizing the Heisenberg Vortex Tube for Hydrogen Cooling *Jacob Leachman, Washington State University*	3.0	X		
IN-016	Free-Piston Expander for Hydrogen Cooling *Devin Halliday, Gas Technology Institute*	3.0	X		
IN-019	Ultra-Cryopump for High-Demand Transportation Fueling *Kyle Gross, RotoFlow/Air Products*	2.9	X		
IN-020	Self-Healable Copolymer Composites for Extended-Service Hydrogen Dispensing Hoses *Marek Urban, Clemson University*	2.9	X		

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
IN-021	Microstructural Engineering and Accelerated Test Method Development to Achieve Low-Cost, High-Performance Solutions for Hydrogen Storage and Delivery *Kip Findley, Colorado School of Mines*	3.5	X		
IN-022	Tailoring Carbide-Dispersed Steels: A Path to Increased Strength and Hydrogen Tolerance *Gregory Thompson, The University of Alabama*	2.9	X		
IN-025	Hydrogen Delivery Technologies Analysis *Amgad Elgowainy, Argonne National Laboratory*	3.5	X		
IN-026	Tailoring Composition and Deformation Modes at the Microstructural Level for Next-Generation Low-Cost, High-Strength Austenitic Stainless Steels *Petros Sofronis, University of Illinois Urbana–Champaign*	3.2	X		
IN-029	Reducing the Cost of Fatigue Crack Growth Testing for Storage Vessel Steels in Hydrogen Gas *Kevin Nibur, Hy-Performance Materials Testing, LLC*	3.4	X		
IN-030	Micro-Mechanically Guided High-Throughput Alloy Design Exploration toward Metastability-Induced Hydrogen Embrittlement Resistance *C. Cem Tasan, Massachusetts Institute of Technology*	3.4	X		

Hydrogen Storage

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
ST-001	System-Level Analysis of Hydrogen Storage Options *Rajesh Ahluwalia, Argonne National Laboratory*	3.5	X		
ST-100	Hydrogen Storage Cost Analysis *Cassidy Houchins, Strategic Analysis, Inc.*	3.5	X		
ST-127	Hydrogen Materials—Advanced Research Consortium (HyMARC) Overview *Mark Allendorf, Sandia National Laboratories*	3.2	X		

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
ST-209	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Theory-Guided Design and Discovery of Materials for Reversible Methane and Hydrogen Storage *Omar Farha, Northwestern University*	3.5	X		
ST-211	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Optimal Adsorbents for Low-Cost Storage of Natural Gas and Hydrogen: Computational Identification, Experimental Demonstration, and System-Level Projection *Don Siegel, University of Michigan*	3.5	X		
ST-212	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Methane and Hydrogen Storage with Porous Cage-Based Composite Materials *Eric Bloch, University of Delaware*	3.6	X		
ST-214	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Heteroatom-Modified and Compacted Zeolite-Templated Carbons for Gas Storage *Nicholas Stadie, Montana State University*	3.4	X		
ST-215	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Developing A New Natural Gas Super-Absorbent Polymer *Mike Chung, The Pennsylvania State University*	2.9		X	
ST-216	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Hydrogen Release from Concentrated Media with Reusable Catalysts *Travis Williams, University of Southern California*	3.7	X		
ST-217	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: A Reversible Liquid Hydrogen Carrier System Based on Ammonium Formate and Captured Carbon Dioxide *Hongfei Lin, Washington State University*	3.1	X		
ST-218	Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: High-Capacity, Step-Shaped Hydrogen Adsorption in Robust, Pore-Gating Zeolitic Imidazolate Frameworks *Michael McGuirk, Colorado School of Mines*	3.6	X		
ST-223	Cost Assessment and Evaluation of Liquid Hydrogen Storage for Medium- and Heavy-Duty Transportation Applications *Rajesh Ahluwalia, Argonne National Laboratory*	3.5	X		

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
ST-227	Integrated Onsite Waste-Heat-Driven Hydrogen Carrier System for Steel and Renewables *Hanna Breunig, Lawrence Berkeley National Laboratory*	3.6	X		
ST-228	Determining the Value Proposition of Materials-Based Hydrogen Storage for Stationary Bulk Storage of Hydrogen *Bruce Hardy, Savannah River National Laboratory*	3.5	X		

Fuel Cell Technologies

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
FC-117	Fiscal Year 2018 Small Business Innovation Research Phase IIB: Ionomer Dispersion Impact on Advanced Fuel Cell Performance and Durability *Hui Xu, Giner, Inc.*	3.3			X
FC-158	Fuel Cell Membrane Electrode Assemblies with Ultra-Low-Platinum Nanofiber Electrodes *Peter Pintauro, Vanderbilt University*	2.6			X
FC-160	ElectroCat 2.0 (Electrocatalysis Consortium) *Deborah Myers, Argonne National Laboratory, and Piotr Zelenay, Los Alamos National Laboratory*	3.5	X		
FC-163	Fuel Cell Systems Analysis *Brian James, Strategic Analysis, Inc.*	3.3			X
FC-167	Fiscal Year 2020 Small Business Innovation Research Phase IIA: Multi-Functional Catalyst Support *Minette Ocampo, pH Matter, LLC*	3.5	X		
FC-170	ElectroCat: Durable Manganese-Based Platinum-Group-Metal-Free Catalysts for Polymer Electrolyte Membrane Fuel Cells *Hui Xu, Giner, Inc.*	3.2		X	
FC-172	ElectroCat: Highly Active and Durable Platinum-Group-Metal-Free Oxygen Reduction Reaction Electrocatalysts through the Synergy of Active Sites *Yuyan Shao, Pacific Northwest National Laboratory*	3.2	X		

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
FC-302	ElectroCat: Developing Platinum-Group-Metal-Free Catalysts for Oxygen Reduction Reaction in Acid: Beyond the Single Metal Site *Qingying Jia, Northeastern University*	3.0		X	
FC-303	ElectroCat: Mesoporous Carbon-Based Platinum-Group-Metal-Free Catalyst Cathodes *Jian Xie, Indiana University–Purdue University Indianapolis*	3.5		X	
FC-305	Active and Durable Platinum-Group-Metal-Free Cathodic Electrocatalysts for Fuel Cell Application *Alexey Serov, Pajarito Powder*	3.2	X		
FC-307	Cyclic Olefin Copolymer-Based Alkaline Exchange Polymers and Reinforced Membranes *Chulsung Bae, Rensselaer Polytechnic Institute*	3.3	X		
FC-308	Advanced Anion Exchange Membranes with Tunable Water Transport for Platinum-Group-Metal-Free Anion Exchange Membrane Fuel Cells *Michael Hickner, The Pennsylvania State University*	3.3	X		
FC-309	Polymerized Ionic Liquid Block Copolymer/Ionic Liquid Composite Ionomers for High-Current-Density Performance *Joshua Snyder, Drexel University*	3.0	X		
FC-310	Composite Polymer Electrolyte Membranes from Electrospun Crosslinkable Poly(Phenylene Sulfonic Acid)s *Ryszard Wycisk, Vanderbilt University*	3.3			X
FC-313	Novel Bifunctional Electrocatalysts, Supports, and Membranes for High-Performing and Durable Unitized Regenerative Fuel Cells *Nem Danilovic, Lawrence Berkeley National Laboratory*	2.9	X		
FC-314	Efficient Reversible Operation and Stability of Novel Solid Oxide Cells *Scott Barnett, Northwestern University*	3.4	X		
FC-316	Durable, High-Performance Unitized Reversible Fuel Cells Based on Proton Conductors *Meilin Liu, Georgia Institute of Technology*	3.3	X		
FC-317	Stationary Direct Methanol Fuel Cells Using Pure Methanol *Xianglin Li, University of Kansas*	3.0	X		

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
FC-319	Low-Cost Gas Diffusion Layer Materials and Treatments for Durable High-Performance Polymer Electrolyte Membrane Fuel Cells *Rod Borup, Los Alamos National Laboratory*	3.3			X
FC-320	Electrode Ionomers for High-Temperature Fuel Cells *Michael Hibbs, Sandia National Laboratories*	3.1			X
FC-323	Durable Fuel Cell Membrane Electrode Assembly through Immobilization of Catalyst Particle and Membrane Chemical Stabilizer *Nagappan Ramaswamy, General Motors LLC*	3.4	X		
FC-324	Reversible Fuel Cell Stacks with Integrated Water Management *Teddy Wang, Plug Power Inc.*	2.9	X		
FC-325	Fiscal Year 2019 Small Business Innovation Research Phase II: Controlled Porosity and Surface Coatings for Advanced Gas Diffusion Layers *Kristina Bennett, Physical Sciences, Inc.*	2.8			X
FC-326	Durable Membrane Electrode Assemblies for Heavy-Duty Fuel Cell Electric Trucks *Vivek Murthi, Nikola Motor Company*	3.0	X		
FC-327	Durable High-Power-Density Fuel Cell Cathodes for Heavy-Duty Vehicles *Shawn Litster, Carnegie Mellon University*	3.6	X		
FC-328	Fiscal Year 2019 Small Business Innovation Research Phase II: Novel Fluorinated Ionomer for Polymer Electrolyte Membrane Fuel Cells *Hui Xu, Giner, Inc.*	3.3			X
FC-330	High-Efficiency Reversible Solid Oxide System *Hossein Ghezel-Ayagh, FuelCell Energy, Inc.*	3.1	X		
FC-331	A Novel Stack Approach to Enable High Round-Trip Efficiencies in Unitized Polymer Electrolyte Membrane Regenerative Fuel Cells *Katherine Ayers, Nel Hydrogen*	3.0	X		
FC-333	Advanced Membranes for Heavy-Duty Fuel Cell Trucks *Vivek Murthi, Nikola Motor Company*	3.3	X		
FC-334	Extending Perfluorosulfonic Acid Membrane Durability through Enhanced Ionomer Backbone Stability *Michael Yandrasits, 3M Company*	3.5	X		

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
FC-335	Additive Functionalized Polymers for Extended Heavy-Duty Polymer Electrolyte Membrane Lifetimes *Tom Corrigan, The Lubrizol Corporation*	3.2	X		
FC-336	A Systematic Approach to Developing Durable Conductive Membranes for Operation at 120°C *Tom Zawodzinski, University of Tennessee, Knoxville*	3.2	X		
FC-337	Cummins Polymer Electrolyte Membrane Fuel Cell System for Heavy-Duty Applications *Darren Hickey, Cummins Inc.*	2.8	X		
FC-338	Domestically Manufactured Fuel Cells for Heavy-Duty Applications *John Lawler, Plug Power Inc.*	2.2	X		
FC-339	M2FCT: Million Mile Fuel Cell Truck Consortium *Rod Borup and Adam Weber, M2FCT*	3.3	X		
FC-341	Advanced Anion Exchange Membrane Fuel Cells through Material Innovation *Yu Seung Kim, Los Alamos National Laboratory*	3.3	X		
FC-342	Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells *Bryan Pivovar, National Renewable Energy Laboratory*	3.5	X		
FC-343	Fiscal Year 2020 Small Business Innovation Research Phase II: Improved Ionomers and Membranes for Fuel Cells *Chris Topping, Tetramer Technologies, LLC*	3.1	X		

Technology Acceleration

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
TA-001	Membrane Electrode Assembly Manufacturing Research and Development *Michael Ulsh, National Renewable Energy Laboratory*	3.1	X		

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
TA-005	In-Line Quality Control of Polymer Electrolyte Membrane Materials *Andrew Wagner, Mainstream Engineering*	3.3	X		
TA-007	Roll-to-Roll Advanced Materials Manufacturing Lab Collaboration *Yarom Polsky, Oak Ridge National Laboratory*	3.4	X		
TA-009	Maritime (Pierside Power) Fuel Cell Generator Project *Lennie Klebanoff, Sandia National Laboratories*	3.2	X		
TA-016	Fuel Cell Hybrid Electric Delivery Van *Jason Hanlin, Center for Transportation and the Environment*	3.4	X		
TA-017	Innovative Advanced Hydrogen Mobile Fueler *Sara Odom, Electricore Inc.*	3.5	X		
TA-018	High-Temperature Electrolysis Test Stand *Micah Casteel, Idaho National Laboratory*	3.5	X		
TA-024	Analysis of Fuel Cells for Trucks: Real-World Benefits *Ram Vijayagopal, Argonne National Laboratory*	3.4		X	
TA-025	Laser Three-Dimensional Printing of Highly Compacted Protonic Ceramic Electrolyzer Stack *Jianhua Tong, Clemson University*	3.0	X		
TA-026	Low-Cost, High-Performance Catalyst-Coated Membranes for Polymer Electrolyte Membrane Water Electrolyzers *Andrew Steinbach, 3M Company*	3.5			X
TA-027	Catalyst Layer Design, Manufacturing, and In-Line Quality Control *Radenka Maric, University of Connecticut*	3.2			X
TA-028	Demonstration of Electrolyzer Operation at a Nuclear Plant to Allow for Dynamic Participation in an Organized Electricity Market and In-House Hydrogen Supply *Uuganbayar Otgonbaatar, Exelon Corporation*	3.3	X		
TA-030	Demonstration of Integrated Hydrogen Production and Consumption for Improved Utility Operations *Monjid Hamdan, Plug Power Inc.*	3.5	X		
TA-032	Electrolyzer Integrated Modular Nano-Array Monolithic Catalytic Reactors *Trent Molter, Skyre, Inc.*	2.8			X

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
TA-033	Developing Novel Electrodes with Ultralow Catalyst Loading for High-Efficiency Hydrogen Production in Proton Exchange Membrane Electrolyzer Cells *Feng-Yuan Zhang, University of Tennessee Space Institute*	3.3			X
TA-034	Rail, Aviation, and Maritime Metrics *Rajesh Ahluwalia, Argonne National Laboratory*	3.5			X
TA-035	Power Convertor for Electrolyzer Applications *Robert Hovsapian, National Renewable Energy Laboratory*	3.3	X		
TA-036	Advanced Electrode Manufacture to Enable Low-Cost Polymer Electrolyte Membrane Electrolysis *Chris Capuano, Nel Hydrogen*	3.3			X
TA-037	Demonstration and Framework for H2@Scale in Texas and Beyond *Nico Bouwkamp, Frontier Energy, Inc.*	3.6	X		
TA-041	Truck Duty Cycle Analysis *Jason Lustbader, National Renewable Energy Laboratory*	3.4	X		
TA-042	Next-Generation Hydrogen Station Analysis *Genevieve Saur, National Renewable Energy Laboratory*	3.5	X		
TA-043	Electrolyzer Stack Development and Manufacturing *Olga Marina, Pacific Northwest National Laboratory*	3.1	X		
TA-047	Rail Refueling Analysis *Brian Ehrhart, Sandia National Laboratories*	3.4			X
TA-048	Advanced Research on Integrated Energy Systems (ARIES)/Flatirons Facility – Hydrogen System Capability Buildout *Daniel Leighton, National Renewable Energy Laboratory*	3.4	X		
TA-049	High-Pressure, High-Flow-Rate Dispenser and Nozzle Assembly for Heavy-Duty Vehicles *Spencer Quong, Electricore Inc.*	3.3	X		
TA-050	Overall Research on Electrode Coating Processes (OREO) *Michael Ulsh, National Renewable Energy Laboratory*	2.9	X		

Safety, Codes and Standards

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SCS-005	Research and Development for Safety, Codes and Standards: Material and Component Compatibility *Chris San Marchi, Sandia National Laboratories*	3.4	X		
SCS-007	Fuel Quality Assurance Research and Development and Impurity Testing in Support of Codes and Standards *Tommy Rockward, Los Alamos National Laboratory*	3.2		X	
SCS-010	Research and Development for Safety, Codes and Standards: Hydrogen Behavior *Ethan Hecht, Sandia National Laboratories*	3.6	X		
SCS-011	Hydrogen Quantitative Risk Assessment *Brian Ehrhart, Sandia National Laboratories*	3.5	X		
SCS-019	Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources *Nick Barilo, Pacific Northwest National Laboratory*	3.6	X		
SCS-021	Hydrogen Sensor Testing Laboratory *William Buttner, National Renewable Energy Laboratory*	3.5	X		
SCS-022	Fuel Cell and Hydrogen Energy Association Codes and Standards Support *Karen Quackenbush, Fuel Cell & Hydrogen Energy Association*	3.1	X		
SCS-029	Point-of-Use Hydrogen Purification and Impurity Reporting Systems that Utilize Metal–Organic Frameworks *William Morris, NuMat Technologies, Inc.*	3.2	X		

Systems Analysis

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SA-169	Market Segmentation Analysis of Medium- and Heavy-Duty Trucks with a Fuel Cell Emphasis *Chad Hunter, National Renewable Energy Laboratory*	3.8			X

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SA-174	Technoeconomic and Lifecycle Analysis of Synthetic Fuels and Steelmaking *Amgad Elgowainy, Argonne National Laboratory*	3.6	X		
SA-175	Regional Hybrid Energy Systems Technoeconomic Analysis *Mark Ruth, National Renewable Energy Laboratory*	3.8	X		
SA-176	Annual Technology Baseline – Transportation *Laura Vimmerstedt, National Renewable Energy Laboratory*	3.0	X		
SA-177	Analysis of Hydrogen Export Potential *Amgad Elgowainy, Argonne National Laboratory*	3.4	X		
SA-178	Cradle-to-Grave Transportation Analysis *Amgad Elgowainy, Argonne National Laboratory*	3.5	X		
SA-179	Transportation Benefits Analysis *Aaron Brooker, National Renewable Energy Laboratory*	3.3	X		
SA-180	Advanced Network Analysis of Hydrogen Fuel Cell Automated Vehicles for Goods Delivery (ATLAS) – Total Cost of Ownership of Autonomous Fuel Cell Fleet Vehicles *Tim Lipman, Lawrence Berkeley National Laboratory*	3.3	X		

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Introduction

The fiscal year (FY) 2021 U.S. Department of Energy (DOE) Hydrogen Program (the Program) Annual Merit Review and Peer Evaluation Meeting (AMR) was held June 7–11, 2021, online as a virtual meeting because of COVID-19 and government-wide travel restrictions. The AMR consists of a detailed merit review and technical expert peer evaluation of DOE's Hydrogen and Fuel Cell Technologies Office (HFTO), in addition to an overview of the entire Hydrogen Program, which includes activities across multiple DOE offices—including Energy Efficiency and Renewable Energy (EERE), Fossil Energy and Carbon Management (FECM), Nuclear Energy (NE), Electricity (OE), Science (SC), and the Advanced Research Program Agency–Energy (ARPA-E). In addition, the AMR provides an update of hydrogen activities across other federal and state agencies involved in key hydrogen- and fuel-cell-related activities.

Consistent with prior AMRs over more than two decades, this year's AMR included detailed independent review of projects funded by HFTO and peer review of the overall activities within the office and the Program. The peer review results take the form of comments and scores provided by AMR peer reviewers in response to presentations on Program and project progress, as shown in the project review chapters and in Appendix A of this report. A representative selection of hydrogen and fuel cell programs and projects funded by other DOE offices comprising the Program are also presented at the AMR, and these presentations are included (together with the HFTO project presentations) in the 2021 AMR Proceedings.[1]

DOE uses the results of this merit review and peer evaluation, along with additional review processes, to help shape priorities and plans for upcoming fiscal years and to help guide ongoing performance improvements to existing projects and the overall strategy of the Program.

The objectives of the AMR include the following:

- Review and evaluate FY 2021 accomplishments and FY 2022 plans for DOE hydrogen programs and projects, including laboratory programs; industry–university cooperative agreements; and related research, development, demonstration, and deployment (RDD&D) efforts, including through rigorous and systematic tracking of progress against targets and metrics.
- Provide an opportunity for stakeholders (hydrogen and fuel cell system developers and manufacturers, component developers, integrators, end users, and others) to provide input to help shape the Program so that it addresses the highest-priority barriers, facilitates technology transfer and market impact, and continually improves its effectiveness in enabling progress toward national goals.
- Foster interactions among national laboratories, industry, and universities conducting RDD&D to enhance collaboration and coordination, leverage resources and talents, and provide a venue for advancing early career development in STEM (Science, Technology, Engineering, and Mathematics) fields, strengthening diversity, equity, and inclusion (DEI) as well as engagement within the energy and environmental justice community.
- Provide transparency regarding the use and impact of taxpayer funding, including on concrete deliverables such as innovations, patents, commercialized or near-commercial technologies, and enabling activities such as manufacturing; safety, codes and standards; and workforce development.

Organization of the Report

This report introduction provides a brief overview of the Program, including highlighted accomplishments in FY 2020–2021. This section includes an introductory discussion of the peer review process and analysis methodology.

Following the introduction are the detailed peer review results. The HFTO project peer review results are grouped by subprogram: Hydrogen Technologies; Fuel Cell Technologies; Technology Acceleration; Safety, Codes and Standards; and Systems Analysis. Each of these sections begins with a brief subprogram overview, including a

[1] DOE, "2021 Annual Merit Review Proceedings," energy.gov, https://www.hydrogen.energy.gov/annual-review/annual_review21_proceedings.html.

summary of key FY 2020–2021 accomplishments. The subprogram overviews are followed by the results of individual project reviews, including the scores and qualitative comments for each project.

Appendix A provides a summary of review comments on the overall Program and HFTO subprograms. Appendix B provides a complete list of the meeting participants. Appendix C provides the evaluation criteria used for the program and project reviews, and Appendix D provides a list of projects that were presented at the AMR but not peer-reviewed, including those funded by other DOE offices or external stakeholders.

Overview of the DOE Hydrogen Program

The Program provides funding and strategic direction for RDD&D activities to advance the production, transport, storage, and use of hydrogen across multiple applications and different sectors of the economy. The Program, which is led through HFTO, coordinates activities within EERE, FECM, NE, OE, SC, and ARPA-E. A growing network of stakeholders informs the Program, including industry representatives across applications and sectors, state and regional organizations, other federal agencies, and international counterparts. The Program's activities are authorized by Title VIII of the Energy Policy Act of 2005[2] and the Energy Act of 2020.[3] This section provides a brief overview of the Program through the 2021 AMR meeting held in June 2021. More information on the activities of the DOE offices and subprograms can be found in the plenary presentations included in the 2021 AMR Proceedings and through the information and links at the Program webpage.[4]

Activities within the Program are aligned with the Biden Administration's goals,[5] including the most recent goal, announced April 22, 2021, for the "United States to achieve a 50–52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution in 2030—building on progress to-date and by positioning American workers and industry to tackle the climate crisis." This "2030 target picks up the pace of emissions reductions in the United States, compared to historical levels, while supporting President Biden's existing goals to create a carbon pollution-free power sector by 2035 and net-zero emissions economy by no later than 2050. There are multiple paths to reach these goals, and the U.S. federal, state, local, and tribal governments have many tools available to work with civil society and the private sector to mobilize investment to meet these goals while supporting a strong economy."[5]

All of the Program's efforts are consistent with the above goals, including ongoing RDD&D efforts such as clean hydrogen production scale-up, affordability, durability, and reliability, which are key to jumpstarting new markets for hydrogen, including heavy-duty applications, new industrial uses, energy storage, and grid integration.

In FY 2021, Congress appropriated $150 million for hydrogen and fuel cell activities in EERE's HFTO and $88.7 million for FECM's activities. In addition, funding for NE, SC, and ARPA-E, relevant to hydrogen and fuel cell activities, amounted to $13 million, $17 million, and $10 million, respectively. This represents a total DOE budget for FY 2021 of almost $279 million related to hydrogen and fuel cell technologies (see Table 1 below).

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[2] Energy Policy Act of 2005 (EPACT 2005) Public Law 109-58, Title VIII – HYDROGEN, Sections 801 to 816 (42 USC Sections 16151 to 16165), August 5, 2005.

[3] Consolidated Appropriations Act, Public Law 116-260, Division Z – Energy Act of 2020, Section 9009, December 27, 2020.

[4] DOE, "Hydrogen Program," accessed 2022, https://www.hydrogen.energy.gov/index.html.

[5] The White House, "President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies," April 22, 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

Table 1. Hydrogen-Focused Funding across DOE ($ in millions)

DOE Office / Program	FY 2020 (enacted)	FY 2021 (enacted)	FY 2022 (requested)
Energy Efficiency and Renewable Energy	**$165.5**	**$155.9**	**$226.5**
Hydrogen and Fuel Cell Technologies	$150	$150	$197.5
Advanced Manufacturing	$12.5	$5	$20
Solar Energy Technologies Office	$0	$0	$4
Vehicle Technologies Office	$3	$0	$0
Wind Energy Technologies Office	$0	$0.9	$5
Fossil Energy and Carbon Management	**$53**	**$88.7**	**$141**
Clean Coal and Carbon Management	$53	$87	$111
Oil and Natural Gas	$0	$1.7	$30
Nuclear Energy	**$14**	**$13**	**$13**
Science	**$15.5**	**$17**	**$20**
Advanced Research Program Agency–Energy	**$36.4**	**$10**	**TBD***
TOTAL	**$284.4**	**$284.6**	**$400.5**

**ARPA-E funding is determined annually based on programs developed through office and stakeholder priorities. Therefore, funding for FY 2022 is not available at this time.*

The Program coordinates across all relevant offices, and pertinent activities are identified based on technical and economic analyses, stakeholder workshops, requests for information, and merit-reviewed project proposals that may be selected through competitive funding opportunities, which vary from year to year.

Background: H2@Scale – A Guiding Framework

H2@Scale is a DOE initiative that provides an overarching vision for how hydrogen can enable energy pathways across applications and sectors in an increasingly interconnected energy system, as shown in Figure 1 below. The main priorities of this vision include:

- Low-cost, clean hydrogen generation
- Low-cost, efficient, safe hydrogen delivery and storage
- End-use applications to achieve scale and sustainability, enable emissions reduction, and address Environmental Justice 40 priorities[6]

H2@Scale RDD&D activities are guided by the administration's goal to equitably transition the United States to net-zero greenhouse gas emissions economy-wide by 2050, while creating good paying jobs and ensuring the clean energy economy benefits all Americans. Hydrogen is one part of a portfolio of activities to enable decarbonizing the electricity, transportation, industrial, buildings, and agricultural sectors, particularly for hard-to-decarbonize applications such as heavy-duty transportation and industry. More details may be found on the H2@Scale webpage.[7]

[6] The White House, "The Path to Achieving Justice40," July 20, 2021, https://www.whitehouse.gov/omb/briefing-room/2021/07/20/the-path-to-achieving-justice40/.

[7] DOE, "H2@Scale," accessed 2022, https://www.energy.gov/eere/fuelcells/h2scale.

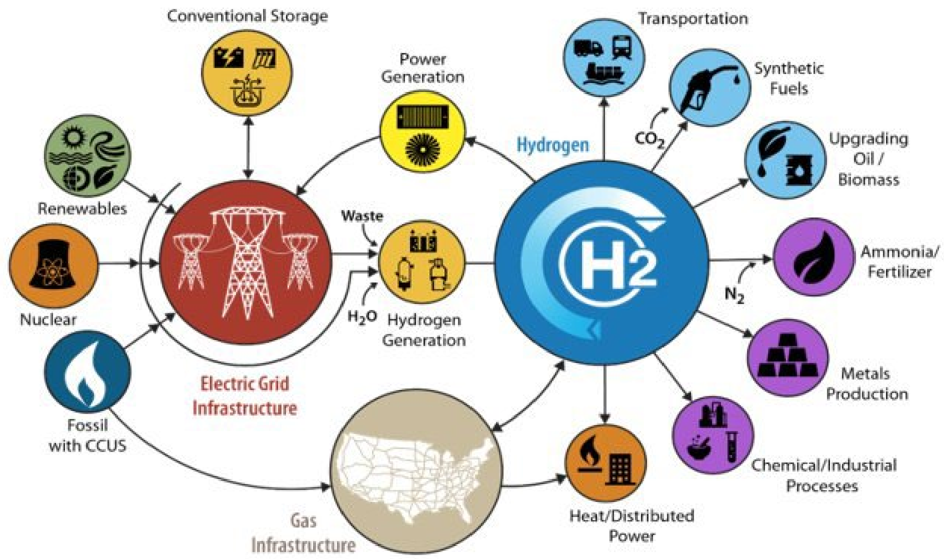

Figure 1. Schematic of H2@Scale

Program Highlights

This year marked an important period in the Program's history, as hydrogen was increasingly recognized globally as an enabler to achieving decarbonization goals. Key Program highlights included the following:

- **DOE-Wide Hydrogen Program Plan:** In November 2020, DOE released its **Hydrogen Program Plan**,[8] providing a comprehensive strategic framework for the Department's hydrogen-related RDD&D. The plan includes input from the offices of EERE, FECM, NE, OE, SC, and ARPA-E and reinforces the Department's commitment to enabling progress in hydrogen technologies in the United States. This overarching Department-wide strategic plan was the first comprehensive update since the previous version published in 2011.
- **Hydrogen Shot:** On June 7, 2021, Secretary of Energy Jennifer M. Granholm launched the DOE **Energy Earthshots Initiative**, a series of bold, ambitious initiatives that will address critical challenges and contribute to achieving net-zero carbon emissions. The first Energy Earthshot—**Hydrogen Shot**—seeks to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade ("1 1 1"). Hydrogen Shot supports the H2@Scale vision and will contribute to addressing the climate crisis. Achieving Hydrogen Shot's goals could result in at least a five-fold increase in clean hydrogen use and unlock new markets for hydrogen, such as steel manufacturing, clean ammonia, energy storage, and heavy-duty trucks. DOE plans to hold a series of events to engage stakeholders, the first of which is the Hydrogen Shot Summit, planned for August 31–September 1, 2021.
- **DOE-Wide Hydrogen Request for Information:** In June 2021, the Program issued a **request for information**, in support of Hydrogen Shot, to solicit information on potential clean hydrogen demonstration opportunities and locations across the United States. The request for information included questions about infrastructure, end users, emissions reduction potential, and basic science needs, as well as DEI needs to ensure our work takes environmental justice issues and disadvantaged communities into consideration.
- **New Consortia:** HFTO launched the **Million Mile Fuel Cell Truck (M2FCT)** and the Hydrogen from Next-generation Electrolysis of Water (**H2NEW**) consortia to advance fuel cell truck and hydrogen production research and development (R&D). This announcement built upon EERE's intention to invest up

[8] DOE, *Department of Energy Hydrogen Program Plan*, DOE/EE-2128, November 2020, https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf.

to $100 million over five years, subject to appropriations, to reduce the cost of fuel cells for trucks and of electrolyzers for hydrogen production.

- **Funding and Financial Opportunity Announcements:** In FY 2020–2021, DOE announced more than $175 million in funding opportunity announcements (FOAs) for hydrogen-related RDD&D, as shown in Table 2 and Table 3, found at the end of this subsection.
- **Program Records:** To document the source of key numbers or facts that are cited by the Program, **program records** have been developed to explain inherent assumptions, source data, and calculation methodologies. Seventeen new program records were published in FY 2020–2021, including records documenting targets for Class 8 long-haul hydrogen fuel cell trucks, durability-adjusted fuel cell system cost, reversible fuel cell targets, hydrogen production cost from electrolysis, hydrogen fueling station costs, and hydrogen delivery and dispensing cost. The complete list of program records published since 2005 is available on the DOE Hydrogen Program webpage.[9]
- **Workshops:** The research community, government, and the private sector came together in **various DOE workshops** to identify gaps in RDD&D and next steps to enable large-scale hydrogen use. Examples of workshops held by HFTO[10] include the following:
  - The **H2@Airports Workshop** was held November 4–6, 2020, in collaboration with the U.S. Department of Transportation (DOT) Federal Aviation Administration, the U.S. Air Force, and the U.S. Navy. This virtual workshop convened experts from civilian government, the military, academia, and industry to share information on the status of hydrogen and fuel cell technologies for unmanned aerial vehicles, aircraft, and ground support applications.
  - The **Marine Energy to Hydrogen Working Meeting** was held February 17, 2021. Research, industry, and government representatives met virtually to discuss opportunities and challenges of integrating marine renewable energy resources with hydrogen energy storage.
  - The **Ammonia for H2@Scale Virtual Panels** were held May 6–7, 2021. These invitation-only panels focused on the growing opportunities for ammonia as a viable clean-hydrogen carrier serving diverse end uses and supporting important economic and environmental imperatives.
  - The **Advances in Liquid Hydrogen Storage Workshop** was held August 18, 2021, in collaboration with the National Aeronautics and Space Administration (NASA). U.S. and international stakeholders from industry, academia, and government agencies met virtually to discuss DOE liquid-hydrogen-related initiatives and outlook and to learn about recent advances in large-scale liquid hydrogen storage technologies and projects at NASA.
- **Interagency Collaboration:** Collaboration among federal agencies was strengthened in FY 2021 through various mechanisms, including a multi-agency announcement from DOE (with contributions from HFTO and EERE's Vehicle Technologies Office [VTO]), the U.S. Department of Defense, and the U.S. Department of Homeland Security to support the H2Rescue truck that will travel to disaster relief sites and provide power, heat, and water. HFTO also continued to lead the **Hydrogen and Fuel Cells Interagency Working Group**, which consists of multiple federal agencies that meet regularly to exchange information about hydrogen and fuel cell RDD&D projects and collaborate and coordinate on related activities.[11]
- **Global Collaboration:** Increased global collaboration in hydrogen emerged as a predominant theme during multiple international engagements with minister-level participation, including the Hydrogen, Clean Energy, and Group of Twenty (G20) Ministerials. These meetings set key priority areas and provided guidance for working-level participation in partnerships between governments. Below are highlights for the government-led global initiatives with which the Program engaged closely during 2021:
  - **International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE):** The IPHE, established in 2003, brings together more than 20 governments at the technical program level to advance worldwide progress in hydrogen and fuel cells. The HFTO Director served as chair while representing the United States from 2018 to 2020; she has completed her term as elected chair and

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[9] DOE, "Program Records," accessed 2022, https://www.hydrogen.energy.gov/program_records.html.

[10] For more information on these and other HFTO workshops, see https://www.energy.gov/eere/fuelcells/workshop-and-meeting-proceedings.

[11] DOE, "Hydrogen Program: Hydrogen and Fuel Cells Interagency Working Group," accessed 2022, https://www.hydrogen.energy.gov/hfciwg.html.

currently serves as a vice chair. In addition to convening several meetings, IPHE, with HFTO leadership, established an International Early Career Network[12] to advance STEM and DEI through a collaborative platform for students, post-docs, and early career professionals; the aim is to foster development of the next generation of hydrogen researchers, experts, and leaders. Other key accomplishments include developing a common analytical framework for calculating the hydrogen greenhouse gas emissions footprint across all countries, as well as a compendium of regulations, codes, and standards to identify gaps and foster harmonization in key areas to ensure interoperability across countries and a robust global supply chain.

- **International Energy Agency:** The United States engages with the International Energy Agency (IEA) Hydrogen and Advanced Fuel Cells Technology Collaboration Programmes (TCPs). These TCPs provide a mechanism for member countries to share the results of pre-competitive RDD&D and analysis related to fuel cell and hydrogen technologies through executive committee and annex meetings, topical and outreach meetings, publications from the annexes and other groups, newsletters, and other forms of exchange. Both HFTO and FECM experts are engaged in steering the TCPs aligned with R&D needs and priorities. In support of the Clean Energy Ministerial, IEA also published a key global report on the status of hydrogen and fuel cells; the DOE Hydrogen Program contributed through analysis and peer review.
- **Hydrogen Energy Ministerial Meeting (HEM):** Japan initiated the HEM in October 2018 as a platform to encourage countries worldwide to promote global use of hydrogen and to engage ministerial-level participation. The United States, through HFTO's participation, has been engaged with HEM since its inception, including through support of the HEM's Global Action Agenda to enable worldwide progress on hydrogen. Thousands of stakeholders joined the 2021 HEM meeting, held October 4, 2021, which included ministers as well as recordings and moderated expert panels, including by the HFTO Director.
- **Clean Energy Ministerial Hydrogen Initiative:** In May 2019, Canada spearheaded the launch of the New Hydrogen Initiative as part of the Clean Energy Ministerial, along with co-leads: the European Commission, Japan, the Netherlands, and the United States. HFTO has been providing leadership and support, as co-lead, and working with the IEA secretariat to ensure resources are leveraged to avoid duplication of efforts already covered under other initiatives and to maximize effectiveness. Key activities in 2021 included the launch of the Global Ports Initiative, led by the European Commission, and development of the H2 Twin Cities initiative, through leadership from HFTO, in collaboration with other countries.
- **Mission Innovation's Clean Hydrogen Mission:** In 2021, Mission Innovation, which was initiated in 2015 as part of the Paris Climate Agreement, launched three new missions: Clean Hydrogen, Power, and Shipping. HFTO is a key contributor to the Clean Hydrogen Mission and serves as co-lead. In addition to the United States, co-leads include Australia, Chile, the European Commission, Saudi Arabia, and the United Kingdom. The key research and innovation goal of the Clean Hydrogen Mission is achieving a target of $2/kg for clean hydrogen across the system, from hydrogen production to the point of end use, and thus is well-aligned with the Hydrogen Shot goal of $1/kg for the production portion of clean hydrogen. Other goals include a commitment to establishing hydrogen "valleys," or clusters of hydrogen initiatives across the complete hydrogen value chain, from production through end use. FY 2021 marked the inception of the mission with broad stakeholder engagement and identification of the path forward through three pillars: Research and Innovation, Demonstrations, and the Enabling Environment. HFTO provides leadership in ensuring this new effort avoids duplication with other initiatives, leverages synergies, and maximizes effectiveness toward common goals.

[12] IPHE, "IPHE E&O WG Early Career Chapter," accessed 2022, iphe.net/early-career-chapter.

Table 2. FY 2021 DOE Hydrogen-Related FOAs

EERE HFTO	**Hydrogen and Fuel Cell RD&D – $36 million** • Fuel Cell R&D for Heavy-Duty Applications ($15 million) • Efficient and Innovative Hydrogen Production ($10 million) • High-Flow Fueling Applications ($7 million) • Cost and Performance Analysis for Fuel Cells, Hydrogen Production, and Hydrogen Storage ($4 million) HFTO FOA Project Selections
EERE VTO	**SuperTruck** • Joint SuperTruck FOA with VTO – anticipated HFTO funding of $60 million over five years ($5 million in FY 2021 and $15 million, pending appropriations, in FY 2022)
FECM	**Fossil-Based Hydrogen Production, Transport, Storage and Utilization – $15.5 million (FECM with HFTO Collaboration)** • Solid Oxide Electrolysis Cell (SOEC) Technology Development for Hydrogen Production ($7 million) • Advanced CCUS Systems ($4 million) • Hydrogen Combustion Systems for Gas Turbines – Industrial Class ($4.5 million) FECM FOA Project Selections **University Turbines Systems Research (UTSR) – Focus on Hydrogen (H_2) Fuels – $7 million** • Hydrogen Combustion Fundamentals for Gas Turbines ($3 million) • Hydrogen Combustion Applications for Gas Turbines ($2.4 million) • Hydrogen–Air Rotating Detonation Engines ($1.6 million) FECM FOA Project Selections
NE, EERE HFTO	**Hydrogen Production and End Use Demonstration – $20 million** • HFTO contribution: $12 million • NE contribution: $8 million FOA Announcement
SC	**DOE Early Career Research Program for FY 2021** SC Announcement

Table 3. FY 2020 DOE Hydrogen-Related FOAs

EERE HFTO	**H2@Scale New Markets – $58.2 million** • Electrolyzer Manufacturing R&D ($13.8 million) • Advanced Carbon Fiber for Compressed Hydrogen and Natural Gas Storage Tanks ($10.4 million) • Fuel Cell R&D for Heavy-Duty Applications ($10 million) • H2@Scale New Markets R&D – Hysteel ($8 million) • H2@Scale New Markets Demonstrations ($14 million) • Training and Workforce Development for Emerging Hydrogen Technologies ($2 million) HFTO FOA Project Selections
FECM (FECM–HFTO)	**Small-Scale Solid Oxide Fuel Cell [SOFC] Systems and Hybrid Electrolyzer Technology Development – $34 million** • Hybrid Systems Using Solid Oxide Systems for Hydrogen and Electricity Production ($26 million) • Small-Scale Distributed Power Generation SOFC Systems ($8 million) FECM FOA Project Selections

Office Overviews and Updates

Hydrogen and Fuel Cell Technologies Office

HFTO conducts comprehensive efforts to overcome the technological, economic, and institutional barriers to the development of hydrogen and fuel cells. Key focus areas include hydrogen production from renewables; hydrogen storage, delivery/infrastructure, and utilization; fuel cells for transportation and small stationary applications; and hydrogen and fuel cells for energy storage and end use (industrial/chemical).

HFTO is responsible for coordinating the RDD&D activities for the Program and works in close partnership with programs at DOE and other federal agencies, industry, academia, and national laboratories to:

- Overcome technical barriers through R&D of hydrogen production, delivery, and storage technologies, as well as fuel cell technologies for transportation, distributed stationary power, and portable power applications.
- Address safety issues and facilitate the development of model codes and standards.
- Validate and demonstrate hydrogen and fuel cells in real-world conditions.
- Educate key stakeholders whose acceptance of these technologies will determine their success in the marketplace.

HFTO's RDD&D activities are organized into the following subprogram/activity areas in this report: Hydrogen Technologies; Fuel Cell Technologies; Technology Acceleration; Safety, Codes and Standards; and Systems Analysis. Overviews of the subprograms are provided below, and highlights of key HFTO RDD&D accomplishments and progress are shown in Table 4. More detailed information on each subprogram is provided in the introductions to each section of the merit review results in this report.

Hydrogen Technologies

The Hydrogen Technologies subprogram focuses on research, development, and demonstration (RD&D) to reduce the cost and improve the reliability of technologies used to produce, deliver, and store hydrogen from diverse domestic feedstocks and energy resources. In support of needs identified through H2@Scale efforts, the subprogram is developing a set of hydrogen production, delivery, and storage technology pathways and addressing technical challenges through a portfolio of projects in three RD&D areas:

- **Hydrogen production** addresses low-cost, highly efficient hydrogen production technologies that utilize diverse domestic sources of energy. RD&D activities include advanced water splitting and innovative concepts such as biological hydrogen production. The former is predominantly coordinated through the HydroGEN Advanced Water Splitting Materials consortium (HydroGEN) and the H2NEW consortium to accelerate RD&D of advanced water splitting technologies for clean, sustainable hydrogen production.
- **Hydrogen infrastructure** addresses low-cost, high-efficiency technologies to move hydrogen from the point of production to the point of use. RD&D activities study liquefaction, pipelines, chemical carriers, and tube trailers to transport hydrogen over long distances, as well as compressors, pumps, dispensers, and stationary storage to support the development of hydrogen stations serving fuel cell electric vehicles. The Hydrogen Materials Compatibility Consortium (H-Mat) coordinates RD&D on accelerated test methods and novel, low-cost, durable metals and polymers for use in hydrogen infrastructure.
- **Hydrogen storage** addresses cost-effective onboard and off-board hydrogen storage technologies with improved energy density and lower costs. RD&D activities study high-pressure compressed storage, materials-based storage, and hydrogen carriers. The latter two are coordinated through the Hydrogen Materials–Advanced Research Consortium (HyMARC) to accelerate the discovery and development of breakthrough hydrogen storage materials.

Fuel Cell Technologies

The Fuel Cell Technologies subprogram applies innovative RD&D, with the main goal of developing a diverse portfolio of low-cost, durable, and efficient fuel cells that are competitive with incumbent and emerging technologies across applications.

The subprogram develops targets based on the ultimate lifecycle cost of using fuel cell systems in diverse applications. While the subprogram has previously developed comprehensive technical targets in areas such as light-duty vehicles, it continues to develop and refine additional targets for emerging and high-impact applications. These include heavy- and medium-duty vehicles, maritime applications, stationary power generation (primary and backup), and reversible fuel cells for energy storage.

Cross-cutting challenges for fuel cell development are strategically addressed by the subprogram through focus on materials and components (especially low-platinum-group-metal [low-PGM] and PGM-free catalysts and electrodes); systems and manufacturing (design, standardization, improved supply chains); and analysis and modeling.

Technology Acceleration

The Technology Acceleration subprogram[13] aims to address technology barriers, systems development and systems integration challenges, and other crosscutting activities to enable the H2@Scale vision and support Hydrogen Shot. The subprogram pursues this goal by identifying hydrogen applications and system configurations that can provide more affordable and more reliable clean energy; validating and testing integrated system development; and bridging the gaps between component-level R&D and industry's role in commercialization by integrating technologies into functional systems, reducing costs, and overcoming other barriers to deployment. The subprogram is currently focused on four technology application areas: (1) grid energy storage and power generation, (2) chemical and industrial processes, (3) transportation, and (4) enabling activities such as manufacturing; safety, codes and standards; and workforce development.

Safety, Codes and Standards

The Safety, Codes and Standards (SCS) activity area, as part of the Technology Acceleration portfolio, supports RD&D to improve the fundamental understanding of the relevant physics and to provide the critical data and safety information needed to develop and revise technically sound and defensible codes and standards. These codes and standards provide the technical basis to facilitate and enable the safe and consistent deployment and commercialization of hydrogen and fuel cell technologies in multiple applications. SCS activities include identifying and evaluating safety and risk management measures that are used to define requirements and close the knowledge gaps in codes and standards in a timely manner. SCS activities also focus on promoting safety practices among DOE projects and developing information resources and best practices.

In FY 2021, SCS focused on validating liquid hydrogen release models to help reduce separation distance requirements for liquid hydrogen storage, developing sensor use guidance and wide-area monitoring capabilities to address improper or inadequate deployment of safety sensors, developing low-cost contaminant detection technology to address fuel quality assurance issues, and analyzing component failure modes and quantifying leak size to address component reliability. Most of these activities are not specific to any particular application but provide information that will enable safe hydrogen use across multiple sectors.

Systems Analysis

The Systems Analysis subprogram funds crosscutting analyses to identify technology pathways that can enable large-scale hydrogen use to enable decarbonization, advance environmental justice, and enhance flexibility and resilience of the energy system. To perform these foundational analyses, the subprogram uses a diverse portfolio of both focused and integrated models and tools that characterize technology costs, performance, impacts, and cross-sector market potential. These tools and capabilities are continuously updated and enhanced, while new tools are also developed as needed. Analyses in FY 2021 focused on identifying the role of hydrogen in hard-to-decarbonize sectors, characterizing factors such as the role of hydrogen in long-duration energy storage, the impact of hydrogen use on lifecycle emissions of industrial applications, market segmentation in medium- and heavy-duty transportation, and the impact of growth in hydrogen and fuel cells on global sustainability.

[13] Technologies Acceleration as referred to in the congressional budget request was renamed Systems Development and Integration.

Table 4. Selected Examples of HFTO RDD&D Progress and Accomplishments, FY 2020–2021

Hydrogen Technologies

Hydrogen Production

- ✓ Launched the H2NEW consortium, convening national labs, industry, and academia, to enable meeting hydrogen production cost and performance targets.
- ✓ Demonstrated improved anion exchange membrane electrolysis durability over ~750 hours at relevant current density.
- ✓ Established a promising interconnect protective coating for the air–O_2 side of high-temperature electrolysis stacks.
- ✓ Achieved a 2.5× higher solar-to-hydrogen efficiency than state-of-the-art perovskite cells in an integrated 3D-printed photoelectrochemical reactor.

Hydrogen Storage

- ✓ Selected four new carbon fiber RD&D projects to address the cost of carbon fiber composite vessels for hydrogen storage.
- ✓ Synthesized the best-performing metal–organic framework (MOF) for room-temperature hydrogen adsorption and the first MOF with a binding enthalpy in the optimal range for ambient temperature storage (-15 to -25 kJ/mol).
- ✓ Improved MgB_2-$Mg(BH_4)_2$ hydrogenation conditions by 100°C and 200 bar over state of the art.
- ✓ Demonstrated 2× (de)hydrogenation rates for high-capacity Li/Mg-amides through nanoconfinement in carbons.

Hydrogen Infrastructure

- ✓ Launched the HyBlend initiative with national labs, industry, and academia to address challenges to hydrogen blending with natural gas.
- ✓ Accelerated progress in materials compatibility through H-Mat:
  - Used advanced imaging and chemical analysis to identify causes for damage to seals in hydrogen service.
  - Determined that ductility was reduced by 50% in austenitic stainless steels in a cryogenic (20 K) hydrogen environment.
- ✓ Completed design and construction of a high-flow hydrogen fueling system at the National Renewable Energy Laboratory (NREL) Energy Systems Integration Facility. The facility will be capable of fueling at 10 kg/min, enabling a first-of-its-kind facility for testing high-flow hydrogen fueling.
- ✓ Developed the publicly accessible H2FillS model, allowing users to simulate the impact of varying fueling methods on the thermodynamics of fueling equipment and on-board hydrogen storage.

Fuel Cell Technologies

- ✓ ***Established the Million Mile Fuel Cell Truck (M2FCT) Consortium:*** This coordinated effort across national labs, academia and industry will enable meeting durability, cost, and efficiency targets for fuel cells in long-haul, heavy-duty truck applications.
- ✓ ***Determined Heavy-Duty Vehicle Fuel Cell Targets and Costs:*** Based on extensive industry input and peer review, Class 8 long-haul tractor–trailer cost targets were determined to be \$80/kW (by 2030), and \$60/kW ultimately. Current (2019) heavy-duty vehicle fuel cell technology was estimated to cost ~\$190/kW (at manufacturing volume of 1,000 units per year).[14]
- ✓ ***Improved Catalyst Activity***: Achieved over 2× improvement in PGM-free catalyst activity over the 2016 baseline of 16 mA/cm^2. Performance exceeded the FY 2021 catalyst activity target (38 mA/cm^2 vs. 35 mA/cm^2). Over 190 unique catalysts were synthesized, with 30% enhancement in oxygen reduction reaction (ORR) activity performance vs. the highest ORR activity reported in 2020.
- ✓ ***Developed Accelerated Stress Testing Protocols***: The Accelerated Stress Test Working Group (ASTWG) was formed to recommend test protocols and performance targets for fuel cells in heavy-duty vehicle applications. M2FCT has developed a membrane electrode assembly durability accelerated stress test, incorporating relevant degradation mechanisms for catalyst, support, electrodes, and membrane, and the test is being validated in coordination with the ASTWG.
- ✓ ***Improved Fuel Cell Bus Durability***: Fuel cell bus durability was determined to be 17,000 hours, with less than 20% degradation, approaching the DOE–DOT interim fuel cell bus target of 18,000 hours.
- ✓ ***Developed Reversible Fuel Cell Targets***: Performance, cost, and durability targets for unitized reversible fuel cells (for electric energy storage applications) were developed and disseminated to stakeholders. These include targets for both low- and high-temperature technologies, at both the cell/stack and system levels, with the same stack operating in both fuel cell and electrolyzer modes.

[14] DOE, Hydrogen Class 8 Long Haul Truck Targets, Hydrogen Program Record #19006, October 31, 2019, https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf; Dimitrios Papageorgopoulos, "Fuel Cell Technologies Overview," presentation at the DOE 2021 Hydrogen Program Annual Merit Review and Peer Evaluation Meeting, June 7, 2021, https://www.hydrogen.energy.gov/pdfs/review21/plenary8_papageorgopoulos_2021_o.pdf.

Table 4 (cont.)

Technology Acceleration

- ✓ Launched new demonstration projects using clean hydrogen to decarbonize industry and power generation:
  - In California, initiated a demonstration for first-of-its-kind maritime hydrogen refueling on a floating barge with up to a half ton of hydrogen per day.
  - In Missouri, kicked off two HySteel projects to demonstrate using hydrogen to decarbonize iron and steel production, with a reduction of 30% in energy and 40% in emissions vs. conventional processes.
  - In Washington, initiated the first-ever at-scale demonstration of hydrogen fuel cell power for data centers to provide reliable and resilient power.
  - In New York, demonstrated a megawatt-scale electrolyzer integrated with a nuclear power plant (in collaboration with NE).
- ✓ Validated two high-temperature electrolyzers from industry, including a 25 kW stack that surpassed 4,000 hours with <0.5% degradation per 1,000 hours.
- ✓ Established an integrated megawatt-scale hydrogen production, storage, and fuel cell system at NREL's Advanced Research on Integrated Energy Systems (ARIES) facility.
- ✓ Supported the launch of global initiatives, including Mission Innovation:
  - Shipping – supported an international effort on decarbonizing marine applications.
  - Clean Hydrogen Mission – co-led initiatives and co-hosted a workshop on hydrogen for mining, agriculture, and construction equipment/vehicles.

Safety, Codes and Standards

- ✓ Developed a comprehensive federal regulatory map to identify gaps across agencies related to the hydrogen value chain.
- ✓ Through collaboration with the Center for Hydrogen Safety, created new safety courses and updated safety best practices.
- ✓ Through ASME Code Case 2938, enabled up to 3× longer life for Type I and II tanks.

Systems Analysis

- ✓ Developed the StoreFAST tool to evaluate the cost of hydrogen energy storage relative to alternatives in user-defined scenarios. Analyzed current and future costs of long-duration energy storage in high-renewable grids.
- ✓ Evaluated the total cost of ownership of batteries, fuel cells, and combustion engines in medium- and heavy-duty vehicles, with varying ranges and operating conditions.
- ✓ Partnered with over 20 countries to develop a common analytical framework for calculating the emissions footprint of hydrogen to enable a harmonized approach and facilitate international trade of clean hydrogen.

Workforce Development and DEI

- ✓ Expanded partnerships enabling national lab engagement with students from historically black colleges and universities to build a diverse hydrogen and fuel cell workforce pipeline.
- ✓ Contributed $2.6 million to a partnership between the University of Tennessee and Oak Ridge National Laboratory in creating a national model for workforce development in energy-related disciplines, enhancing interdisciplinary R&D.
- ✓ Aligned FOAs, lab calls, and cooperative research and development agreements (CRADAs) to encourage broader engagement and demonstrate DEI benefits.

Office of Fossil Energy and Carbon Management

In FY 2021, FECM's hydrogen-focused funding was $88.7 million. Related focus areas were low-cost, carbon-neutral hydrogen production and utilization technologies (turbines, gasification, reforming/pyrolysis, SOFCs, and point source carbon capture R&D) and low-cost, reliable, and safe options for bulk hydrogen transport (pipelines) and subsurface storage. Key activities and accomplishments through June 2021 included:

- Developing hydrogen combustion fundamentals and analysis tools to enable low-nitrogen oxide hydrogen combustor designs and zero-carbon power generation.
- Conducting successful commercial demonstration of the world's largest clean hydrogen facility (Port Arthur, Texas), which is based on steam methane reforming with carbon capture and utilization and has been in operation for seven years.
- Completing pre-front-end engineering design (pre-FEED) studies for a clean hydrogen production facility, which is now shifting the design to using waste coal, biomass, and plastic feedstocks.
- Developing several pre-combustion (CO_2/H_2) separation technologies at a small pilot scale.
- Developing reversible SOFC technologies to produce either hydrogen or electricity, depending on grid demand.

Office of Nuclear Energy

In FY 2021, NE focused on RD&D to support hydrogen production applications for the existing nuclear fleet and advanced reactors. Ongoing research includes five projects demonstrating hydrogen production capabilities at four existing nuclear power plants, including efforts to test human interfaces for integrated plant operation using real operators in a control room environment.

Key activities and accomplishments in FY 2021 included the following:

- Completed high-fidelity technical and economic modeling for integrated design and operation (electricity and hydrogen) of energy systems using a suite of dynamic analysis and optimization tools.
- Confirmed system design and probabilistic risk assessment of commercial-scale heat delivery and hydrogen production at a nuclear plant site.
- Completed the development of a full-scope simulator for a nuclear power plant coupled to a high-temperature steam electrolysis hydrogen plant.
- Developed a prototype human–system interface and used it to test operating concepts for dispatching thermal energy and electrical power to a high-temperature steam electrolysis plant. An interdisciplinary team of operations experts, nuclear engineers, and human factors experts evaluated the performance of previously licensed nuclear plant operators enlisted to test the possible tie of a nuclear reactor to a hydrogen plant.
- Initiated preliminary operational testing of a thermal energy distribution system, an electrically heated system that will allow demonstration of a wide array of integrated energy system configurations, at Idaho National Laboratory. In collaboration with EERE, NE will also establish interconnection with SOECs for hydrogen production at a scale of up to 250 kWe (~125 kg H_2/day).

Office of Science, Basic Energy Sciences

In FY 2021, SC focused on fundamental chemical and materials science research to advance understanding and transformative approaches for hydrogen generation and use. Recent accomplishments included:

- Materials discovery and mechanistic study of semiconductor–electrolyte interfaces, which led to an efficiency of 19% for photoelectrochemical production of hydrogen.
- Demonstration of high activity and durability of a novel electrocatalyst in a fuel cell membrane electrode assembly.

Planning is under way for an SC-led Roundtable on Foundational Science for Carbon-Neutral Hydrogen Technologies, to be held in August 2021.[15]

Advanced Research Projects Agency–Energy

ARPA-E FY 2021 funding was $10 million. ARPA-E catalyzes transformational energy technologies to enhance the economic and energy security of the United States. The agency funds high-potential, high-impact projects that are at too early a development stage for private-sector investment but could disruptively advance the ways energy is generated, stored, distributed, and used. Some programs at ARPA-E have sought to develop technologies involving renewable energy, carbon-neutral liquid fuels, and natural gas, with applications in the transportation, commercial, and industrial power sectors; in these areas, there are a number of efforts related to hydrogen. Focused R&D programs relevant to hydrogen or related technologies include:

- Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH)
- Duration Addition to electricitY Storage (DAYS)
- Methane Pyrolysis Cohort
- Innovative Natural-gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-generation (INTEGRATE)
- Integration and Optimization of Novel Ion-Conducting Solids (IONICS)
- Renewable Energy to Fuels through Utilization of Energy-dense Liquids (REFUEL)
- Reliable Electricity Based on ELectrochemical Systems (REBELS)

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[15] The roundtable was held in August 2021: https://science.osti.gov/-/media/bes/pdf/reports/2021/Hydrogen_Roundtable_Brochure.pdf

In Closing…

Despite unprecedented challenges due to COVID-19, including the inability of researchers to return to the laboratory to perform experimental work and supply chain delays, the Program continued to see significant progress during FY 2020 and FY 2021. On the global front, hydrogen continues to gain momentum, with multiple countries developing national hydrogen strategies recognizing the need for hydrogen to meet their climate goals. Large-scale hydrogen use applications are ramping up, with significant public- and private-sector investment across sectors.

The progress is encouraging, but important work remains to be done on multiple fronts: cost needs to be reduced in several areas—without compromising performance—for technologies to be competitive, infrastructure needs to be addressed, and scaling up is key. The next few years will be critical to moving the needle toward sustainable market adoption and realization of the environmental, energy, and economic benefits that can be enabled by hydrogen technologies across the nation.

New flagship initiatives such as the Hydrogen Energy Earthshot will pave the way to success in enabling low-cost hydrogen and its ability to decarbonize applications across sectors. Since the previous AMR, development of the DOE-wide Hydrogen Program Plan set the strategic direction for our activities; the establishment of new consortia and projects set the stage to address the challenges; and collaboration across government, industry, labs, academia, and the environmental and energy justice communities––with emphasis on diversity, equity, and inclusion—will set the stage for continued progress.

DOE will continue to work in close collaboration with key stakeholders and will continue its strong commitment to effective stewardship of taxpayer dollars in support of its mission to enable the energy, environmental, and economic security of the nation. In support of these efforts, the following several hundred pages document the results and impacts of the Program since the previous AMR.

Peer Review Introduction/Methodology

The AMR peer review process followed the guidelines in the Peer Review Guide developed by EERE. Project reviewers provided comments about selected HFTO-funded projects presented during the event. (Not all ongoing HFTO-funded projects were reviewed, particularly those that had just started and made little progress. Appendix D provides a list of projects that were presented at the AMR but not reviewed, including those funded by other DOE offices or external stakeholders.) Panel members included experts from a variety of backgrounds related to hydrogen and fuel cells. As shown in Table 5, these experts represented national laboratories; universities; various government and non-government organizations; and developers and manufacturers of hydrogen production, storage, delivery, and fuel cell technologies. Each reviewer was screened for conflicts of interest, as prescribed by the Peer Review Guide. The project comments, recommendations, and scores are provided in the following sections of this report, grouped by subprogram.

A subset of the reviewers was also asked to provide feedback on the overall DOE Hydrogen Program and HFTO subprograms; a summary of the Program review results is included in Appendix A.

Table 5. Peer Review Panel: Represented Organizations

3M Company	National Institute of Standards and Technology
A.V. Tchouvelev & Associates Inc.	National Renewable Energy Laboratory
Advanced Materials Testing & Technologies	National Research Council Canada
Air Products and Chemicals, Inc.	National Science Foundation
Argonne National Laboratory	Nel ASA
Arizona State University	New Energy and Industrial Technology Development Organization, Japan
Atrex Energy, Inc.	New Jersey Fuel Cell Coalition
AvCarb Material Solutions	Nexceris, LLC
AVL Fuel Cell Canada	Nikola Motor Company
Ballard Power Systems	Northeastern University
Bar-Ilan University	Nuclear Regulatory Commission

Booz Allen Hamilton	Nuvera Fuel Cells, LLC
Boston University	Oak Ridge National Laboratory
California Air Resources Board	Pacific Northwest National Laboratory
California Energy Commission	Pajarito Powder, LLC
California Fuel Cell Partnership	PH Matter
California Governor's Office of Business and Economic Development	Plug Power Inc.
Carnegie Mellon University	Praxair, Inc.
Center for Transportation and the Environment	Precision Combustion, Inc.
Chevron Corporation	Princeton University
Colorado School of Mines	Raytheon Technologies
Commissariat à l'énergie atomique et aux énergies alternatives (CEA, French Atomic Energy Commission)	Redox Power Systems, LLC
Commonwealth Scientific and Industrial Research Organisation, Australia (CSIRO)	Rutgers University
Compagnie de Saint-Gobain S.A.	Sandia National Laboratories
Connecticut Center for Advanced Technology, Inc.	Savannah River National Laboratory
CSA Group	SBC Global Alliance
Cummins Inc.	Schaeffler Technologies AG & Co. KG
Department of Science and Innovation (South Africa)	Secat, Inc.
DJW Technology, LLC	Shell
Drexel University	Someday Consulting, LLC
DuPont Company	Southern California Gas Company
Exelon Corporation	Southern Company Services, Inc.
Exxon Mobil Corporation	Stellantis
Ford Motor Company	Stottler Development LLC
Form Energy, Inc.	Strategic Analysis, Inc.
Frontier Energy	Strategic Marketing Innovations
Fuel Cell and Hydrogen Energy Association	T2M Global
Fuel Cells and Hydrogen Joint Undertaking (FCH JU)	The Chemours Company
FuelCell Energy, Inc.	The Pennsylvania State University
FuelScience, LLC	Toyota Motor North America
General Dynamics Information Technology	U.S. Army, Tank Automotive Research, Development and Engineering Center (TARDEC)
General Motors Company	U.S. Department of Energy, Bioenergy Technologies Office
Georgia Institute of Technology	U.S. Department of Energy, Office of Fossil Energy
Giner, Inc.	U.S. Department of Energy, Office of Science
Graz University of Technology	U.S. Department of Transportation
GVD Corporation	U.S. Department of Transportation, Maritime Administration
Hawaii Natural Energy Institute	U.S. Environmental Protection Agency
Hawaiian Electric Company, Inc.	U.S. Naval Research Laboratory
Helmholtz-Zentrum Geesthacht	University of Arizona
Hyzon Motors Inc.	University of California, Berkeley

Indiana University–Purdue University Indianapolis	University of California, San Diego
International Energy Agency	University of Connecticut
Ion Power, Inc.	University of Illinois at Urbana-Champaign
Largo Clean Energy	University of Maryland
Lawrence Berkeley National Laboratory	University of Michigan, Ann Arbor
LIFTE H2, Inc.	University of New Mexico
Los Alamos National Laboratory	University of South Carolina
Louisiana State University	University of Virginia
Ludlow Electrochemical Hardware	University of Colorado Boulder
Michigan State University	Vanderbilt University
Ministry of the Interior and Kingdom Relations (Netherlands)	Versogen
Nanosonic, Inc.	West Virginia University
NASA, Glenn Research Center	WPCSOL, LLC
NASA, White Sands Test Facility	Xergy, Inc.
National Energy Technology Laboratory	Zero Carbon Energy Solutions

Analysis Methodology

A total of **125** HFTO-funded projects were reviewed at the meeting. A total of **189** review panel members participated in the AMR process, providing **534** project evaluations.

The projects were evaluated using pre-established criteria. Reviewers were asked to provide numeric scores (on a scale of 1–4, including half-point intervals, with 4 being the highest) for five aspects of the work presented. For all projects, reviewers were also asked to provide qualitative comments regarding the five criteria, specific strengths and weaknesses of the project, and any recommendations relating to the work scope. Scores and comments were submitted to a private online database.

The five criteria and weighting were identical for the significant majority of projects, allowing for easy comparison within and across subprograms. There were slight differences in the evaluation forms for HydroGEN Seedling projects and some Fuel Cell Technologies projects that were recently awarded. This section explains these small variations; sample evaluation forms are provided in Appendix C.

For most projects, scores were based on the five criteria and weights provided below.

Score 1: Approach to performing the work (20%)

Score 2: Accomplishments and progress toward overall project and DOE goals (35%)

Score 3: Collaboration and coordination with other institutions (10%)

Score 4: Relevance/potential impact on DOE Program goals and RD&D objectives (20%)

Score 5: Proposed future work (15%)

The individual reviewer scores for each question were averaged to provide information on each of the five key aspects. In addition, an overall score was calculated for each project, as follows: individual reviewer scores for each of the five criteria were weighted using the formula in the box below to create an overall score for each reviewer for that project; then, the overall scores from individual reviewers were averaged to determine one overall project score. In this manner, a project’s final overall score can be meaningfully compared to that of another project.

Final Overall Score = [Score 1 x 0.20] + [Score 2 x 0.35] + [Score 3 x 0.10] + [Score 4 x 0.20] + [Score 5 x 0.15]

A perfect overall score of "4" indicates that a project satisfied the five criteria to the fullest possible extent; the lowest possible overall score of "1" indicates that a project did not satisfactorily meet any of the requirements of the five criteria.

The evaluation form for HydroGEN Seedling projects (included in Appendix C) was modified to address their unique features; the scores for these projects were based on the following five criteria and weights:

Score 1: Approach to performing the work (20%)

Score 2: Accomplishments and progress toward overall project and DOE goals and the HydroGEN Consortium mission (30%)

Score 3: Collaboration effectiveness with HydroGEN and, as appropriate, other research entities (25%)

Score 4: Relevance/potential impact on DOE Program goals and RD&D objectives and the HydroGEN Consortium mission (15%)

Score 5: Proposed future work (10%)

The 2021 AMR also included some recently awarded projects that were placed in a separate scoring panel with modified scoring criteria and weights. The scores for new projects were based on the following five criteria and weights:

Score 1: Approach to performing the work (40%)

Score 2: Accomplishments and progress toward overall project and DOE goals (5%)

Score 3: Collaboration and coordination with other institutions (10%)

Score 4: Relevance/potential impact on Hydrogen Program goals (20%)

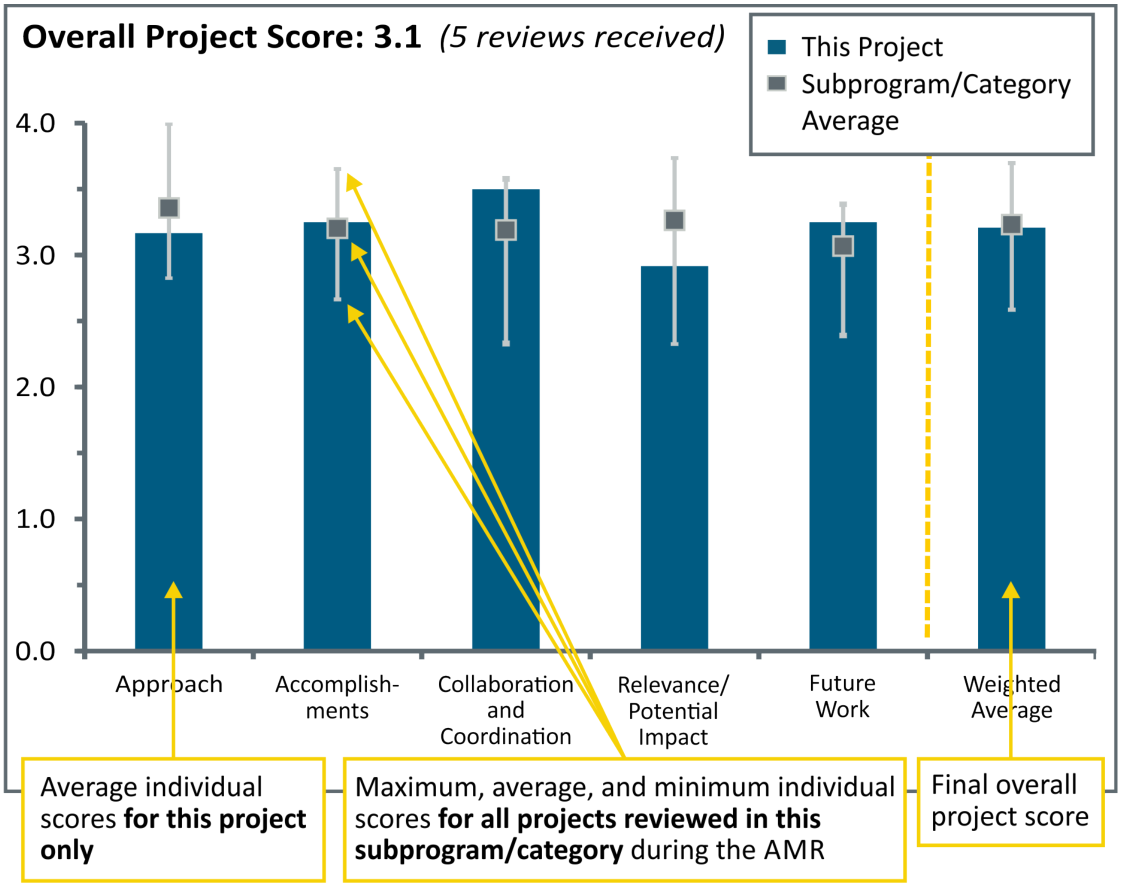
Score 5: Proposed future work (25%)

For this new projects panel, reviewers were given the option not to evaluate Score 2: Accomplishments. (In such instances, the other criteria were re-weighted to total 100%.)

For the Fuel Cell Technologies panel, overall scores were developed in stages. Scores for new projects were first calculated separately, using the weighting above. Scores for projects in the remainder of the panel were computed using normal weighting. Then the two sets of scores were combined so that the minimum, average, and mean scores could be computed for the entire Fuel Cell Technologies panel (new projects included).

Each individual project report also includes a graph showing the overall project score and a comparison of how each project aligns with all of the other projects in its subprogram or category. Projects are compared based on the consistent set of criteria described above. Each project report includes a chart with bars representing that project's average scores for each of the five designated criteria. The gray vertical hash marks that overlay the blue bars represent the corresponding maximum, average, and minimum scores for all of the projects in the same subprogram or category. A sample graph is provided.

Sample Project Score Graph with Explanation



For clarification, consider a hypothetical review in which only five projects were presented and reviewed in a subprogram. Table 6 displays the average scores for each project according to the five rated criteria.

Table 6. Sample Project Scores

	Approach (20%)	Accomplishments (35%)	Collaboration and Coordination (10%)	Relevance/ Potential Impact (20%)	Future Work (15%)
Project A	3.4	3.3	3.3	3.2	3.1
Project B	3.1	2.8	2.7	2.7	2.9
Project C	3.0	2.6	2.7	2.8	2.9
Project D	3.4	3.5	3.4	3.2	3.3
Project E	3.6	3.7	3.5	3.4	3.4
Maximum	3.6	3.7	3.5	3.4	3.4
Average	3.3	3.2	3.1	3.0	3.1
Minimum	3.0	2.6	2.7	2.7	2.9

Using these data, the chart for Project A would contain five bars representing the values listed for that project in Table 6. A gray hash mark indicating the related maximum, average, and minimum values for all of the projects in Project A's subprogram or category (the last three lines in Table 6) would overlay each corresponding bar to facilitate comparison. In addition, each project's criteria scores would be weighted and combined to produce a final, overall project score that would permit meaningful comparisons to other projects. Below is a sample calculation for the Project A weighted score.

Final Score for Project A = [3.4 x 0.20] + [3.3 x 0.35] + [3.3 x 0.10] + [3.2 x 0.20] + [3.1 x 0.15] = 3.3

Hydrogen Technologies – 2021

Subprogram Overview

INTRODUCTION

The Hydrogen Technologies subprogram focuses on research, development, and demonstration (RD&D) to reduce the cost and improve the reliability of technologies used to produce, deliver, and store hydrogen from diverse domestic feedstocks and energy resources. In support of RD&D needs identified through the U.S. Department of Energy's (DOE's) H2@Scale efforts, the Hydrogen Technologies subprogram is developing a set of hydrogen production, delivery, and storage technology pathways. The subprogram addresses technical challenges through a portfolio of projects in three RD&D categories:

- **Hydrogen Production** addresses low-cost, highly efficient hydrogen production technologies that use diverse domestic sources of energy. RD&D activities include advanced water splitting and innovative concepts such as biological hydrogen production. The former is predominantly coordinated through the HydroGEN Advanced Water Splitting Materials consortium (HydroGEN) and the Hydrogen from Next-generation Electrolysis of Water consortium (H2NEW) to accelerate RD&D of advanced water-splitting technologies for clean, sustainable hydrogen production.
- **Hydrogen Infrastructure** addresses low-cost, high-efficiency technologies to move hydrogen from the point of production to the point of use. RD&D activities investigate liquefaction, pipelines, chemical carriers, and tube trailers to transport hydrogen over long distances, as well as compressors, pumps, dispensers, and stationary storage to support the development of hydrogen stations serving fuel cell electric vehicles. The Hydrogen Materials Compatibility Consortium (H-Mat) coordinates RD&D on accelerated test methods and novel, low-cost, durable metals and polymers for use in hydrogen infrastructure.
- **Hydrogen Storage** addresses cost-effective onboard and off-board hydrogen storage technologies with improved energy density and lower costs. RD&D activities investigate high-pressure compressed storage, materials-based storage, and hydrogen carriers. Activities in the latter two topic areas are coordinated through the Hydrogen Materials–Advanced Research Consortium (HyMARC) to accelerate the discovery and development of breakthrough hydrogen storage materials.

In fiscal year (FY) 2020 and FY 2021,[1] projects in the Hydrogen Production category focused primarily on RD&D for advanced water-splitting materials and systems through HydroGEN, which is part of the DOE Energy Materials Network, and the H2NEW consortium. Production pathways under investigation include four advanced water-splitting technologies: high- and low-temperature electrolysis, direct solar thermochemical hydrogen production, and photoelectrochemical water splitting. Additional work outside of HydroGEN included RD&D on microbial-based processes using biomass and waste-stream feedstocks and efforts leveraging electrolysis technology for carbon dioxide (CO_2) reduction to useful chemicals and fuels. Hydrogen Infrastructure projects included (1) low-cost, high-efficiency liquefaction, pipelines, chemical carriers, and tube trailers; (2) low-cost and reliable compressors, pumps, dispensers, and stationary storage; and (3) hydrogen delivery technologies analysis. Hydrogen Storage projects in FY 2020 and FY 2021 focused on materials-based hydrogen storage RD&D through HyMARC, advanced tanks through innovative approaches to develop low-cost carbon fiber precursors, large-scale hydrogen storage through hydrogen carriers, and storage technologies for medium- and heavy-duty transportation.

GOAL

The overarching goal of the Hydrogen Technologies subprogram is to enable commercialization of sustainable and efficient hydrogen technologies that are competitive with incumbent technologies in terms of cost and performance, across diverse applications. The subprogram pursues this goal by developing solutions for all aspects of the

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[1] This subprogram overview covers the period since the publication of the last annual progress report in April 2020 (see U.S. Department of Energy, *DOE Hydrogen and Fuel Cells Program 2019 Annual Progress Report*, https://www.hydrogen.energy.gov/annual_progress19.html).

hydrogen pathway—from hydrogen production, leveraging the nation's diverse renewable resources, to all aspects of hydrogen infrastructure, including the storage, transmission, distribution, delivery, and dispensing of hydrogen for various delivery pathways and end uses.

KEY MILESTONES

- Reduce the cost of clean hydrogen production from diverse domestic resources to <$2/kg by 2025 and to $1/kg by 2030.
- Reduce the cost of delivering and dispensing hydrogen to a fuel cell electric vehicle to <$2/kg by 2025. This cost is independent of the technology pathway and takes into consideration a range of assumptions for fuel cell electric vehicles to be competitive.
- Develop onboard hydrogen storage systems for Class 8 long-haul tractor-trailers, achieving a cost of $9/kWh by 2030 and the capability to withstand 11,000 pressure cycles.

FISCAL YEAR 2021 TECHNOLOGY STATUS AND ACCOMPLISHMENTS

The Hydrogen Technologies subprogram actively monitors technical progress achieved through the Hydrogen Production, Hydrogen Infrastructure, and Hydrogen Storage RD&D project portfolios. That progress is incorporated into the technology status with respect to performance metrics such as cost, efficiency, and energy density. The status of various technologies being funded by the subprogram is described below.

Hydrogen Production

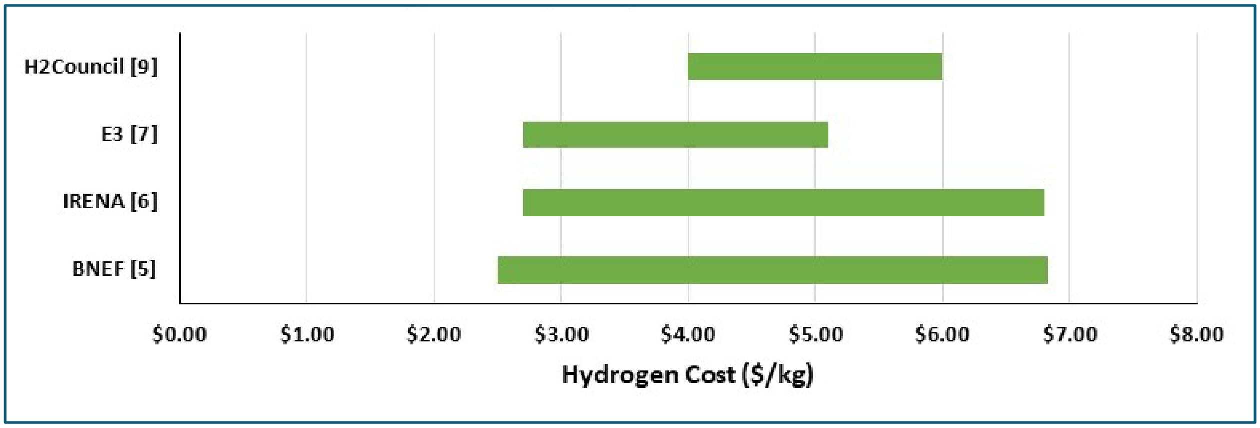
RD&D is focused on reducing the cost and improving the efficiency of producing clean hydrogen from domestic, renewable feedstocks and energy resources. Feedstocks include water, biomass, and organic waste such as wastewater and food waste. Clean hydrogen can be produced at either large centralized or smaller distributed production facilities.

- **Near- to Mid-Term Electrolysis Options:** These approaches for clean hydrogen production use different electrolyzer technologies—with some operating at low temperatures (using polymer membranes limited to <100°C) and others at high temperatures (using solid oxide membranes that operate efficiently at >600°C). Low-temperature polymer electrolyte membrane (PEM) electrolyzers are commercially available at the megawatt scale but currently provide a relatively small portion of the hydrogen in the United States. High-temperature solid oxide electrolyzers offer higher electrical conversion efficiencies but are at an earlier stage of development, with only small-scale manufacturing under way. There is a growing interest in integrating electrolyzers with renewable energy sources, which could lead to greater manufacturing demand for both low- and high-temperature electrolysis. Higher volumes of electrolyzer manufacturing, coupled with further RD&D advances, are needed to achieve cost parity with hydrogen produced from natural gas.

  The figure below shows published costs of hydrogen production from currently available PEM electrolyzers, collected from several external sources.[2] Overall, these data show that hydrogen can be produced today within a cost range of ~$2.50–$6.80/kg from a mix of renewable and grid feedstocks. This is in good alignment with the DOE analysis, which shows that hydrogen can be produced via PEM electrolysis at a cost of ~$4–$6/kg for specific conditions.

[2] U.S. Department of Energy, "Cost of Electrolytic Hydrogen Production with Existing Technology," Program Record #20004, September 22, 2020.

Existing PEM Hydrogen Production Costs



- **Longer-Term Innovative Hydrogen Production – Beyond Electrolysis:** Emerging longer-term options for hydrogen production from renewable resources are at varying stages of development. While there are currently some plant-scale operations in service to extract hydrogen from biomass and waste-stream feedstocks using thermal and catalytic processes (such as biomass gasification), newer and more promising approaches using these feedstocks are in earlier stages of development. These include microbial processes such as fermentation and microbial electrolysis. Other promising renewable approaches in their early stages include photoelectrochemical and solar thermochemical processes, which use direct solar and solar thermal energy, respectively, to split water without the efficiency losses associated with converting the energy source into electricity.

Hydrogen Infrastructure

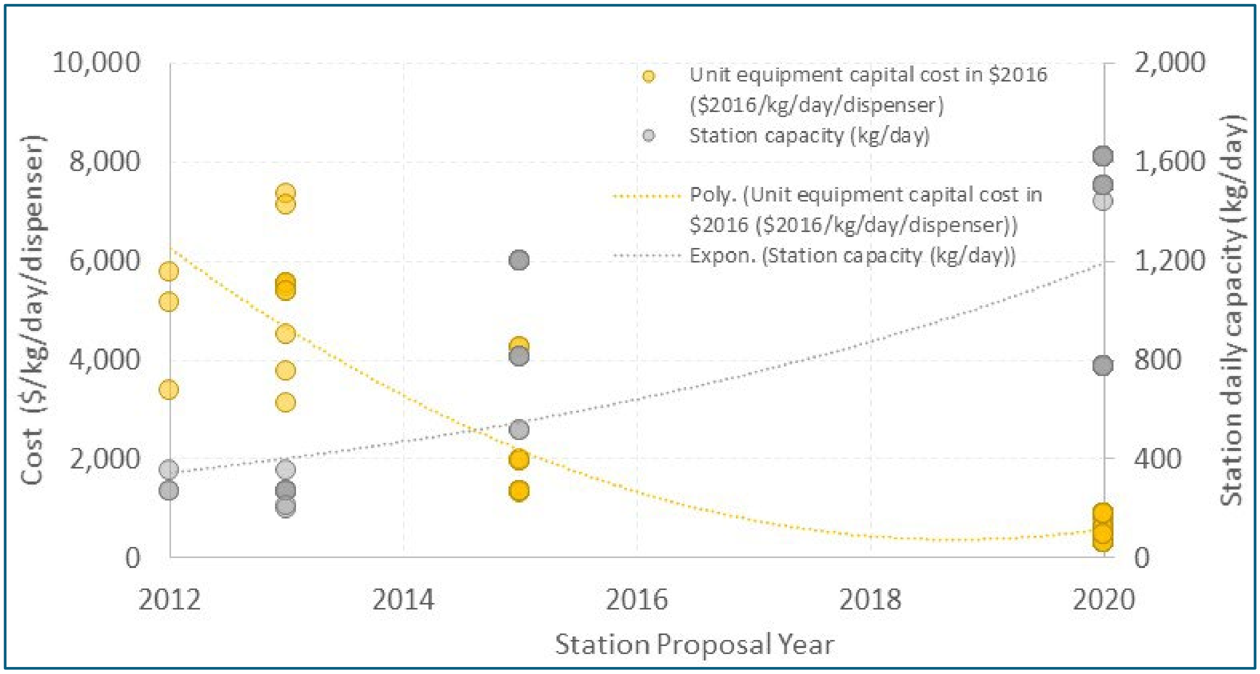
Hydrogen can be transported and distributed as a compressed gas, as a cryogenic liquid, or bound within a chemical hydrogen-carrier material. Each of the delivery methodologies requires a range of technologies, such as compressors, liquefiers, and dispensing technologies (which may need to meet specific needs for the particular application). The Hydrogen Infrastructure activity focuses on developing these technologies to meet targets for dispensed hydrogen. It also works to identify materials for hydrogen delivery technologies (e.g., pipelines) that are compatible with hydrogen under various operating conditions. Hydrogen delivery options in the subprogram's RD&D portfolio are discussed below.

- **Near- to Mid-Term Hydrogen Transport and Dispensing for Heavy-Duty (and Other Near-Term) Applications:** In the near- to mid-term, it is expected that most of the hydrogen for these applications will be delivered as a compressed gas—either via pipeline or using high-pressure tanks—or as a cryogenic liquid. Most hydrogen is supplied via pipeline today for use in petroleum refining. For other current end uses in the transportation, industrial, and chemical sectors, hydrogen is commonly transported and stored as either a high-pressure compressed gas (via pipeline or truck) or cryogenic liquid (via tanker). Near- and mid-term RD&D efforts are focused on reducing the cost of these technologies and minimizing the losses of hydrogen that occur during transport and dispensing.

  Over the past decade, hydrogen fueling stations have declined in cost as a result of both RD&D and economies of scale. The evolution of costs and capacities of stations proposed for construction in California is depicted below.[3] Stations for heavy-duty fueling are expected to be several-fold larger in capacity than those proposed to date for light-duty markets in California, and to also require fueling at about 5X faster flow rates than light vehicles. These deployments will require designs for components such as compressors, dispensers, and chillers. In support of this market, in FY 2021, the DOE issued multiple solicitations around development of high-flow fueling equipment, including a funding opportunity announcement and two Small Business Innovation Research (SBIR) topics.

[3] U.S. Department of Energy, "Hydrogen Fueling Stations Cost," Program Record #21002, February 11, 2021.

Costs of Hydrogen Fueling Station Equipment in Proposals to the California Energy Commission



- **Longer-Term Advanced Hydrogen Liquefaction and Carrier Distribution Approaches:** Over the longer term, innovative approaches to liquid hydrogen production, storage, transport, and dispensing are expected to enable new, expanded opportunities for large-scale liquid hydrogen use. Key challenges include minimizing hydrogen losses and reducing the cost of liquefaction technologies. Another emerging option is the use of chemical hydrogen carriers, which are solid or liquid materials to which hydrogen temporarily bonds, enabling low-pressure, high-capacity transport and storage. Carriers have been deployed in prototype demonstrations to supply hydrogen to industrial applications (such as thermal power generation) and are currently being explored for use in bulk transport and storage of hydrogen, including on marine vessels for a potential export market.

Hydrogen Storage

Hydrogen can be stored either physically, as a compressed gas or cryogenic liquid, or as a material within which the hydrogen is physi- or chemisorbed. Each storage methodology has advantages and disadvantages, making it more or less suitable for specific applications. Key challenges for all are reducing the cost of storage and improving the overall performance of the technology.

- **Near- to Mid-Term High-Pressure Tanks and Other Physical Hydrogen Storage Options:** RD&D to improve physical storage methods is focused primarily on reducing cost and minimizing losses from tanks and other technologies in use today for compressed gaseous and liquid hydrogen storage. Compressed gaseous hydrogen can also be contained in bulk in caverns (i.e., underground rock-lined or salt caverns) for long-duration storage applications; however, this approach is limited to specific geographical areas, and further research and optimization are needed to address cost and safety issues. Activities also look at development of other large-scale bulk storage technologies for practical applications.
- **Longer-Term Material-Based Hydrogen Storage Options:** Longer-term RD&D is focused on material-based options such as adsorbents, metal hydrides, and chemical hydrogen carriers to open new opportunities in affordable hydrogen storage. These approaches offer the potential to achieve comparable hydrogen storage densities, but at near-ambient operating conditions, without the need for high pressures (as in compressed hydrogen storage) or very low temperatures (as in cryogenic liquid hydrogen storage), both of which add significant energy expenditures and costs to the entire pathway.

SUBPROGRAM-LEVEL ACCOMPLISHMENTS

The Hydrogen Technologies subprogram made significant progress during FY 2020 and FY 2021. The subprogram released two funding opportunity announcements (FOAs), resulting in the award of five new electrolyzer manufacturing projects; two microbial electrolysis projects to produce hydrogen from biomass waste streams; two analysis projects to assess the cost and performance of hydrogen production and hydrogen storage pathways, respectively; three RD&D projects to build the domestic supply chain for high-flow hydrogen fueling stations for heavy-duty applications; four RD&D projects to develop advanced carbon fiber for compressed hydrogen and natural gas storage tanks; and one project on developing and validating the engineering design of ultra-large-scale liquid hydrogen storage tanks. In addition, eight Small Business Innovation and Research (SBIR) Phase I projects were awarded: three to address hydrogen RD&D challenges and advance progress in hydrogen production from wind power, three to develop low-cost scalable hydrogen pre-cooling and filter technologies for heavy-duty stations, and two to mitigate boil-off losses in liquid hydrogen storage systems. The subprogram also awarded one Phase II SBIR project on the evaluation of micrometer-scale flaws in pressure vessels and six Cooperative Research and Development Agreement (CRADA) projects.

Another notable development in the Hydrogen Technologies subprogram is the merger of the U.S. DRIVE Partnership's Hydrogen Delivery and Hydrogen Storage Tech Teams into one technical team: the Hydrogen Delivery and Storage Tech Team (HDSTT). The HDSTT works to ensure close communications across delivery and storage pathways to focus efforts on viable, long-term solutions that are compatible and complementary, while also identifying technology gaps impeding commercialization.

Accomplishments in each of the subprogram's RD&D areas are described below.

Hydrogen Production

- The HydroGEN Benchmarking Project team held the 2nd and 3rd Annual Advanced Water-Splitting Technology Pathways Benchmarking and Protocols Workshops.
    - The second annual workshop for the HydroGEN Benchmarking Project was held October 29–30, 2019, at the Scottsdale campus of Arizona State University. The workshop, which was open to international participants, was attended by about 90 people, with representation evenly distributed across the water-splitting technology areas. Effort was made to engage at least one international representative for each technology to summarize related initiatives in Europe and encourage communication and awareness.
    - The third annual workshop for the HydroGEN benchmarking project, originally scheduled for fall 2020, was rescheduled to March 2021 and held as a virtual workshop. Approximately 200 people attended, with 20–50 participants across each of 29 breakout sessions. Participation was evenly distributed across the water-splitting technology areas. At least three countries were represented.
    - The HydroGEN Benchmarking Project drafted four advanced water splitting pathway roadmaps and drafted and reviewed 45 test protocols. The team is currently drafting 25 additional protocols. The protocols are to be published in an upcoming issue of *Frontiers in Energy*.
- The subprogram awarded the HydroGEN Energy Materials Network Phase 2 project (HydroGEN 2.0), a three-year project comprising five new lab projects and five supernode projects.[4] The lab projects will focus on low-technology-readiness-level advanced water-splitting materials for alkaline exchange membrane electrolysis, metal-supported solid oxide electrolysis cells (SOECs), proton-conducting SOECs, photoelectrochemical hydrogen production, and solar thermochemical hydrogen production.
- The H2NEW consortium was launched in October 2020. This consortium consists of nine national laboratories, led by the National Renewable Energy Laboratory and Idaho National Laboratory. H2NEW will conduct RD&D to enable large-scale manufacturing of affordable electrolyzers that use electricity to split water into hydrogen and oxygen. The work will focus on materials and component integration,

[4] In 2019, DOE established five new "supernodes" within the HydroGEN consortium through which multiple lab capability nodes and experts work synergistically to address specific water-splitting materials problems or research needs.

manufacturing, and scale-up to help support large industry deployment of durable, efficient, and low-cost electrolyzers for hydrogen production.

- The subprogram developed four program records (Records 19009, 20004, 20006, and 20009) documenting the 2019 hydrogen production cost from PEM electrolysis, the cost of electrolytic hydrogen production with existing technology, the hydrogen production cost from high-temperature electrolysis, and electrolyzer capacity installations in the United States.

Hydrogen Infrastructure

- The National Renewable Energy Laboratory, in partnership with Air Liquide, Honda, Shell, and Toyota under the Innovating Hydrogen Stations CRADA, is currently in the process of commissioning a test facility with first-of-its-kind, experimental research capability for 10 kg/min, 60+ kg hydrogen fueling for heavy-duty applications. This facility will be used to conduct experimentation that informs the laboratory's computational models of high-throughput fueling and may be used in future RD&D to develop and test new fueling technologies.
- The subprogram developed three program records (Records 19001, 21002, and 20007) documenting the current cost status of hydrogen liquefaction, hydrogen delivery and dispensing, and hydrogen fueling stations.

Hydrogen Storage

- The subprogram hosted the Novel Pathways for Optimized Hydrogen Transport & Storage Workshop on November 13–14, 2019, to engage stakeholders from industry, academia, and DOE national laboratories in determining the suitability and requirements of hydrogen carrier materials as a novel pathway for hydrogen transport and stationary storage. The workshop was attended by approximately 75 participants.
- The subprogram hosted the Compressed Gas Storage for Medium- and Heavy-Duty Transportation Workshop on January 21, 2020. Participants identified performance gaps and technology metrics (e.g., weight, volume, cost, and durability) that can enable competitiveness of compressed gas storage technologies in medium- and heavy-duty transportation. The workshop was attended by 63 representatives of government, laboratory, academia, and industry.
- The subprogram published a program record (Record 19008) documenting the cost and performance status of onboard Type IV compressed hydrogen storage systems.

NEW PROJECT SELECTIONS

In FY 2020 and FY 2021, the Hydrogen Technologies subprogram added a number of new projects to the portfolio: 19 projects selected from the competitive FOAs, 9 SBIR projects, 6 CRADA projects, and 7 projects selected from the annual competitive Lab Calls. The projects are listed below.

Funding Opportunity Announcements

Hydrogen Production

- 3M Company – Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzer Oxygen Evolution Reaction Catalysts and Electrodes
- Plug Power (formerly Giner ELX, Inc.) – Integrated Membrane Anode Assembly and Scale-up
- Proton Energy Systems, Inc. – Enabling Low-Cost PEM Electrolysis at Scale through Optimization of Transport Components and Electrode Interfaces
- Cummins, Inc. – Automation of Solid Oxide Electrolyzer Cell and Stack Assembly
- Nextech Materials, Ltd. – Low-Cost Manufacturing of High-Temperature Electrolysis Stacks
- The Pennsylvania State University – Novel Microbial Electrolysis Cell Design for Efficient Hydrogen Generation from Wastewaters

- Southern Company Services, Inc. – Novel Microbial Electrolysis System for Conversion of Biowastes into Low-Cost Renewable Hydrogen
- Strategic Analysis, Inc. – Hydrogen Production Analysis

Hydrogen Infrastructure

- Czero, Inc. – Advanced High-Throughput Compression System for Medium- and Heavy-Duty Transportation
- Gas Technology Institute – Cost-Effective Pre-Cooling for High-Flow Hydrogen Fueling
- Nikola Corporation – Autonomous Fueling System for Heavy-Duty Fuel Cell Electric Trucks

Hydrogen Storage

- Collaborative Composite Solutions Corporation – Melt Spun Polyacrylonitrile (PAN) Precursor for Cost-Effective Carbon Fiber in High-Pressure Compressed Gas Tankage
- Hexagon R&D LLC – Carbon Composite Optimization Reducing Tank Cost
- University of Kentucky – Low-Cost, High-Strength Hollow Carbon Fiber for Compressed Gas Storage Tanks
- University of Virginia – Low-Cost, High-Performance Carbon Fiber for Compressed Natural Gas Storage Tanks
- Strategic Analysis, Inc. – Hydrogen Storage Analysis
- Shell – First Demonstration of a Commercial-Scale Liquid Hydrogen Storage Tank Design for International Trade Applications

Small Business Innovation and Research Phase I

- Alchemr – Hydrogen from Wind
- Giner, Inc. – Cost Model and Design Requirements for a Wind-to-Hydrogen Generation System
- Greenway Energy – New Low-Cost and Efficient Electrolysis System That Can Be Directly Coupled with Wind Turbine Power
- Skyhaven Systems – Hydrogen Pre-Cooling System Using Phase Change Materials, for Use in Medium- and Heavy-Duty Fueling
- NanoSonic, Inc. – Electrospun In-Line Filters for Heavy-Duty Hydrogen Fueling Stations
- Global Research and Development, Inc. – Ceramic In-Line Particulate Filter for Heavy-Duty Hydrogen Stations
- NuMat Technologies – Evaporative Emission Control for Hydrogen: Boil-Off Mitigation with an Adsorbent-Based System
- The Protium Company – Tank-Integrated Heat Exchanger for Boil-Off Reduction

Small Business Innovation and Research Phase II

- Luna Innovation – Use of Wave Mixing for Non-Destructive Evaluation of Micrometer-Scale Flaws in Pressure Vessels

H2@Scale CRADA Projects

- The HyBlend project – Launched to address the technical barriers to blending hydrogen in natural gas pipelines – National Renewable Energy Laboratory, Sandia National Laboratories, Pacific Northwest National Laboratory, Oak Ridge National Laboratory, Argonne National Laboratory, and the National Energy Technology Laboratory, and more than 20 participants from industry and academia

- Analytic Framework for Optimal Sizing of Hydrogen Fueling Stations for Heavy-Duty Vehicles at Ports – CRADA between Pacific Northwest National Laboratory, Seattle City Light, Port of Seattle, Northwest Seaport Alliance, and PACCAR/Kenworth
- Heavy-Duty Reference Station Design, Test Device Development, and Capacity Modeling –CRADA between National Renewable Energy Laboratory, Sandia National Laboratories, California Governor's Office of Business and Economic Development, California Energy Commission, California Air Resources Board, and South Coast Air Quality and Management District
- Optimization of Pre-Cooling at Heavy-Duty Stations and Cyber Vulnerability Analysis – CRADA between Savannah River National Laboratory, Sandia National Laboratories, Argonne National Laboratory, and Nikola
- Development of High-Flow 350 bar Hydrogen Fueling Method – CRADA between National Renewable Energy Laboratory and Frontier Energy
- Assessment of Heavy-Duty Fueling Methods and Components – CRADA between National Renewable Energy Laboratory, Argonne National Laboratory, NextEnergy, and Chevron

Lab Call

- Argonne National Laboratory – Cost Assessment and Evaluation of Liquid Hydrogen Storage for Medium- and Heavy-Duty Transportation Applications
- Lawrence Berkeley National Laboratory – Integrated Onsite Waste-Heat-Driven Hydrogen Carrier System for Steel and Renewables Coupling
- Savannah River National Laboratory – Determining the Value Proposition of Materials-Based Hydrogen Storage for Stationary Bulk Storage of Hydrogen
- Oak Ridge National Laboratory – Cost-Optimized Structural Carbon Fiber for Hydrogen Storage Tanks
- Argonne National Laboratory – Hydrogen Carriers for Renewable Energy Farm Application
- National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Sandia National Laboratories, Lawrence Livermore National Laboratory, and Idaho National Laboratory – HydroGEN 2.0: A multi-lab approach, utilizing and integrating national laboratory capabilities to address critical research gaps in each of the advanced water splitting pathways
- National Renewable Energy Laboratory, Idaho National Laboratory, Lawrence Berkeley National Laboratory, Argonne National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Lawrence Livermore National Laboratory, and National Energy Technology Laboratory – H2NEW (H2 from the Next-generation of Electrolyzers of Water): A multi-lab consortia addressing components, materials integration, and manufacturing research and development to enable affordable, reliable, and efficient electrolyzers

PROJECT-LEVEL ACCOMPLISHMENTS

During FY 2020 and FY 2021, projects in the Hydrogen Technologies R&D portfolio made important progress in several key areas, as highlighted below.

Hydrogen Production

- Demonstrated improved anion exchange membrane electrolysis durability over ~750 hours at relevant current density. (Georgia Institute of Technology)
- Established a promising interconnect protective coating for the air/O_2 side of high-temperature electrolysis stacks. (Nexceris)
- Aided by high-performance computing, discovered a new water-splitting material family, $(Ca,Ce)(X,Y)O_3$. (Arizona State University)
- Achieved a 2.5 times higher solar-to-hydrogen efficiency than state-of-the-art perovskite cells in an integrated 3D-printed photoelectrochemical reactor. (Rice University)

- Doubled hydrogen production at 60 g/L crystalline cellulose loading via fed-batch operation scheme. (National Renewable Energy Laboratory, Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, and Argonne National Laboratory)
- Increased hydrogen production 33% from the original baseline via better hemicellulose and cellulose co-utilization. (National Renewable Energy Laboratory, Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, and Argonne National Laboratory)
- Increased hydrogen production rate 100% over the state of the art using brewery wastewater. (Oregon State University)
- Described the chemical mechanisms behind curiously resilient photocathodes made from silicon and gallium nitride (Si/GaN). (University of Michigan, Lawrence Livermore National Laboratory, and Lawrence Berkeley National Laboratory)

Hydrogen Infrastructure

- The H-Mat consortium is focused on RD&D to enhance the durability of materials in hydrogen service. Key recent accomplishments are described below.
    - The H-Mat polymers team has identified mechanisms by which rubber materials fail in hydrogen, as well as likely locations of failure. Using advanced imaging capabilities (e.g., helium ion microscopy) and chemical analysis of materials stressed in hydrogen, the team identified that plasticizers used in commercial rubbers can separate from the material and migrate when stressed in hydrogen. The researchers additionally found that zinc oxide activators (used in rubber manufacturing to expedite the curing process) are likely locations of void formation in hydrogen, which can result in material failure. These results are informing efforts in FY 2022 to synthesize model materials with increased resistance to hydrogen effects. (Pacific Northwest National Laboratory)
    - The H-Mat metals team has identified that austenitic stainless steels saturated in hydrogen at cryogenic temperatures (20 K) experience approximately 50% reduction in ductility (characterized via reduction of area measurements) relative to testing in hydrogen at ambient temperatures. Previously available reports had indicated that hydrogen effects at cryogenic temperatures would be minimal because of limitations in the kinetics of hydrogen at these temperatures. Results generated by the H-Mat team may inform future RD&D to understand and enhance the long-term durability of materials used in liquid hydrogen infrastructure. (Sandia National Laboratories)
- The National Renewable Energy Laboratory completed design and construction of a high-flow hydrogen fueling system at the lab's Energy Systems Integration Facility, through a CRADA project co-funded by the Hydrogen and Fuel Cell Technologies Office, Shell, Air Liquide, Toyota Motor Company, and Honda R&D Americas. The facility will be capable of fueling at 10 kg/min. when commissioning is complete (anticipated by the end of 2021), such that it can be used for future experimentation on high-flow fueling components.
- Sandia National Laboratories and the National Renewable Energy Laboratory collaborated with the DOE Office of Fossil Energy and Carbon Management and Southern Company to complete an evaluation of codes and standards relevant to hydrogen blending in pipelines, identifying current gaps. The analysis is currently in press.
- A team led by the National Renewable Energy Laboratory developed the publicly accessible H2FillS model. H2FillS allows users to generate 1-dimensional simulations of the impact of varying fueling methods on the thermodynamics of fueling equipment and hydrogen storage onboard. The National Renewable Energy Laboratory is now expanding H2FillS to be capable of 3-dimensional simulations of high-throughput fueling of medium- and heavy-duty vehicles. The other team members were Kyushu University, Frontier Energy, Ford Motor Company, General Motors, LLC, Honda R&D Americas, Hyundai, IVYS Energy Solutions, Shell, Toyota, Sandia National Laboratories, and Argonne National Laboratory. H2FillS is available here: https://www.nrel.gov/hydrogen/h2fills.html

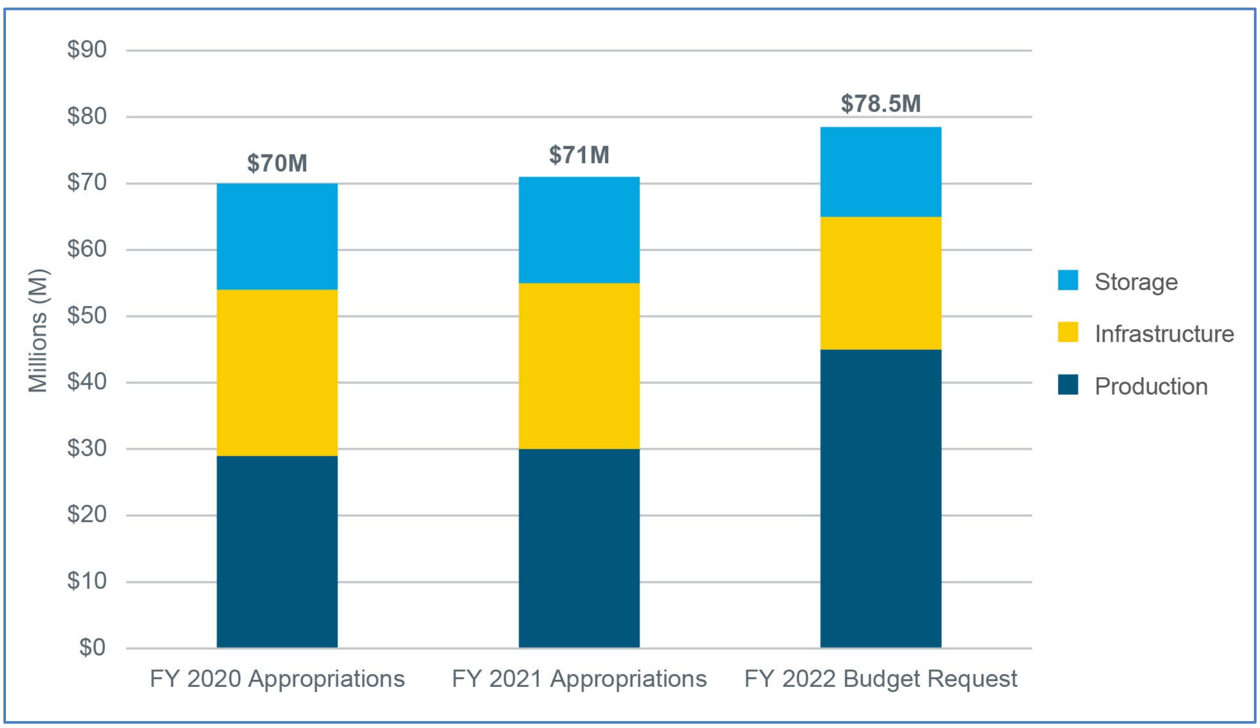
Hydrogen Storage

- Synthesized $V_2Cl_{2.8}$(btdd), the best-performing metal–organic framework (MOF) for room-temperature hydrogen adsorption and the first MOF with a binding enthalpy in the optimal range for ambient temperature storage (-15 to -25 kJ/mol). (Lawrence Berkeley National Laboratory)
- Improved MgB_2-$Mg(BH_4)_2$ hydrogenation conditions by 100°C and 200 bar over the state of the art. (University of Hawaii/HyMARC)
- Demonstrated 2x (de)hydrogenation rates for high-capacity Li/Mg-amides through nanoconfinement in carbons. (Sandia National Laboratory)
- Applied machine learning and modeling to identify thousands of MOFs with potential to exceed state-of-the-art hydrogen volumetric capacities. (University of Michigan and Northwestern University)

BUDGET

The appropriations for the Hydrogen Technologies subprogram totaled $70 million in FY 2020 and $71 million in FY 2021. Of these appropriations, $29 million and $30 million were allocated for hydrogen production research in FY 2020 and FY 2021, respectively. In both FY 2020 and FY 2021, $25 million was allocated for infrastructure research and $16 million for hydrogen storage research. These allocations are shown in the graph below. Projects funded in the Hydrogen Technologies portfolio are expected to accelerate development of low- and high-temperature electrolyzers, materials for advanced water-splitting technologies, electrolyzer manufacturing technologies, microbial hydrogen production, and hydrogen infrastructure and storage technologies. Specific emphasis is focused on meeting the DOE Hydrogen Shot goal of producing clean hydrogen for $1/kg by 2030. This emphasis is expected to continue into FY 2022.

Hydrogen Technologies RD&D Funding



Annual Merit Review of the Hydrogen Technologies Subprogram

SUMMARY OF HYDROGEN TECHNOLOGIES SUBPROGRAM REVIEWER COMMENTS

Reviewers commended the Program for achieving a hydrogen production cost of $5–$6/kg and expressed support for the Hydrogen Energy Earthshot hydrogen production target of $1/kg by 2030. Reviewers stated that the new target will require re-balancing the RD&D activities to prioritize end-use demonstrations of hydrogen production and scale-up of mature electrolysis technologies, as well as new ideas with potential for transformational changes. More active engagement of the Hydrogen Program with other DOE offices, other federal agencies, and state and regional stakeholders was recommended. In particular, reviewers recommended increased engagement with the Office of Fossil Energy (to advance carbon capture and storage and "blue hydrogen" production technologies from steam methane reforming plants or other fossil fuel sources), the Office of Basic Energy Sciences, and the Advanced Manufacturing Office, as well as the National Science Foundation.

Reviewers of the Hydrogen Production category commented that the projects were relevant and potentially impactful and, if successful, would contribute to achievement of DOE's cost and performance targets. The reviewers responded favorably to the approaches of these R&D efforts, describing them as reasonable and effective, and were particularly supportive of integrated approaches that include both experimental and computational methods. Review panels welcomed the addition of the H2NEW consortium and praised the HydroGEN, H2NEW, and BioH2 consortium projects for their coordination between the national laboratories. However, reviewers encouraged adding industrial partners, both to obtain their input and to enhance and encourage technology transfer. Adding international partners and increasing engagement with academia were also recommended. Projects were commended for making use of the HydroGEN Benchmarking Project and for their contributions of resources to the HydroGEN Data Hub. Reviewers commented that they would like to see increased attention to technoeconomic assessments of the technologies and validation of results. Reviewers also suggested increased focus on stability, degradation, and mechanistic understanding of the processes involved for some of the HydroGEN seedlings.

Reviewers of the Hydrogen Infrastructure category applauded the projects' novel and sound scientific approaches. The infrastructure RD&D projects were deemed to be relevant to meeting the Program's goals and, if successful, potentially impactful in enabling hydrogen infrastructure implementation. Reviewers praised the Innovating Hydrogen Station at the National Renewable Energy Laboratory for addressing critical information needs for hydrogen fueling for heavy-duty vehicles, as well as providing significant and reliable demonstrations of equipment performance and capabilities in line with industry needs, combined with valuable multiscale modeling. Review panels noted the importance of Argonne National Laboratory's hydrogen delivery technologies analysis in providing input to guide RD&D funding decisions, as well as informing industry investment decisions. Reviewers commented favorably on the progress that many projects have made in spite of the COVID-19-related restrictions that have been in place for the last year but noted that the level of collaboration on the Hydrogen Infrastructure projects should be improved as restrictions are lifted. Recommendations included increased focus on obtaining input from industry, technologies with potential to be broadly applicable and scalable, leveraging ongoing hydrogen infrastructure developments in California, characterization efforts, and validation of results. The Program was commended for its increased focus on infrastructure to support medium- and heavy-duty vehicles, but reviewers cautioned that light-duty transportation applications still require data, research, and demonstration. An explanation of the reasons for discontinuing work on electrochemical compression was requested. Coordination with Canada on hydrogen blending with natural gas was recommended.

Reviewers of the Hydrogen Storage category commended the projects for their novel and innovative approaches, their solid progress toward meeting project objectives during the COVID-19 pandemic, and their relevance and alignment with the Program's goals and objectives. The project teams were described as competent and experienced, and the projects were deemed well-managed and -coordinated. Reviewers commented that some projects, if successful, could lead to major breakthroughs in hydrogen storage technology. Reviewers found the storage analysis projects to be complementary to each other and to the materials development efforts and to have thorough and systematic approaches. Reviewers recommended that the analysis projects seek additional industrial input and partners to validate cost assumptions. Reviewers commented favorably on HyMARC's use of "push projects" that complement the core HyMARC efforts and expand the technical scope and depth of the consortium, as well as seedling projects pursuing high-risk research. The hydrogen carrier projects were particularly praised for integrating analysis, computation, experimental kinetics, and catalysis into their approaches. Some projects included machine learning, which was considered a valuable addition. Reviewers emphasized the importance of continuing research on hydrogen storage and noted that progress needs to be accelerated, observing that materials-based approaches have made only incremental advances in recent years.

Six Hydrogen Production projects (not including the HydroGEN Seedling projects) were reviewed, with overall favorable scores ranging from 2.9 to 3.7, with 3.3 as the average score. Eleven HydroGEN Seedling projects were reviewed, with scores ranging from 2.8 to 3.8, with 3.2 as the average score. Fourteen Hydrogen Infrastructure projects were reviewed; their scores ranged from 2.3 to 3.8, with the average score being 3.2. Fourteen Hydrogen Storage projects were reviewed; the highest, lowest, and average scores were 3.7, 2.9, and 3.4, respectively.

Following this subprogram introduction are individual project reports for each of the projects reviewed. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Project Reviews

PRODUCTION

Project #P-148: HydroGEN Overview: A Consortium on Advanced Water-Splitting Materials

Huyen Dinh, National Renewable Energy Laboratory

DOE Contract #	WBS 2.7.0.518 and 2.7.0.513
Start and End Dates	6/1/2016
Partners/Collaborators	HydroGEN Consortium
Barriers Addressed	• Cost • Efficiency • Durability

Project Goal and Brief Summary

The HydroGEN Consortium's objective is to facilitate collaborations between federal laboratories, academia, and industry to evaluate and accelerate the research and development (R&D) of innovative, advanced materials that are critical and necessary to advanced water-splitting technologies for clean, sustainable, and low-cost hydrogen production. Water-splitting (WS) technology pathways supported by HydroGEN include (1) photoelectrochemical (PEC), (2) solar thermochemical (STCH), (3) low-temperature electrolysis (LTE), and (4) high-temperature electrolysis (HTE). In addition to collaborating with industry and academia, HydroGEN uses a synergetic, multi-laboratory approach, utilizing and integrating the labs' world-class capabilities to address the critical research gaps identified by the lab teams and HydroGEN Benchmarking and Protocol workshops in each of the advanced water-splitting (AWS) technologies.

Project Scoring

The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production projects.

Question 1: Approach to performing the work

This project was rated **3.7** f for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The HydroGEN Advanced Water Splitting Materials Consortium (HydroGEN) makes up a good blend of AWS technologies and ensures some coordination within the community. The coordination among the laboratories is a much-improved model versus previous history, when the laboratories had to compete against each other for funding. This approach allows much higher effectiveness and teamwork. The capabilities within the laboratories are also impressive, and if directed properly, can help advance U.S. research and product development at an accelerated pace to compete globally. HydroGEN 1.0 started out with funded projects that leveraged the nodes, which was somewhat constraining for the laboratories in terms of being able to work on new ideas. The super nodes addressed this to an extent, with laboratory-only projects addressing broader challenges. HydroGEN 2.0 is early in its lifetime, but initial projects seem to represent more individual laboratory projects. The team should be cautious in maintaining a balance and not going too far the other way versus maintaining the consortium model.
- The HydroGEN 1.0 consortium approach adopts a highly interactive model for collaboration across national laboratory members, extramural community (including both academia and industrial laboratories), and other agencies (e.g., National Science Foundation, National Institute of Standards and Technology). It features multiple mechanisms for providing exchange of information, benchmarking, and sharing of samples and data. It represents an outstanding approach to accelerating learning and achieving technical objectives. Dr. Dinh, who manages this consortium, is highly motivated to coordinate and facilitate the numerous efforts.
- The demarcation of HydroGEN 2.0 and Hydrogen from Next-generation Electrolyzers of Water (H2NEW) based on current technology readiness levels (TRLs) is smart and practical to move the two consortiums forward. It is a good idea to focus HydroGEN 2.0 on low-TRL areas of AWS R&D, since low-temperature polymer electrolyte membrane (PEM) electrolyzers are far more advanced compared to other AWS routes. Although the HydroGEN 2.0 scope seems to specifically exclude PEM-based LTE technologies (slide 5), it is not clear why PEM electrolysis projects are still in the portfolio, as shown in slide 14. The goals of STCH approaches to develop a theory-guided material-design strategy for optimizing the capacity/yield tradeoff and use machine learning to find new STCH WS materials are reasonable. However, given the basic state of current STCH concepts, it is not clear if the implied progress in the label STCH 2.0 is justified.
- This is an excellent approach to supporting lower-TLR hydrogen production technologies.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The funded projects are addressing key fundamental challenges and appear to be making good progress. Since this was an overview of the full consortium, there were not sufficient details to evaluate the specific projects, which are presumably being reviewed separately, but the portfolio seems generally robust.
- HydroGEN 1.0 had many successful outcomes, both technical and in terms of people working together from diverse sectors. The cooperative spirit was a major outcome and led to accelerating the pace of discovery and validation. HydroGEN 1.0 evolved to HydroGEN 2.0 in 2021. Information was not shared on how projects were deemed successful or not successful. It is unclear how the selection was done, how the most promising technical advances were selected for further development in HydroGEN 2.0, and what other factors contributed to selection (e.g., public communication, number of graduating students, etc.). More information on this topic would help in the future.
- The highlighted accomplishments are impressive; however, it would be beneficial to understand the likely tradeoffs between efficiency, durability, and cost, which historically has been the key challenge in most WS approaches. It is possible that this performance tradeoff concern is addressed at the individual project level.
- More effort on technology transfer, beyond filing patents, is recommended.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The collaboration between the five core laboratories and U.S. academia is strong. Even if not formally, the HydroGEN consortium is highly encouraged to continue to engage with the international research community through the annual workshops.
- This is definitely a strong component of the consortium. The external collaboration has greatly improved the productivity of the national laboratory system and energized the academic and industrial partners. This model should be continued and stressed.
- The current form of the consortium is extremely laboratory-heavy. HydroGEN 1.0 had 30 funding opportunity announcement projects, and HydroGEN 2.0 appears to have five to date. While the laboratories within the consortium are collaborating very well together, HydroGEN 2.0 should ensure that similar outreach and external interaction to HydroGEN is achieved. In addition, STCH is very modeling-heavy. While this is important work, and the focus of the Energy Materials Network is materials, there are cases where infrastructure and equipment are necessary to really understand material performance, such as some of the reactor facilities in Europe. The strategy should include evaluating the need for a domestic resource for these development efforts.
- The project is driving laboratory interactions.

Question 4: Relevance/potential impact

This project was rated **3.8**.for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project topics represent highly relevant and multidisciplinary challenges within the WS field. By design, projects directly address the DOE Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan targets and DOE Hydrogen Program (the Program) objectives.
- The goals of HydroGEN are very much relevant and consistent with the goals of the Program in advancing knowledge at all levels—theory, synthesis, characterization, and analysis—toward low-carbon and low-cost hydrogen generation.
- The benchmarking and standards component is a highlight; however, the setting of future goals for technical metrics and cost metrics is one of the more obscure processes that DOE management controls. This apparent absence of discussion within the extramural (and possibly the intramural) community could be improved so that one could recognize what is the basis for these expectations. Without such information exchange, participants will eventually come to believe that there is an arbitrary selection. The net outcome could then be disengagement.
- The community would benefit from more thought around how research in each of the different technology areas can support success in the others. The obvious mechanism is modeling, but it would be good to see this fleshed out more. The "roadmap for cross-cutting modeling" is a great way to start.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The proposed future work is appropriate and builds on past progress in most areas.
- The proposed work for HydroGEN 2.0 is reasonable given this is the first year of the new funding period. Preparing a roadmap for cross-cutting modeling is worth doing; however, there could be a bit more specific and quantifiable tasks and goals. For example, future work could include growing the HydroGEN Data Hub usership by xx% or something similar.
- Fiscal year (FY) 2021 funding is down from FY 2020. It would be good to understand what research is not being continued.
- The Annual Merit Review (AMR) has been an effective means to share future plans for both technical follow-up and future funding opportunities.

Project strengths:

- The HydroGEN consortium's strength is its collaborative approach in facilitating knowledge sharing of old and new AWS concepts and projects among core laboratories and the research community, including the Data Hub approach. The consortium's cross-cutting effort to develop multiscale modeling capability to simulate performance, durability, and material properties among various AWS concepts is a good example. The consortium's effort in seeking broad input from the research/user community in developing performance benchmarks is also an important feature.
- The laboratory capabilities are some of the best in the world. Key barriers are being investigated across a wide range of technologies. The coordinated projects and tasks lead to much more effective utilization of laboratory scientists than previous models.
- HydroGEN 1.0 has been a great success in technical advances, introducing new ideas, and creating new partnerships.
- Overall, this is a great initiative to bring together all fundamental R&D related to hydrogen. Also, the work makes good use of national laboratory resources.
- The decision to focus fundamental studies on selected early-TRL areas is a strength.

Project weaknesses:

- A potential weakness is the project's lack of a defined pathway to transfer laboratory knowledge to other researchers. For example, while the super nodes were formed to address key challenges, there is no connection to the balance of the community. It is unclear how the advancements in IrO_2 roll-to-roll coating will get to the U.S.-based companies, such as Plug Power and Nel Hydrogen, or a U.S.-based membrane electrode assembly manufacturer. It is unclear how the improved solid oxide electrolysis cell (SOEC) electrode will get utilized by Oxeon or other SOEC companies. In addition, the benchmarking effort appears to disappear from HydroGEN 2.0. It is unclear how the workshops and other activities will be maintained.
- Whether this will be sustained by the newly launched HydroGEN 2.0 consortium, which focuses on national laboratory projects with no extramural component, remains to be seen. Leadership by the consortium's director will be a key in guiding future success.
- Given the commercial state of LTE PEM technology, it is not clear that the consortium should continue to invest in PEM electrolyzer component integration. The project should consider moving PEM electrolysis work to H2NEW instead. It is not compatible with the rest of the low-TRL efforts.
- It is understood that HydroGEN still supports separately funded projects via the node structure, but it is not clear how this effort is different from or synergistic to the efforts that HydroGEN funds at the laboratories.
- This project has no major weaknesses at this point.

Recommendations for additions/deletions to project scope:

- Overall, this project is great. It is recommended to include a bit more emphasis on alkaline electrolyte membrane (AEM) water electrolysis and SOEC electrolysis, given their potential for future impact on bringing the cost of hydrogen down to the $1/kg range.
- HydroGEN 2.0 and H2NEW are very valuable consortia that are needed in this competitive and rapidly growing technology space. However, with the split, it is not clear where some aspects fall. For example, benchmarking is not called out in either consortium and spans technologies in both. Also, HydroGEN 2.0 has a stated goal of materials research for AEM water electrolysis, proton-conducting SOEC, metal-supported SOEC, PEC, and STCH, while H2NEW focuses on integration for PEM and SOEC. There are still material improvements required for PEM and it isn't clear where these are covered. Materials such as membranes, gas diffusion layers, and porous transport layers still need development. These should be explicitly included in either HydroGEN or H2NEW.
- It is a good idea to focus HydroGEN 2.0 on low-TRL areas of AWS R&D and not on PEM electrolyzer technology, since it is far more advanced and commercial compared to other AWS routes. It is understood that the HydroGEN consortium, through its community benchmarking activities, has prioritized some attributes (such as material durability for PEC) more than others; however, the go/no-go milestones should

try to incorporate some form of all three key barriers that HydroGEN aims to address (i.e., efficiency, durability, and cost). Considering the basic research nature of the consortium's activities, the cost estimates may not be as firm or meaningful as efficiency or durability estimates at this early stage of technology development. Nevertheless, the consortium should still attempt to establish some sort of guardrails against potential cost-tradeoff efforts (intentional or not) by projects to achieve their efficiency and/or durability targets. For instance, if not dollars per unit hydrogen, there could be an upper limit of platinum or other precious metal loadings per unit hydrogen produced. That way, real and meaningful advances can be realized. The consortium should continue to build robust benchmarking protocols through the annual community discussions or other means on all portfolio areas (LTE, HTE, PEC, and STCH) and ensure projects frequently update their performance against the benchmark. Projects/concepts that seem to be challenged to meet the minimum benchmark performance expectations should be encouraged to quickly adjust or move on.

- The partnership between national laboratories and academic research and engineering programs has been abandoned in HydroGEN 2.0 in favor of national laboratory funding only or national laboratory and industry funding. The notion that DOE can turn on/off academic research, development, and engineering as needed is likely to create poor engagement in the long term.
- The philosophy for allocating funds among the four technology areas (AEM, SOEC, PEC, STCH) is not clear, but a strong recommendation would be to overweight on the electrolyzer technologies.

Project #P-179: BioHydrogen (BioH2) Consortium to Advance Fermentative Hydrogen Production

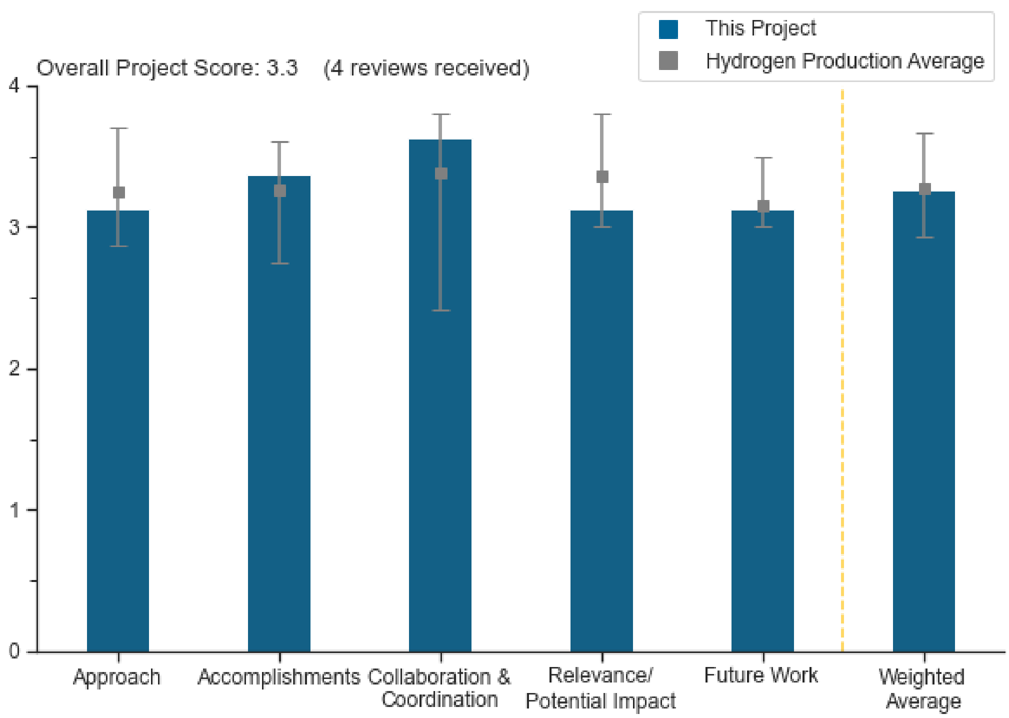
Katherine Chou, National Renewable Energy Laboratory

DOE Contract #	WBS 2.4.0.516
Start and End Dates	10/1/2018
Partners/Collaborators	Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, Argonne National Laboratory
Barriers Addressed	• Hydrogen molar yield • Feedstock cost • System engineering

Project Goal and Brief Summary

The goal of the BioHydrogen Consortium is to develop a direct, high-solids-loading microbial fermentation technology integrated with a microbial electrolysis cell (MEC) to convert renewable lignocellulosic biomass resources into low-cost hydrogen. This collaborative team of national laboratory scientists aims to (1) improve the rates and molar yields of hydrogen production (moles of hydrogen/moles of sugar) via metabolic engineering of the cellulose degrader, Clostridium thermocellum, (2) optimize the bioreactor for high solids loading to reduce reactor cost, (3) develop an integrated MEC system to improve hydrogen molar yield and reduce fermentation waste product, and (4) conduct a technoeconomic analysis (TEA) and lifecycle analysis (LCA) with data generated by team partners to identify major cost drivers and guide integration efforts.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project is exploring several different approaches to maximize hydrogen yield. Tasks 1 and 2 are highly synergistic, and Task 3 complements by reducing some of the waste. In tandem, this makes for a nice research consortium. With hydrogen as a goal, the two-stage approach makes sense, utilizing organisms that produce hydrogen concurrently with acids and other volatile chemicals that are later converted in the MEC system.
- The team has followed a well-defined and effective approach in meeting the project goals. The members have complementary expertise and work on tackling different aspects of the challenges to develop the hybrid process to convert high-solids lignocellulosic biomass to hydrogen with a cost goal of $2/kg hydrogen. The approach is reasonable and well-executed.
- The main barriers are identified and presented, and an approach to overcoming most of them has been proposed. There are a few remaining issues that need to be addressed in the near future:
  - It is not clear if the purity of the cultures can be maintained over one/multiple cycles during fermentation.
  - It is not clear why the fermentation is operated for 30+ hours even though the maximum production rate typically occurs in the first 5–10 hours or what the reason is for the decrease in hydrogen productivity over time.
  - The approach of using a pure co-culture in the MEC is questionable. Maintaining a pure culture over several consecutive cycles and for more than 200 hours can be challenging, and whether or when an MEC was contaminated and the relative impact on the performance can be complicated to investigate.
  - The impact of the electrode catalyst on the MEC performance (slide 13) is misleading. Several different parameters, ranging from the electrode spacing and solution conductivity (solution resistance) to the anode material (carbon felt, brush, and cloth) to the solution buffer capacity (50 mM, 200 mM phosphate or carbonate buffer), can have drastic impacts on the current density in a bioelectrochemical system. It is not clear whether the current densities reported were obtained from a singular study using only different cathode materials or from different MEC configurations and setups. This can be misleading, as the TEA will then suggest to the public a focus on a specific catalyst (Mo in this case), even though the performance improvement in that specific study can be due to factors other than the catalyst. For example, a typical current density of an MEC with a brush anode and a Pt/C cathode is 12 A/m^2 in 50 mM phosphate buffer. In a different study, Ni is used, a higher-buffer-capacity solution is used (200 mM), and the current density is increased up to 25 A/m^2. However, the increase in current density will be due to the Ni catalyst and the higher buffer capacity, and it will not be correct to report that Ni is a better catalyst than Pt. A fair evaluation of the impact of the catalyst on the performance can be obtained only in a standardized MEC configuration. Moreover, there is no literature on MECs achieving up to 180 A/m^2 in peer-reviewed journals; such a high current density is around six times larger than that typically reported for MECs (around 30 A/m^2), and it is not clear how or in which conditions it was obtained. A few studies in the literature claim high current densities by normalizing the current produced by arbitrary areas and typically small areas to inflate the performance and try to make the results appear better; it is not clear from the presentation if this is the case for the high current density reported. Several years ago, the International Society for Microbial Electrochemistry and Technology community agreed to use primarily the cross-sectional area or the largest electrode area to normalize the current and power density in bioelectrochemical systems for a system with one anode and one cathode (stacked systems will have higher projected areas). Thus, it is suggested that the project use a standard configuration for the catalyst comparison to determine how the current density was obtained and whether the reported method is correct.
- Overall, the team has taken a reasonable approach to converting plant biomass to hydrogen. An initial focus on xylose utilization to increase yield was a good choice, but devoting more effort to engineering Clostridium thermocellum fermentation pathways will likely be important for the future progress. The

complexity of the solids that are left over after fermentation is concerning. It is unclear how many recalcitrant sugar linkages remain, what happens with the lignin, how these components interface with the MEC system, and how many of the electrons can be captured by the MEC. The plausibility of reaching feedstock loadings of 175 g/L is also concerning. If high loading is critical to the current TEA, the team may want to consider other processing modalities that are more feasible.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made significant accomplishments overall in the past years and met the performance milestones. Improvements in the rate of hydrogen production through fermentation and hemicellulose utilization are impressive, and the system scale-up is well on the way. The TEA estimates provided clear guidance on major barriers to be overcome, and the team has identified clear steps in addressing the challenges and meeting the milestones. The connections between different aspects of the project in achieving the overall goals could be better elaborated.
- Better utilization of the biomass for increased hydrogen production represents an outstanding achievement. The progress in the MEC appears to be less relevant. The TEA will have a tremendous impact on the MEC community—the reviewer is not aware of any study of this kind in the literature—however, for this reason, more attention should be paid in the selection of the studies for the MEC performance in the TEA.
- The project has made significant strides in sugar conversion and hydrogen production, with a >10% increase in hydrogen production rate. The hemicellulose utilization work demonstrates impressive five-carbon sugar consumption improvements. The team has achieved long-duration demonstration of the MEC cells (>200 hours). While improvements have been made for the solids loading, significant work remains. In particular, there are concerns about how the organism will handle and be able to hydrolyze the solids at these higher levels. Task 4 details on the LCA are lacking.
- The team has generally made sufficient progress to date, but the project has a long way to go to get a functional system. The hydrogen yield's not being part of the cost sensitivity analysis is surprising, as this is presumably a major cost driver. Similarly, it is unclear what productivity is needed to be economically competitive. The project is at 2.75 L of hydrogen per day, but there needs to be clarity as to whether, for instance, a 20% increase or an order-of-magnitude increase is needed.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- The research activity seems to be perfectly coordinated, and each participant is working on a specific task to advance the overall project goals.
- This project has a robust collaboration between four national laboratories, leveraging expertise from each team to be greater than the sum of the individual parts.
- The national laboratory teams assembled bring expertise across the value chain. National Renewable Energy Laboratory has demonstrated expertise in cellulose/hemicellulose conversion, Lawrence Berkeley National Laboratory is a leader in fermentation and strain development, Pacific Northwest National Laboratory brings experience in MEC development, and Argonne National Laboratory has core capabilities in LCA development. The consortium could benefit from industrial partners, if nothing else, to comment on the industrial relevance and viability of the approach.
- The project is carried out by a very capable team coming from four national laboratories. The consortium has a clear goal, and members are addressing different barriers to meeting the Hydrogen and Fuel Cell Technologies Office hydrogen production cost goal. Each member has made good progress individually, but more coordination could further help identify the weak links of the project, such as the relationships between fermentation effluents, compatibility with the designed pure cultures in MECs, and the overall hydrogen production yield and rates from all systems.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project provides a unique approach for biological hydrogen production from renewable biomass. It complements other hydrogen production technologies and helps accomplish the DOE Hydrogen Program goals. While it is understandable that cost is still high compared to abiotic systems, the project has identified the barriers and made good progress in addressing the challenges.
- The potential impact is excellent; a few remaining points (mentioned in the approach section) will need to be addressed to further increase the project's impact on the scientific community.
- The work is very relevant for the development of technologies for hydrogen production from plant biomass. The impact will really depend on whether high titer/rate/yield, high solids loadings, and robust/cheap MECs are plausible. The MEC work, in particular, could be very impactful, but the impact of actual lignocellulose on MEC function is concerning. The team should consider prioritizing evaluation of real biomass effluent rather than Avicel effluent.
- Based on the TEA provided, it is difficult to see a line of sight to \$2/kg H_2. The overall feasibility of hydrogen from cellulosic materials seems difficult without comparison of the current state of the art (hydrogen productivity, yield, recovery, etc.) versus the ultimate technoeconomic targets. The supply chain aspects of the project are not described. Lignocellulosic materials such as corn stover are located in rural areas, but it seems unlikely that there would be the hydrogen product demand in close proximity.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The team has identified many areas that need to be targeted for improvement. Improving hemicellulose utilization would certainly be beneficial, but so would increasing yield and rate. Also, it is surprising that the team is trying to eliminate "inhibitors" such as protein and alcohols (and possibly sugars) since these are going to be present in the system and they represent electrons that are not being captured as hydrogen. This could be an opportunity to increase the utility of MECs and capture more electrons.
- The project clearly identifies critical barriers to the project goals and proposes an actionable plan overall on the next steps.
- The proposed future work will address most of the remaining challenges of the project.
    - The assumption that improving the MEC cathode catalyst alone will substantially improve the performance is not convincing. The project should invest in other factors that can potentially affect the MEC performance, such as the reactor configuration. The H-cell reactors are not the best option for improving MEC performance, even though they are the most-used configuration for pure culture MECs. Using smaller spacing MECs can potentially reduce the solution resistance and improve the overall maximum current density. Increasing the electrode area/volume will also increase the performance; unfortunately, it will be more complicated to maintain the purity of the cultures.
    - The project should standardize the TEA to a single/similar MEC configuration before further implementing the current model.
- Limited time was allocated to discussing future work activities.
    - Task 1: Integration of the genes is an important step. The utility of the hemicellulose degradation process is less certain, given the strides already made.
    - Task 2: Further fermentation engineering work is relevant and necessary as the system increases solids loadings. Loadings of 175 g/L would be approaching pilot readiness.
    - Task 3: There are not enough details on what current density, lifetime, yields, and other targets are proposed for this task.
    - Task 4: Ongoing TEA will be refined, which is appropriate, as well as considering particular incentives.

Project strengths:

- The project brings DOE experts of different areas together to advance biological hydrogen production and overcome the technological barriers to meet the DOE's cost goal for hydrogen. This hybrid approach with dark fermentation and microbial electrolysis is considered the most feasible approach for achieving hydrogen goals biologically, and it targets a unique feedstock that complements other abiotic approaches. The researchers have made good progress, and they know what barriers are ahead. The TEA findings are valuable and bring insights for technology development, and the high hydrogen rates from actual biomass demonstrate the potential of applicability.
- The accomplishments with regard to hemicellulose utilization are very significant and notable and have led to significant increases in hydrogen production rate. Feeding strategies and modifications are starting to yield modest improvements in hydrogen yield. The project is well-coordinated across the member laboratories and uses appropriate steps to maximize system-level conversion of carbohydrates to hydrogen.
- The project addresses several outstanding questions in biohydrogen generation. Each member of the team appears to contribute perfectly to the overall project goal with that member's own technical capabilities. The team seems to be collaborating effectively to advance to the project goals.
- This is a strong team with expertise that spans all of the areas needed for this project. The team is focusing on some of the major challenges that need to be addressed to further develop this technology.

Project weaknesses:

- The overall concept of producing hydrogen (with no co-products) from cellulosic materials seems daunting from a technoeconomic perspective. Based on the data provided, it is difficult to see how hydrogen could approach $2/kg from this approach, even if every metric and target were achieved. The project lacks industrial partners to inform project targets or other risks and barriers. The presentation does not lay out clear technical targets for key performance parameters such as carbon conversion in the MEC and hydrogen production rate in the dark fermentation step. LCA was not presented.
- The project could better elaborate and carry out coordination between different tasks, such as:
  - How to better design an overall system that can convert cellulosic biomass more efficiently to hydrogen (and CO_2) with defined microbial cultures. The current MEC co-culture can be optimized to convert fermentation effluent more effectively.
  - How the two systems can be scaled together to take advantage of the liquid flow connection, as well as hydrogen production.
  - How to make sure the two reactors are compatible in terms of flow rate, size, product reconciliation, etc.
- A better understanding is needed of the importance of yield and productivity in the TEA. The impact of real lignocellulose effluents on the MEC will also be critical to determine.
- The main weaknesses to address are in the approach, as has been reported in that section. There are no other apparent weaknesses.

Recommendations for additions/deletions to project scope:

- There could be value in performing reactor modeling, especially for gas delivery, which could become a significant mass transfer issue at larger scales. Rheology will become an issue at higher solids, and alternative reactor designs should be considered (e.g., paddle reactors). The team might consider scaling some of the steps with industrial partners (e.g., at existing corn ethanol refineries or breweries) to further scale and de-risk particular unit operations. Market assessment and viability should be considered. It is unclear what distribution/transportation costs would need to be considered for the hydrogen produced.
- The project should investigate TEA parameters and prioritize testing of lignocellulose effluents in the MEC.
- No addition or deletion is recommended.

Project #P-182: Binary Chloride Salts as Catalysts for Methane to Hydrogen and Graphitic Powder

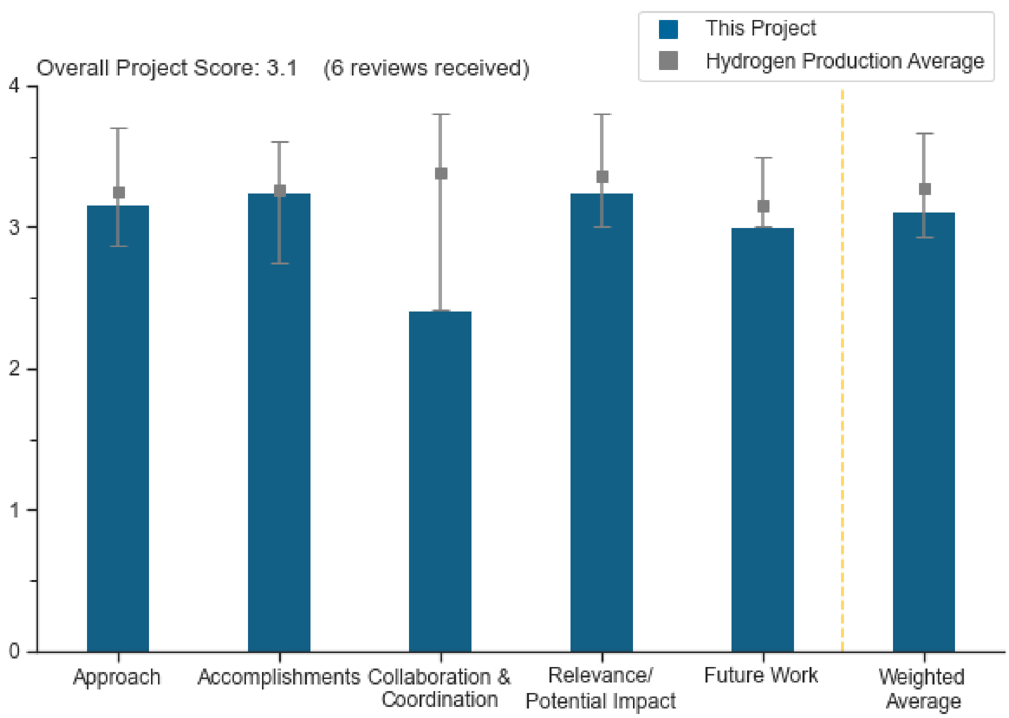
Eric McFarland, C-Zero, LLC

DOE Contract #	DE-EE0008845
Start and End Dates	12/1/2019–5/31/2022
Partners/Collaborators	University of California, Santa Barbara
Barriers Addressed	• High-temperature robust materials • Material and catalyst development • Chemical reactor development and capital costs

Project Goal and Brief Summary

This project aims to develop a scalable methane pyrolysis process that produces inexpensive low-emission hydrogen from natural gas. Ideally, the process will also result in a useful byproduct: graphitic carbon with properties favorable for battery anodes and additives. If successful, this project could reduce the carbon dioxide (CO_2) emissions associated with hydrogen production from natural gas and facilitate CO_2 removal in areas not amenable to CO_2 sequestration.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- A simple and accurate identification of the project objectives and critical barriers was presented. It would be very helpful to identify significant elements that underlie each barrier to more clearly demonstrate the comprehensive nature of C-Zero, LLC's (C-Zero's) efforts. The carbon product is defined as battery anodes and additives. The correlation between barriers, tasks, and approaches to achieving U.S. Department of Energy goals would be helpful.

- The project develops a molten salt pyrolysis process that decomposes natural gas to produce hydrogen and solid carbon. Because less hydrogen is produced from the decomposition process than from steam methane reforming (SMR), where part of the produced hydrogen comes from water, product carbon needs to be valorized to be cost-competitive with SMR. The team realizes this and is looking to produce graphitic carbon, which can be used in batteries. There should be closer correlation between the salt development task and the carbon properties task. The salts should be selected based not only on the catalytic activity toward methane decomposition but also on the morphology and cleanliness of the produced carbon, which should be important criteria.
- Although natural gas pyrolysis concepts are not new, the use of binary salt catalysts is an interesting approach that aims to reduce energy input and CO_2 emissions per unit of hydrogen produced. However, the approach on how to achieve the second objective of making a "graphitic carbon product that has properties favorable for battery anodes and additives" is vague. It is unclear whether the bimetallic test runs were aimed at optimizing hydrogen yield, graphite carbon quality, or both. The project seems to aim its process as an alternative to traditional CO_2 sequestration. It may be wise to settle quickly on what to do with the carbon product. The research approach for simple carbon sequestration or disposal is vastly different from targeting revenues from battery electrodes that require a high-quality carbon product with well-controlled metallic impurities or even for the proposed future work as cement additives.
- The binary/ternary salt carbon decomposition has been demonstrated and will work. The team should test real natural gas in addition to methane to better understand the impact on the process. The quality of the carbon produced will likely be low. A task on potential carbon uses and/or on how to improve the carbon produced would be useful. The carbon separation will be a tremendous problem. The research team is targeting 75% reduction in CO_2 emissions compared to SMR. The researchers are planning on using renewably powered electric heating. It is unclear what CO_2 emissions are being generated by the project so that it is not at a higher CO_2 emissions reduction.
- The approach is proprietary and unlikely to contribute to general knowledge.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The accomplishments and progress toward the overall project and DOE goals were impressive and include the following:
  - The melt system design was completed.
  - The catalytic action and mechanism were identified.
  - Catalytic activity was determined to be greater than the milestone goals (<250 kJ/mol).
  - The project operated a molten salt system at a high temperature and pressure.
  - Carbon analog was removed from the aqueous system (~500 g/hour).
  - The technology was successfully demonstrated in a high-temperature molten salt system.
  - The centrifugal carbon removal system demonstrated less wet salt in the carbon product.
  - The carbon produced was tested for both battery anode use and for cement additives.
  - The project updated and refined the Aspen model with the ongoing process, with the goal of a process showing <$2/gge hydrogen production and carbon production cost of <$1/kg.
- In spite of the difficulties imposed by the COVID-19 restrictions, the project made very good progress in the first year. The team has assembled the melt system activity apparatus and started measuring binary chloride salt activity. The computational evaluation of the salt systems to guide the composition development is done in parallel. The project designed and demonstrated high-pressure operation at up to 17.7 bar pressure with a methane feed. The team also started verification of the types of carbon produced. In Task 2, the team is developing and testing multiple approaches to carbon removal. Carbon analysis of the produced carbon for electrochemical applications demonstrated that graphitic carbon has been

produced, yet still the conductivity properties are not as good as those of the commercial graphitic carbon. Good overall system integration analysis has been performed using Aspen Plus system modeling.

- The project's overall goals are consistent with DOE's goals. The identification of the binary melt systems, as well as the reactor testing at high pressure and temperature conditions, is encouraging.
- This project had good progress during its initial year, which was during the pandemic (although it is not clear whether any progress results from efforts prior to the award).
- Since this project just started, it is hard to judge the accomplishments. The project is addressing some key issues. The operation temperature of 1000°C is very high and will cause material compatibility issues. The carbon being made is not crystalline carbon. This results in very low-quality carbon that has low value. For the carbon used in the electrochemistry tests, it would have been good to know if the team cleaned the carbon to remove the salts or if the carbon was used without any processing. The way the discharge capacity is reported on slide 14 is somewhat misleading. While it is true that the initial capacity is around 279 mAh/g, the shape of the I-V (current–voltage) curve is such that the realistically usable capacity is closer to 110 mAh/g. In addition, the project reported only the first five cycles. Lithium-ion batteries typically go through five to ten cycles for a break-in period, so the actual capacity in a real system would be lower. The researchers have shown some initial concepts for the carbon separation but have a long way to go for a real solution. The amount of salt removed with the carbon was not reported. The process and economic modeling are for conditions different from those used in the experimental tests and assume much higher conversion than what is being achieved. The natural gas, landfill gas, and biogas will need a good deal of cleanup prior to use. The flowsheet does not include any cleanup prior to use, which raises the question of whether the costs are captured. It is also unclear what the "LT processing" in slide 16 is.

Question 3: Collaboration and coordination

This project was rated **2.4** for its engagement with and coordination of project partners and interaction with other entities.

- There is good work sharing between C-Zero and the University of California, Santa Barbara (UCSB). The team needs to look for industrial partners, such as Cabot, especially for carbon applications.
- The project could greatly benefit from having some input from subject matter experts in the natural gas processing and conversion sector, such as refineries, hydrogen plant operators, or industrial gas companies, as well as battery electrode manufacturers.
- It is recommended that the team make further use of national laboratory resources on high-temperature materials and process equipment. There are quite a few similarities with work done in the past on solar thermal.
- There is some collaboration between C-Zero and UCSB. It is unclear what the UCSB collaborators are doing for the project.
- The presenter did not identify or discuss significant activities in collaboration and coordination with other institutions. Collaboration could reduce the project costs and decrease DOE project risks, as well as overall C-Zero risks associated with the burn rate required to support 30 or more employees over the life of the project and beyond.
- Collaboration was discussed only briefly. Its impact on the project is not apparent.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project has a potentially high impact due to the large availability of natural gas versus renewable electricity. Hence, hydrogen produced via pyrolysis could be a strong alternative to green hydrogen.
- The project is targeting production of hydrogen at <$2/kg and a 75% reduction in CO_2 emissions relative to SMR.
- The process is relevant to DOE's ultimate goals, although it is unclear what technical goals the project is trying to address. The stated potential impact of C-Zero's process as "75+% reduction in CO_2 emission from hydrogen production from natural gas" is well-supported. It looks unreasonably high, given the

nonsignificant energy input to drive the high-temperature pyrolysis process, heat recuperation, and multiple separation steps. The team should clearly show the impact of the process with high-level mass–energy balance compared to conventional SMR.

- An updated and refined Aspen model was reported as progress to the goal of a process toward <$2/gge hydrogen production and a carbon production cost of <$1/kg. The Aspen model results need to be presented and supported in greater detail. The Aspen mass and energy balance was not offered in support of progress. A defined path toward the DOE goal could be helpful.
- The reduction-of-CO_2 target of only 75% seems inconsistent with the Hydrogen and Fuel Cell Technologies Office goals of low or no CO_2 emissions. The team should consider electric heating and recycling of the unreacted natural gas to reduce CO_2 emissions.
- The project will need to target greater than 75% reduction in CO_2 versus the benchmark (unabated SMR).

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The project's plan to continue work on each task is logical and efficient.
- Given that the project has less than a year left, the project team may consider narrowing the focus of the remaining work on optimizing bimetallic melt catalysts and process conditions around hydrogen yield and efficient catalyst recycling (i.e., assume for now disposal of solid carbon byproduct). Going after testing for battery electrode or cement additives may be distracting from the primary DOE goal. The proposed technoeconomic analysis and process modeling tasks are reasonable.
- The team needs to develop a viable carbon separations approach. The filtration approach has some potential, but the researchers did not discuss how they will recover the carbon from the filter. The carbon will likely need further processing to make it usable, which was not discussed. It was not clear in the economic analysis how much loss of the salts was planned or is acceptable. The project proposed using the carbon in cement, but it is not clear whether trace amounts of the salts will have a negative impact on the cement.
- The technoeconomic analysis, from Task 5, may need to wait until the carbon separation problem from Tasks 2 and 3 is solved.
- This reviewer would seriously challenge the use of pyrolytic carbon for battery applications. Impurities in the produced carbon would be a bit too high for battery anodes.
- Task 3 is not defined or discussed.

Project strengths:

- The project effectively combines scientific research on molten salts and the methane pyrolysis process with an engineering development of the reactors, separation systems, and overall project integration. Proper attention is given to mass–heat balance and how it affects the carbon properties and the overall process economics.
- Overall, C-Zero is a very strong organization that has a strong team working on this project. It is not surprising that the team has produced such robust results. Whatever the challenge is, the team is capable of achieving remarkable results.
- It is appreciated that the team is already looking at pilot-scale opportunities and related process modeling. That will lead to many learnings along the way.
- The main strength of the project is the capability to test high-temperature and pressure pyrolysis reactor systems.
- This is a well-funded project with a very large team. The concept is very innovative.
- The focus on fundamentals and key hurdles/showstoppers is a strength.

Project weaknesses:

- The project team is very large and seems management-heavy (seven managers/directors/associates and six scientists/engineers). Carbon separation is a major issue. Operating at pressure will increase the difficulty of the separations. The researchers need to describe any cleanup they are doing with the carbon for additional salt recovery or other processing to improve the carbon quality. The high temperature and use of molten salts may produce material compatibility problems. The project should consider recycling the unreacted methane rather than burning it to produce heat. The team needs to test real natural gas to better understand the process. The natural gas, landfill gas, and biogas will need a good deal of cleanup prior to use. The flowsheet does not include any cleanup, so it is unclear whether the costs are included in the analysis. The carbon produced is low-quality.
- The approach is simple and elegant at first blush, so it is easy to underestimate the actual difficulty of what is being attempted. Issues such as thermal management, materials handling, media and product contamination and purification, carbon morphology and uniformity, and component durability present significant challenges. It is unclear that the team has a comprehensive plan that will carry the project all the way to a commercially viable system.
- The greatest project uncertainty and challenge remain the molten salt composition and the ability to produce the desired carbon morphology and purity. More efforts should be directed toward finalizing the salt composition, as it may affect the rest of the project tasks.
- Because of the relatively high operation temperature (1100°C) of the pyrolysis unit, the team needs to pay further attention to what materials and equipment reliably work under those conditions at scale. Finding equipment fit for this purpose may not be the easiest.
- The presentation lacked discussion of the scale mismatch between hydrogen production and the solid carbon market being targeted (battery anodes).
- The project is trying to demonstrate too many unproven early-stage concepts in such a short time. The team should note that, to date, there are no pyrolysis-based commercial processes to make hydrogen or carbon products.

Recommendations for additions/deletions to project scope:

- Future work could include thermal integration pilot system design, including pressure swing adsorption tail gas heat recovery, resolution of potential coking issues, assessment of potential toxic waste production, salt recovery and purification for reuse, and characterization of produced gas content based on various feedstock assumptions. Additionally, the team should also consider how to achieve uniform pressure, temperature, bubble size, and space velocity to produce carbon with a more consistent, precise, and higher-value morphology.
- Considering the relatively short funding period, the project needs to focus on narrower and more achievable tasks to advance the key concepts. The project could choose to address potential scale-up challenges, including the reactor system, solids separation, catalyst recirculation, and product gas purification. The project should also clearly demonstrate the energy and greenhouse gas reduction benefits of its process against conventional SMR.
- Based on the energy analysis, it seems that more of the effort should go toward solving the carbon separation step (Tasks 2/3). Optimization of the salt composition (Task 1) and assessing the carbon as a cathode material (Task 4) can come later.
- The team should look further at the materials and corrosion aspects of the design. Several pathways (hydrogen embrittlement, halide-induced corrosion, carbon deposition, etc.) might severely limit the scale-up and increase the probability of unsafe conditions.
- No changes are recommended.

Project #P-183: Extremely Durable Concrete Using Methane Decarbonization Nanofiber Co-Products with Hydrogen

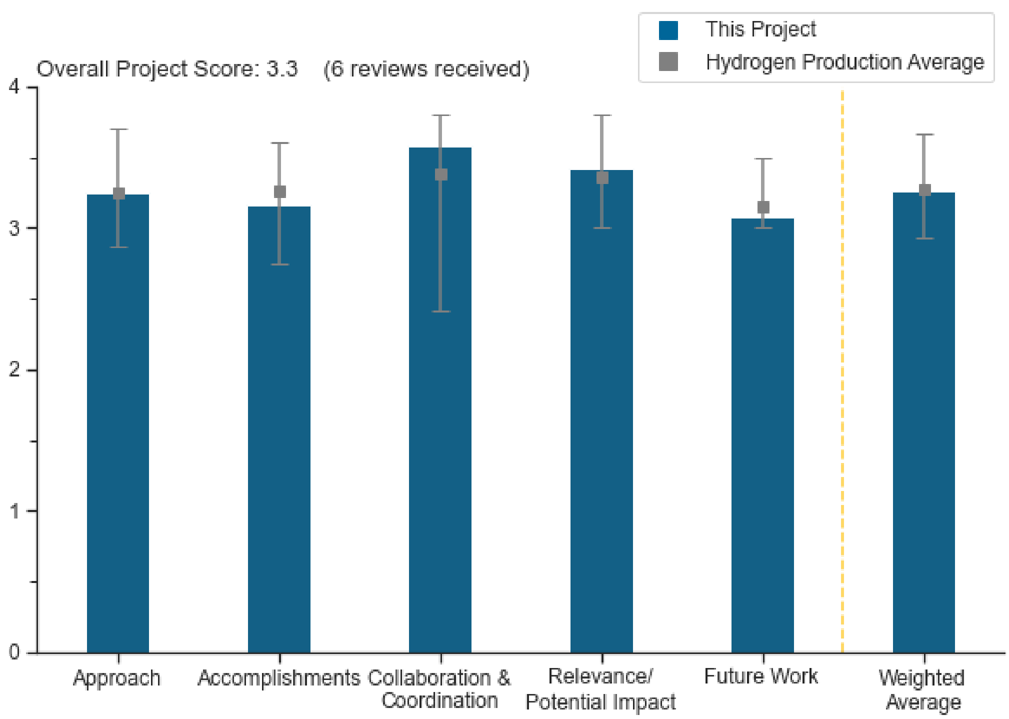
Alan W. Weimer, University of Colorado, Boulder

DOE Contract #	DE-EE0008846
Start and End Dates	5/1/2020 to 5/1/2023
Partners/Collaborators	Forge Nano, Inc., National Ready Mixed Concrete Association
Barriers Addressed	• High-temperature robust materials • Material and catalyst development • Chemical reactor development and capital costs

Project Goal and Brief Summary

The University of Colorado is developing a scalable, low-cost chemical vapor deposition (CVD) process to produce carbon nanofibers (CNFs) and hydrogen from methane using a sacrificial atomic layer deposition (ALD) catalyst deposited on a fumed silica substrate. This process offers a cleaner alternative to steam methane reforming, as it allows hydrogen to be produced without releasing carbon dioxide through the co-production of CNFs. The CNFs sequester the carbon and can be added to a concrete mix to improve durability and performance, offering a value-added byproduct. The project will design a commercial path forward for a typical hydrogen plant producing 480,000 kg H_2/day, with 70% conversion efficiency of CH_4 to H_2, and will identify potential industrial collaborators and customers.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- A brief, precise, and detailed identification of the project objectives and critical barriers is presented. It is a brilliant approach that is clearly described and very well-organized. Goals, barriers, approach, tasks, and milestones are clearly and precisely connected.
- The project is developing the process for growing CNFs on fumed silica, coated with sacrificial Fe (or Ni or Co) catalyst through the ALD and using this CNF to improve the performance of concrete. In situ catalyst synthesis will be conducted from a metallocene precursor. Other projects are developing similar processes for carbon nanotube (CNT) growth on stand-alone Fe nanoparticles. The project should compare the advantages and disadvantages of having Fe supported on Si rather than just Fe catalyst for the CNF growth and for the concrete stabilization. Ferrocene is a rather expensive feedstock, so other precursors and techniques to generate catalyst nanoparticles should be investigated. In the proposed process, it is likely that each Si bead will support a large number of CNFs, which are likely to entangle and may not be easy to disperse in the concrete.
- The idea is very interesting: methane pyrolysis for carbon nanofibers for cement. The use of silica seems like a reasonable approach, but the choice of nickel seems relatively expensive, especially since the project will not be recovering its catalyst. Even if the process uses only a very little catalyst, it will be producing many metric tons of carbon fibers, and it will soon add up. It is not clear why ALD is required; it might make sense to use a less expensive catalyst synthesis technique. It is not clear that ALD can be economically scaled to the level needed for this process to be commercially acceptable.
- The project's approach and goals are clear. The three tasks—namely, CNF/hydrogen production, CNF use, and technoeconomic analysis (TEA)—are well-defined and aim to address specific technical challenges. However, the ultimate feasibility of the scale-up process may be doubtful, given the inherent dependence of the CVD process on vacuum or clean-room-type environments, which tend to be rather expensive to operate and more common in high-value products compared to commodity products such as hydrogen or concrete.
- It is great that the intent to jointly evaluate a process concept with the utility of the product in a high-volume application. However, it is not clear from the presentation that the research plan will support a direct test because of a mismatch in scale.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The presentation provides detailed documentation of significant progress achieved on challenging tasks:
    - Construction and start-up of in situ ALD/CVD reactor systems
    - Deposition of ALD catalyst onto fumed silica
    - Demonstration of in situ carbon growth
    - Completion of preliminary TEA and analysis via the Hydrogen Analysis (H2A) model.
- All Task 1 objectives for the first year have been met, with the exception of the characterization of CNF produced in the process. It is important to get to the CNF characterization as soon as possible, as these CNFs may be very different from the commercially acquired CNFs that are currently used in the concrete testing. A good set of testing has been performed on the effects on concrete properties of adding CNFs. Uncertainty remains as to how much these results could be reproduced with the actual CNF obtained from the pyrolysis process. The project is using the Aspen Plus simulation for the system integration development. The gas pre-heat heat exchanger (HX) needs to be carefully considered. It appears in the process schematic that the 900°C reactor effluent flows to that HX. This will cause coking of the incoming gas and plug the tubes.
- The project has well-defined tasks and milestones, and it has demonstrated progress toward project objectives and achievement of DOE goals.

- The methane conversion seems low at 20%. It would be helpful if the space velocity was reported. On slide 15, the presenter says "...as catalyst deactivates." The purpose is growing CNFs on the catalyst, so it does not seem like the catalyst is deactivating; it seems to be operating as expected. Also, the catalyst synthesis seems expensive. It is not clear that the ALD process is needed. The cement testing with the commercial CNFs was interesting. It was unclear why the CNF percentage in the cement changed from 0.1 wt.% on slide 17 to 1 wt.% on slide 18. The flowsheet does not include natural gas cleanup. This needs to be included in the analysis. The TEA is interesting. The cost assumed for the catalyst synthesis using ALD should be shared, as well as the percentage of the operational cost it represents. The CNF cost range was \$1.50–\$2.50/kg, and it was not clear that the improved cement characteristics support the increased cost of adding this additive. The team needs to be careful when comparing the CNF cost to the price paid for the commercial CNFs; cost and price are very different.
- It would have been good to see some evaluation of the silica particles with tethered CNTs that is the basis for the project's approach. It is suggested this be an immediate focus.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- The project demonstrates close collaboration between participants from the chemical, biological, and civil engineering departments of the University of Colorado, Boulder. The project also collaborates with Forge Nano, Inc. (Forge Nano) for the reactor and process development, along with the National Ready Mixed Concrete Association (NRMCA) on concrete properties and testing.
- Forge Nano and NRMCA are strong partners for overcoming both technical and commercialization challenges.
- The internal collaboration is applauded, even if the activities are not synched up so far. Two external partners are mentioned as well, but it is not apparent what impact they had on the progress.
- The collaboration with NRMCA is really appreciated, as it gives strong credibility to the durable concrete workstream.
- The project has clearly defined roles. The collaboration seems to be going very well.
- The project collaborated with Forge Nano and the NRMCA. However, to better inform the TEA, the project could benefit from additional discussions with other experts on ALD/CVD scale-up challenges and related greenhouse gas (GHG) lifecycle analysis (LCA).

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project offers the potential to develop a large-scale hydrogen production process competitive with steam methane reforming (SMR), while drastically decreasing the amount of carbon dioxide emissions. The market for use of co-produced carbon in concrete production is large enough so as not to be saturated by the amounts of hydrogen production consistent with H2@Scale.
- The sufficiently large scale of the concrete market and the value-add associated with the CNF/silicon product make this approach highly impactful. The estimated cost of hydrogen is low enough to make this approach economically viable. However, the feasibility of scaling the proposed process to the match the potential market is uncertain at this stage. Additionally, the economic impact of the various catalyst options is unclear. A sacrificial iron catalyst should be much more economically viable than a nickel catalyst and may be essential to commercial adoption. This issue was not sufficiently discussed.
- This process may result in a low-carbon-intensity hydrogen that captures the carbon in structural materials, effectively sequestering the carbon.
- There is potentially high impact for pyrolysis as a low-carbon-intensity alternative to green hydrogen.
- The intended use of solid carbon as a concrete additive has the scale potential to be relevant in a hydrogen economy.

- The research objectives are relevant; however, it is highly unlikely that the process will have the stated impact of the "potential to displace U.S. hydrogen production by SMR with a low-cost and scalable CVD process" any time soon, given the current state of the technology and the mere scale of the existing SMR-based hydrogen, domestic or global. When considering GHG impact, the project team should incorporate the LCA of the whole process, not just "CO_2 produced directly from CVD of CH_4," such as excess reactants associated with the sacrificial catalyst feed (which appears incredibly significant at more than 600,000 metric tonnes per year for the commercial plant).

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The future work should assess the economic impact of the various catalyst options on performance and production costs. It would be good to know the expected incremental impact, if the system is developed at scale, on Fe, Ni, and Co global demand and on prices. A conceptual design for a commercial-scale (10,000 ton/d) CNF/silicon production system should be developed.
- The project should focus on low-cost catalysts and avoid expensive ones such as nickel and cobalt. The researchers should not look at cobalt (slide 22 states that they will). There is already high demand for cobalt and nickel. Using cobalt and nickel to make cement does not seem like the best use of these valuable metals. The researchers should do some tests with real natural gas as part of their future work. The researchers should compare the ALD synthesized catalyst to the conventionally synthesized catalyst to see whether the ALD process is needed.
- The process needs to start generating and analyzing sufficient quantities of CNF from the ALD process as soon as possible to make sure that the CNF is consistent with the properties of the commercial CNF. More effort should be put toward a lower-cost Fe catalyst precursor and Fe delivery into the reactor.
- The project's impact would benefit from the following two efforts, which were not seen as part of the plan: (1) estimating the cost of the ALD catalyst and (2) testing, or at least modeling, the impact of the expected filler morphology (silica particles with CNT hairs) versus free CNT.
- The future work looks good, but it could include a rough estimate of an LCA of the logistics and impact of a sacrificial catalyst on the concrete performance.

Project strengths:

- The project develops a large-scale process for low-carbon-intensity hydrogen production by natural gas pyrolysis, which can be competitive with SMR and have a large enough market to be consistent with the large-scale hydrogen economy.
- This project's strengths include the following: the University of Colorado, Boulder, team and other collaboration partners; the well-organized approach and tasks; and the integration of methane pyrolysis CNF production with a potentially high-volume end-use product (ultra-strong cement) that suggests potential commercial viability.
- The project's strength is the overall project team mix of chemical engineers and subject matter experts (concrete and ALD) who contribute to the project team. The results from mixing CNFs into concrete seem promising.
- The project's strength lies in its clarity of tasks and the potential to carry out all three tasks in parallel.
- This project has a strong team and addresses a critical need.
- The combined research on process and product is this project's strength.

Project weaknesses:

- The team is using an expensive process (ALD) to make a catalyst. It is not clear that if it is successful, the ALD process could be economically scaled to the level required for cement manufacturing. The current work is using nickel, and the team is proposing using cobalt. Less expensive alternative sacrificial catalysts should be considered. The researchers need to report more details on the TEA to validate their findings. The TEA is assuming process performance that is not yet achieved.

- The scale-up pathway does not have an existing market along the scale of the cement market. Metal catalyst by ALD is not being practiced at the scale of the cement market. Cement is a bulk commodity that, as such, cannot tolerate price increases.
- The TEA assumptions are almost too hopeful. Instead of assuming ideal parameters such as DOE hydrogen targets, the team should consider a scenario with assumptions of current natural gas and CNF costs with a 20- to 30-year lifetime to come up with a more realistic hydrogen estimate. Currently, there is no commercial hydrogen manufacturing process involving pyrolysis of natural gas, so the TEA should reflect realistic challenges common to new technology platforms. A minor criticism is that there seems to be some confusion around the definition of the gas conversion milestone (and thus accomplishment) with respect to the methane-to-hydrogen volume ratio as stated in slides 5 and 11. It is not clear whether it is 20% or 80%.
- For the TEA, it is recommended that the team use economic steering values (capital cost, indirect costs, etc.), which are the same as the H2A model. Otherwise, comparisons with the $2/kg target price will be difficult.
- This project's weakness is the mismatch in material availability, specifically the amount of CNT hairy silica particles that can be made versus the amount needed to conduct meaningful evaluation in concrete.
- There is still significant uncertainty about the quality of the CNF that can be produced by the process.

Recommendations for additions/deletions to project scope:

- Assuming additional technical progress and a viable TEA update, a commercial-scale concept could be developed to attract additional funding. Even at this early stage, a line of sight to commercialization is important.
- It is not clear whether the sacrificial catalyst ALD/silica fume is separately manufactured or whether it is designed to be part of the commercial plant. The project team should consider carrying out high-level GHG LCA, including, but not limited to, the logistics of hauling a significant volume of the sacrificial catalyst, ~14 kg/kg of H_2 produced. Task 2 should separately explore the impact of the sacrificial catalyst ratio on the concrete performance. For Task 2's fiscal year 2021 go/no-go, the team should consider alternative concrete tests using simulated additives (e.g., commercial CNF + fumed silica + metal catalyst mixture) in the event that suitable quality and/or volume of CNF from Task 1 is not realized.
- The team should focus on low-cost catalysts and avoid expensive ones, such as nickel and cobalt. The researchers should not look at cobalt (slide 22 states that they will), given that there is already high demand for this material. Using it to make cement does not seem like the best use of this valuable metal. The researchers should make some catalysts using conventional high-volume catalyst synthesis techniques and compare their results to see whether the expensive ALD process is required.
- The project may benefit from collaboration with the Carbon Hub run by Rice University, where similar concepts are being developed and similar issues and challenges are considered.
- A TEA of catalyst production should be added.

Project #P-184: Scalable and Highly Efficient Microbial Electrochemical Reactor for Hydrogen Generation from Lignocellulosic Biomass and Waste

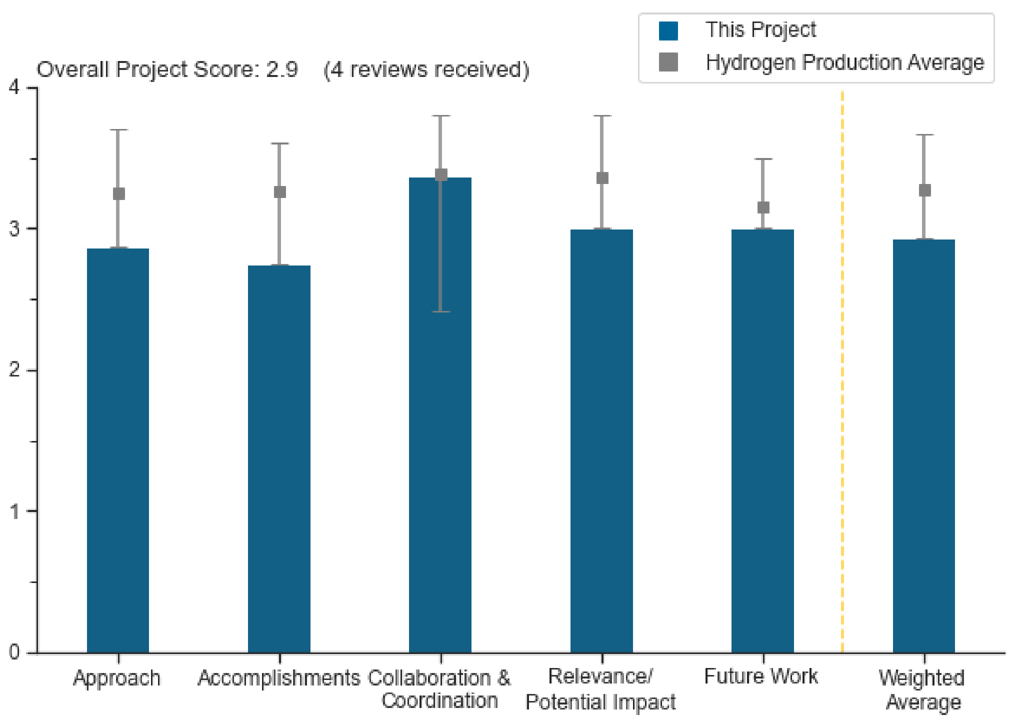
Hong Liu, Oregon State University

DOE Contract #	DE-EE0008844
Start and End Dates	1/1/2020 to 12/30/2023
Partners/Collaborators	Texas A&M University, Pacific Northwest National Laboratory
Barriers Addressed	• High electrode cost • Low hydrogen production rate

Project Goal and Brief Summary

This project is developing a scalable hybrid microbial electrochemical reactor to produce hydrogen from waste streams. The reactor design combines fermentation and microbial electrolysis cells (MECs) and includes low-cost electrodes and catalysts. Robust microbial communities will be used to optimize operating conditions, reducing the operating cost. This project will provide a method of producing hydrogen from waste streams at a cost of close to or less than \$2/kg H_2 (the U.S. Department of Energy target).

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production projects.

Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- If successful, the conversion of wastewater to hydrogen has the potential to be both cheap and sustainable. Printing carbon nanotubes (CNTs) on steel mesh to increase conductivity and decrease cost seems like a good approach, owing to the greatly increased surface area of CNTs as compared to carbon fiber. Because this will be expensive to build, the team modeled a 10-year lifespan for the electrode, but it is unclear whether this is plausible, given the fact that the current version loses 25% activity in 50 days. Approaches to determining the cause of the decreased activity over time, as well as approaches to solving this issue, will be critical to demonstrating improved lifespan and commercial potential.

- The project identifies that cathode material is a key barrier to MEC scale-up and focuses on addressing this issue. The team is well-qualified to perform the tasks and has made good progress overall. The MoP_X-based catalysts have gained good interest in hydrogen evolution in recent years.
- The approach sounds rational and articulated to overcome the most limiting barriers in an MEC.
    - The scalability and application of the CNT-based anode in this project seem questionable. Currently, the team can develop an electrode with an area of a few square centimeters, and the scaling up of the equipment for the CNT growth will increase the complexity and the cost for the electrode development. From the performance evaluation, it also seems that the CNT anodes do not perform statistically better than the carbon cloth anodes, and the CNT anodes' performance quickly decreases over time. Based on these considerations, the CNT approach, even though extremely interesting, might need to be redirected.
    - The polymer coating of the CNT appears to increase the mechanical strength of the material; it is suggested that the project investigate whether such modification also changes the electrical properties (conductivity) of the material.
- The work to develop a new CNT fabrication approach is novel and could have benefits beyond this project. The project does not contain lifecycle analysis to compare the hydrogen produced from this method to steam methane reforming (SMR) or other sources. Waiting until late in the project—when real wastewater is being used—is a significant weakness and risk to the overall project. The project should explore the impacts of fouling, poisoning, etc. as early as possible so that if mitigation steps are necessary, they can be considered.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The researchers made good progress on catalyst development, and they have compared the performance with existing materials. The CNT and MoP_X ideas are interesting and new, and they showed potential in improving hydrogen production. The current data show that the performance in terms of hydrogen production from these new materials is not significantly higher than benchmarks, so more improvements will be needed, and the team has shown the project plan to do so. The longevity of the materials soaking in the electrolyte is not clear. There have been studies reported that CNT could fall off after a certain period, which in this case may cause issues. The technoeconomic analysis (TEA) could give more details on comparing with current benchmarks so one can better understand the cost levels.
- The team has demonstrated increased conductivity at much lower costs by using CNTs on the stainless steel mesh. Other improvements have been conferred by the CNT approach, including mechanical strength and pore size control. These results are muddied somewhat by some impacts of the coatings. The data on corrosivity are useful, particularly exploring 50 to 100 cycles. In the question-and-answer session, it was explained that 50-day testing on acid whey has occurred and that there is an accelerated testing system. No data were presented, even on mock streams, about how much biological oxygen demand (BOD) reduction or waste carbon conversion was realized.
- Several excellent accomplishments were obtained toward the overall project goal. However, a few results presented do not allow for fair evaluation of the progress made, such as using high buffer capacity and substrate loading that are not representative of real wastewater feedstocks (acid whey in 200 mM phosphate buffer is not a real feedstock), and claiming excessively high current density that does not reflect the real performance of the cell.
    - The exceptional performance of the MoP_X cathode compared to Pt represents an outstanding advancement.

  - The anode performance steeply decreased over time, reaching 48 A/m^2 in 150 hours, but decreased to 35 A/m^2 after only an additional 50 hours. A similar decrease can be observed in the larger-scale system (12.5 cm^2) where the carbon cloth outperformed the CNT at 1,200 hours. The reason for such a steep decrease, particularly for the CNT electrode, could be further explicated.
  - It is not evident that testing the MEC or anode performance in 200 mM phosphate buffer will produce insightful results for evaluating the performance of the system in real wastewater, typically characterized by a low buffer capacity.
  - On slide 16, current densities ranging from 80 to 180 A/m^2 were claimed. These current densities are around five to six times larger than the highest current densities ever claimed in MECs (30–40 A/m^2). The carbon cloth used here has been used previously in MECs with current densities never exceeding 20 A/m^2, and the principal investigator reported on slide 15 that the anode current density cannot exceed a stable current density of 35 A/m^2. It is not clear how such a high number was calculated. (It is well-known that the current density cannot be calculated by normalizing the current by the smallest area in the reactor, as this inflates the current density, resulting in unreproducible results). It is also not clear whether the extremely high current density that was reported was due to a biotic electrochemical reaction or the abiotic water-splitting reaction. With a current density claimed here and an electrode packing density of 28 m^2/m^3, the theoretical hydrogen production rate can be calculated as follows: 180 A/m^2 * 28 m^2/m^3 = 5,040 A/m^3 * 86400s = 435,456,000 C/m^3 / 96485 F / 2 nH_2-e^- = 2256 mol H_2/m^3-d = > 50 L/L-d. With a packing density of 100 m^2/m^3, the hydrogen production rate will be 180 L/L-d, which seems unrealistic.
- Good progress has been made on the electrode development, but a more balanced focus—that includes work on the microbial community—is needed.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- The team seems well-suited to performing this work, and the roles of each partner are well-defined.
- The team members have complementary areas of expertise, and they work well to advance the different tasks to achieve the common goal of the project.
- Each team member is operating on a different aspect of the project (cathode, anode, configuration, and microbial community) to advance the final project goals.
- The project team and institutions involved have experience relevant to the MEC design. The project could benefit from collaborations with wastewater treatment plants, environmental engineering firms, or other industrial entities. Likewise, hydrogen customers could be useful as well, to assess the market potential for a process if it becomes successful.

Question 4: Relevance/potential impact

This project was rated **3.0** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project aligns well with the DOE Hydrogen Program (the Program) and will contribute to advancing the DOE research, development, and demonstration goals. The material cost is a major barrier, and the team is targeting this.
- The findings on increasing current density and cathode costs could have benefits to similar projects/approaches. The overall approach of utilizing wastewater streams for hydrogen production is a compelling value proposition. There are significant wastewater resources available, and high-strength wastewaters (acid whey, industrial wastewater, etc.) are a considerable liability to producers. It is difficult to assess the project's progress toward the ultimate objective of producing hydrogen from wastewater. No data were presented on hydrogen production rates or yields for the new materials or baseline materials. The technoeconomics rely heavily on the $10/kg hydrogen credit. It is unclear whence the assumptions for this are derived, specifically in regard to the BOD reduction credit. The project is assuming a 10-year catalyst

lifetime in the economics and has not done sensitivity analysis to explore the impact of this. In other applications, commercial catalyst lifetime is usually assumed to be in the one- to two-year range.

- The project is certainly relevant and has the potential to be impactful to the goals of the Program. However, this is dependent on the proposed technology working and the TEA actually reflecting reality. A greater focus is needed to determine whether a 10-year lifespan for the electrode is realistic.
- The project is aligned well with the progress required to advance the Program. A few reported results do not allow anyone to fairly evaluate the progress made, such as using high-buffer-capacity solutions and claiming excessively high current density that does not reflect the real performance of the cell.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The team identified the work needed in the near future and developed a plan to carry out the tasks.
- The future work sounds rational and developed adequately to address the remaining challenges of the project.
- It is correct that developing strategies to maintain stable performance of the electrodes in MECs will be critical, but it is not clear that this critical issue is being addressed. Modifying the microbial community is also mentioned, but there is no real description of how the project team intends to do that, or to what extent. Also, a sensitivity analysis on each component of the TEA will be critical to determining which parameters are most critical to an economical process.
- Scale-up activities seem risky without knowing whether the materials are compatible with real wastewater streams. If there are no issues, the rate of scaling is otherwise appropriate. The source of the wastewater is not defined, and it is unclear whether any cleanup will be necessary. More specifics on the coating mitigation work would be useful.

Project strengths:

- The project has made significant strides in CNT fabrication as it relates to MECs. This will have benefits to a variety of industries that might consider MECs or a similar technology. The team has clear expertise in materials science to bring to the project. In this regard, the researchers are mindful of the performance parameters—pore size, conductivity, etc.—to track on these systems. The overall concept of using wastewater streams to produce hydrogen has significant promise. The results on current density are encouraging to date and relative to Pt-C.
- The project team is developing a unique technology to produce CNT-coated electrodes for wastewater cleanup via MECs. Electrode development seems to be making substantial progress.
- The project is carried out by experts in different fields and aimed at addressing a key challenge of cathode materials in MECs. The researchers have made good progress in cathode development, and they aim to significantly improve the performance to meet the hydrogen cost goals.
- The project advances biohydrogen production through MEC technology by addressing important challenges such as cost reduction and performance improvement. The approach is on anode, cathode, and MEC configuration improvement.

Project weaknesses:

- It is not clear that modeling a 10-year lifespan for the electrodes is realistic. More information on the microbial community and modifications to that community needs to be provided.
- The newly developed materials need to be further improved and tested to demonstrate their superiority over existing benchmark materials. TEA analysis can be more detailed to provide guidance for technological development.
- Most of the data were reported in unrealistic conditions, such as high-buffer-capacity solutions, and reported current density was also unrealistic, likely because of an arbitrary normalization of the current. This does not allow for a fair evaluation of the performance. The CNT approach to improving the performance appears to provide limited improvements.

- It is difficult to assess this project as a potential approach for producing renewable hydrogen since no data were presented to compare to other approaches. This is a major weakness. Lifecycle analysis—to compare to SMR or other hydrogen production processes—does not appear to be part of project scope. Details on the TEA are limited. The project team does not contain external partners or advisors to contextualize or guide the research to commercial relevance.

Recommendations for additions/deletions to project scope:

- The project is encouraged to start testing real wastewater as soon as possible to evaluate impacts of fouling, solids, and potential poisons such as nitrogen or sulfur. The project is encouraged to partner externally to gain access to real wastewater streams and understand the design/siting considerations at a wastewater source. The project should track BOD reduction, which is a key value proposition for the industry with which the project is trying to partner.
- A greater focus on mitigating the decrease in electrode activity over time is needed, as is an understanding of the importance of different parameters in the TEA via sensitivity analysis.
- No changes are suggested.

Project #P-196: H2NEW Consortium: Hydrogen from Next-Generation Electrolyzers of Water

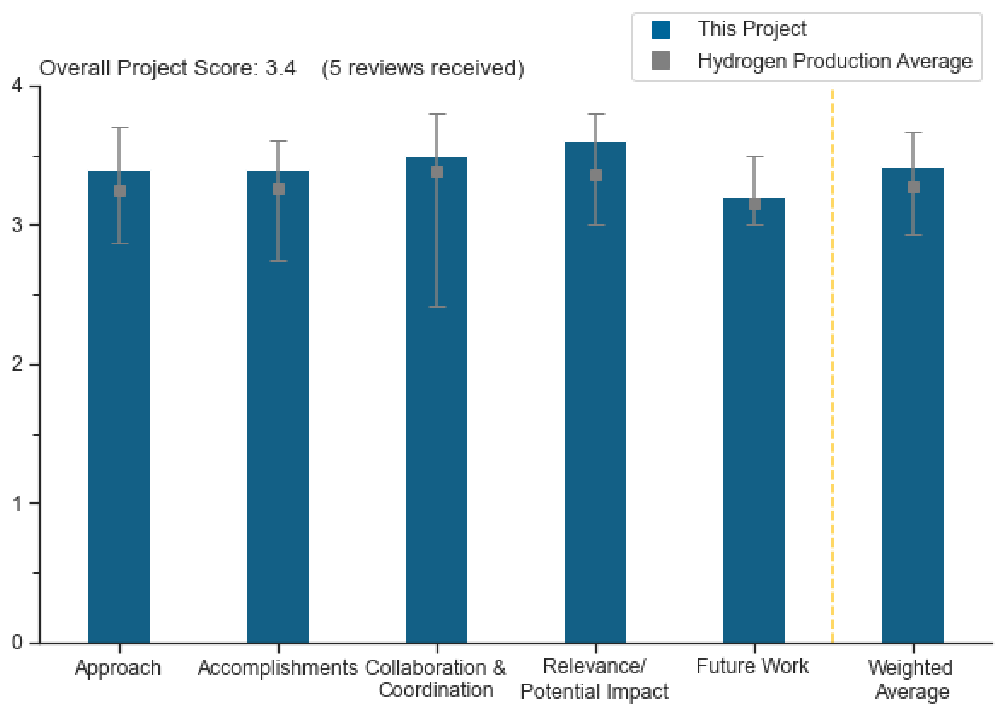
Bryan Pivovar, National Renewable Energy Laboratory, and Richard Boardman, Idaho National Laboratory

DOE Contract #	WBS 2.7.0.519 and WBS 2.7.0.1003
Start and End Dates	10/1/2020
Partners/Collaborators	National Renewable Energy Laboratory, Idaho National Laboratory, Argonne National Laboratory, Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, National Energy Technology Laboratory, National Institute of Standards and Technology
Barriers Addressed	• Durability • Cost • Efficiency

Project Goal and Brief Summary

The H2NEW (Hydrogen from Next-generation Electrolyzers of Water) consortium is a comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable, and efficient electrolyzers that can achieve <$2/kg H_2 by 2025. H2NEW is studying both low-temperature electrolysis (LTE), based on an acidic polymer electrolyte membrane (PEM), and high-temperature electrolysis (HTE), based on oxide-ion-conducting solid electrolyte. The core H2NEW national laboratory team is addressing components, materials integration, and manufacturing research and development. The team is working to improve scientific understanding of the performance, cost, and durability tradeoffs in electrolysis systems, including under predicted future dynamic operating modes, by using a combination of experimental, analytical, and modeling tools.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- A concerted, focused effort on reducing the cost of green hydrogen is both needed and an excellent aspect of the project's approach. A consortium approach is appropriate. This is a lab-only effort but with industry observation and recommendation through the LTE and HTE stakeholder advisory boards. This makes sense for core technology development to be shared by all, but extra efforts should be made to involve industry as much as possible.
- This seems like a comprehensive approach to PEM and solid oxide electrolyzer cell (SOEC) technology challenges. The project helps developers by setting industry targets.
- This project uses comprehensive advanced approaches to study PEM and SOEC performance and durability. The approaches cover cell testing, characterizations, advanced characterizations, modeling, and analysis. The project takes advantage of state-of-the-art facilities and strong capabilities in the national laboratories. This project is large and is solely undertaken by national laboratories. However, given the complexities and practical applications of electrolyzer technologies, industrial leaders should actively participate in this project. Additionally, there remains a question about how SOEC technology can reduce hydrogen cost to <$1/kg H_2 because of the technology's lifetime constraints. The technology still has a long way to go. The scale-up of electrolysis, using automated processes, is key to reducing hydrogen cost. The project needs to put more effort on this aspect.
- This consortium aims to integrate materials, components, and manufacturing processes to advance water-splitting technologies to achieve goals in durability, cost, and efficiency. This initiative is perceived as an intermediary vehicle between fundamental research and product development.
- The approach, consortium structure, and 75/25 weighting for LTE/HTE are sound, as is the effort to go after the right barriers, at a high level. The only concern is whether the next level of scientific targets, while worthwhile, are the key ones from an industry perspective. It may be that they are, but it is not clear how hard that has been tested or whether input from the stakeholder advisory board is enough. If the board is helping to set directions, the board's voice needs to be more apparent.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The work done on LTE for marginal pricing, heat maps, and hydrogen cost impacts is meaningful and worthy analysis. LTE cell aging studies and characterization are very helpful. HTE development and understanding are critically important because of the potential high electrical efficiency. The detailed and methodical HTE experiment and characterization work is a very good achievement to date. The focus is appropriately placed on the identification of the HTE degradation modes. HTE multiscale modeling, validated by experiment, is a key aspect of the project.
- Very good progress has been made on identifying degradation sources for both HTE and LTE.
- Given the short time of this project in this year, this project's progress is satisfactory.
- A good start has been established.
- Results on durability and interfaces are highly anticipated. More emphasis on multi-physics modeling is suggested—in fact, for future presentations, the team should lead with this aspect as the "one ring to rule them all" for the other efforts.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The LTE/HTE multi-laboratory approach fosters excellent collaboration and synthesis of lab capability. The stakeholder advisory board is a very good structure for input and review from the industry.

- There is clearly a great deal of interaction at the national laboratory level. More outreach to industrial partners would be beneficial. One concern is that efforts are being made to dig deeply into issues that will not have the biggest return on investment for the industry.
- There is good collaboration between national laboratories. The stakeholder advisory board that has been set up for the LTE work is good. The advisory board for HTE does not contain any major commercial companies developing solid oxide electrolyzer products (granted, there are very few from which to choose).
- This project is a collaboration of multiple national laboratories. The principal investigator (PI) and co-PI have strong experience in a variety of areas. Unfortunately, industry participation is largely missing from this project. It involves a large number of researchers across national laboratories, and the tasks are also very broad. A more stringent coordination plan is needed to ensure the good progress of this project.
- This is a consortium involving almost all major national laboratories.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is highly relevant and directly advances the achievement of long-term DOE goals. The DOE Hydrogen Program's focus on identifying, understanding, and modeling degradation modes is critical to goal achievement. There would be a major beneficial impact on achievement of Hydrogen Program goals.
- The consortium has the potential to accelerate the commercialization of water-splitting technologies. It aligns well with DOE's overarching goals promoting hydrogen technologies.
- These are critical technologies. Maximizing our understanding of the fundamentals will help support needed cost and performance improvements—and even more so if the work is focused on industry's most pressing problems.
- This project is very relevant and will help industry develop lower-cost, more durable electrolyzers.
- This project is very relevant to DOE's H2@Scale goals. It can provide insightful information to the electrolysis community for renewable hydrogen production. It is not clear yet how the information attained from this project can be shared with the electrolysis community

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- The LTE future work is described at a high level, but substantial further activity is indicated in each of the four main tasking areas. The HTE future work tasks are clear and appropriate.
- There are no reservations with the work plan. However, the team should seek and incorporate deep industrial perspectives on priorities and impact.
- The identified challenges are well-articulated and proposed to be addressed in the future.
- Future plans are very comprehensive.
- The future work makes sense.

Project strengths:

- Project strengths include the following:
    - The focus on reducing LTE stack and system capital cost, the Argonne National Laboratory LTE system diagram and energy balance, and LTE durability focus on operational, material, and cell-design-based mitigation techniques—all three are important to pursue
    - Leveraging across other consortia
    - LTE technoeconomic analysis
    - HTE extensive test stands and testing plans
    - HTE multi-scale modeling, when validated by experiment
    - HTE focus on identification and understanding of degradation modes

  - Having 28+ HTE test stands
  - HTE cost analysis

  HTE cost analysis should be extended to the balance of plant (BOP), and the project should examine the levelized cost of electricity sensitivity to stack and BOP cost.
- This project's strength is in the amazing power of the national laboratories being focused on a couple of specific technologies. It is bound to have a significant impact. Bryan Pivovar is a great champion and voice for this effort.
- This is a large consortium that is much needed for water-splitting technologies and that will play a key promoting role in meeting DOE goals in cost, durability, and efficiency.
- This project's strengths consist of the following points:
  - There is a strong collaboration across multiple DOE laboratories.
  - Advanced and comprehensive approaches are used in the project.
  - The PI and many co-PIs are highly technologically competent.
- There is a strong focus on understanding the problem areas in PEM and SOEC technologies.

Project weaknesses:

- The project has the following weaknesses:
  - The project is performed solely by national laboratories, so industry participation is largely missing.
  - The project needs a more stringent project coordination plan because of the project's high budget and complexity. For example, it is not clear how the attained information from this project can be used to achieve \$1/kg H_2.
  - There should be more transparency in budget spending, and project progression is also needed for such a high budget.
  - The project combines LTE PEM with HTE SOEC. They both have different materials, focuses, and applications.
  - This project focuses on testing, characterization, and analysis. Clear innovations should be identified.
- The LTE waterfall graph showing \$0.86/kg H_2 for the ultimate goal seems to require about \$0.01/kWh electricity. This assumption should be clearly stated, as it may not be realistic as an average price for intermittent electricity. Alkaline electrolysis is not addressed in the project, yet there have been substantial technology advances in recent years, and it is likely to capture a large market share in 2030 and beyond. The lack of details in validating the multiscale modeling effort is a weakness.
- The project feels a bit like everything but the kitchen sink is being thrown at understanding cell performance. This makes it hard to conceptualize the progress. It is unclear which pieces are the more scientifically interesting (long shots) and which are the technology advancement priorities. Perhaps the efforts should be organized around objectives instead of methods.
- The difference of the programmatic focus from the current industrial efforts in developing water-splitting technologies is not very clear.
- There is no mention of other emerging technologies, such as HTE proton-conducting technology or LTE anion exchange membrane technology.

Recommendations for additions/deletions to project scope:

- It needs to be clearer whether the capital cost targets are for the stack alone or for the full system. The HTE capital cost goal of \$100/kW should explicitly state this is for the stack, not the system. HTE stack performance and durability are primary factors in reducing the levelized cost of hydrogen, but BOP is reported at \$550/kW and needs to be addressed, too. Ways to reduce HTE BOP cost should be explored. There are seemingly no milestones (or a clear detailed timeline) for the HTE multiscale modeling. Modeling is insufficient without validation, and the timeline to achieve a validated model should be explicitly stated. Like the LTE advisory board, the HTE advisory board structurally draws in outside commercial electrolyzer expertise. This is good, but ways to further capture industry ideas and capabilities should be explored.

- The project should add the participation of industry leaders, and the interactions between national laboratories and industry should be strengthened. This project can be separated into two projects, as the focuses, technology readiness levels, and applications of PEM and SOEC are different.
- The project is focused on standard technologies and material sets. It would be great to see some investigation into promising alternatives that have the potential to leapfrog over the existing state of the art. The recommendation is not necessarily for an in-depth study but rather for some assessment of the potentials and problems with these promising alternatives.
- There should be even more emphasis on facilitating scale-up of electrolyzer production. The benefits of economies of scale are a huge assumption behind estimates of future low-cost electrolyzers. Manufacturability should be a key lens for the entire consortium.
- The pathways toward mitigating degradation should be clearly identified.

PRODUCTION—HydroGEN Seedling

Project #P-185: High-Performance Alkaline Electrolyte Membrane Low-Temperature Electrolysis with Advanced Membranes, Ionomers, and Platinum-Group-Metal-Free Electrodes

Paul A. Kohl, Georgia Institute of Technology

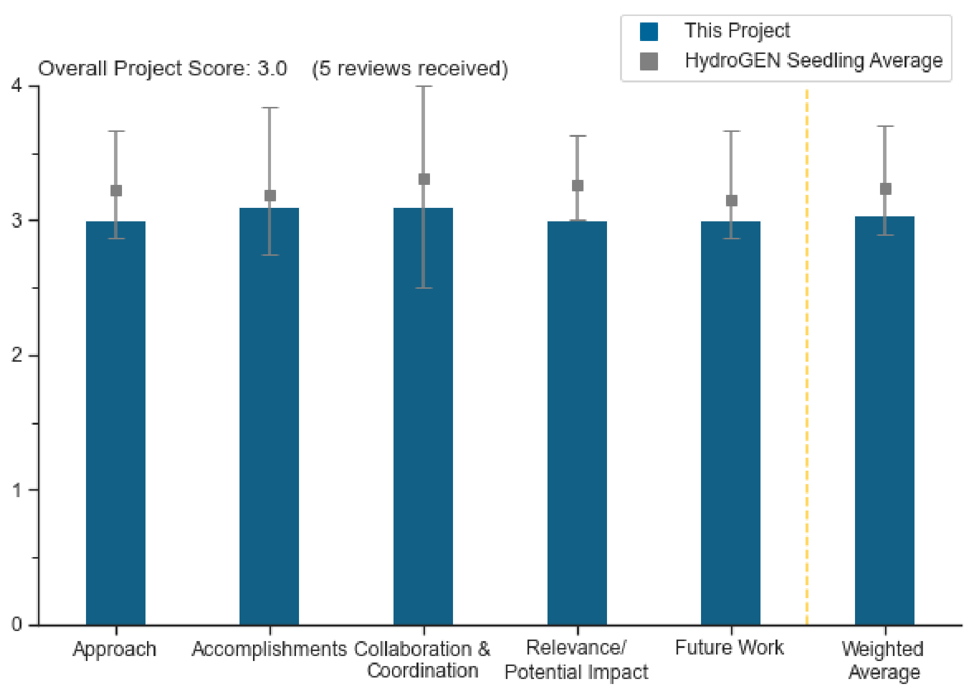
DOE Contract #	DE-EE0008833
Start and End Dates	1/1/2020 to 4/30/2023
Partners/Collaborators	Pajarito Powder, University of South Carolina, NEL Hydrogen
Barriers Addressed	• None listed

Project Goal and Brief Summary

The objective of this project is to combine state-of-the-art alkaline polymer electrolyzer components into one optimized membrane electrode assembly (MEA) system to achieve U.S. Department of Energy low-temperature electrolysis goals. The project will first implement the best materials at hand and establish best practices in each of the individual component areas (membranes, catalysts, ionomers, electrodes, and MEAs), leading to performing single-cell scale-up, as well as evaluating the electrolyzer performance and durability. This will lead to a platinum-group-metal-free (PGM-free) MEA optimization effort for operation on pure water (i.e., no added salt or base), as well as scale-up and detailed degradation modeling and mitigation studies. By the end of this project, the team expects to meet the following three metrics with a PGM-free alkaline electrolyte membrane (AEM) electrolyzer MEA operating on pure water:

- Performance: 1 A/cm^2 at 1.75 V
- Durability: <4 mV/1000 hour degradation
- H_2 production cost: <$2/kg.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- This project is very well-rounded; it not only has polymer/ionomer development but also has low-loading PGM catalyst development and cost model projections. This holistic approach is rarely seen but is appreciated.
- This project is conducting interesting work on alkaline membrane/ionomer development, combined with electrode integration and understanding of the related effects on electrolysis cell performance and stability. The project's development of high-stability, low-cost hydrocarbon-based membrane and ionomer materials seems promising for advancing AEM electrolysis. The role of cost analysis in guiding the project's approach is confusing. Some other important aspects of the project approach were not clearly presented, especially regarding the use of the supporting electrolyte that appears to be used in most or all experiments, although it was not made clear whether the project vision is to develop cells running with supporting electrolyte or pure water. This is important because it seems likely that the use of the supporting electrolyte will change the relevant degradation and performance loss mechanisms, as well as optimal ionomers and electrode structures, in comparison to a pure water system. For instance, the project found good performance prioritizing adhesion/binding of the electrode over conductivity, though this may not translate to a system without the supporting electrolyte.
- The approach to developing AEM with glass transition temperature is commendable. The $PbRuO_X$ catalyst has caused some concerns. Pb is a hazard material. RuO_X is not thermodynamically stable (from the Pourbaix diagram).
- The approach slide is missing. Performance and durability improvement using membrane and ionomer development looks reasonable. The team has extensive experience synthesizing high-performance and alkaline-stable anion exchange ionomers. Therefore, leveraging such expertise in the project is low-risk and saves resources. Catalyst development seems to be separated from ionomer development. However, in many cases, the performance of electrolyzers largely depends on catalyst–ionomer interaction. No strong justification is provided to use perovskite catalysts versus PGM-free, metal-based catalysts for oxygen evolution reaction (OER).
- There is no clear approach slide in the presentation. No risk and risk mitigation strategy is outlined. There is no clear strategy to identify possible durability issues. Membrane development is, however, impressive. The project needs a clear strategy to understand the issues about local hydroxide ion concentration and its effect on OER performance.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- There is appreciable progress on all fronts, with membrane, ionomer, and electrocatalyst development.
- There is, overall, good progress with ionomer development. There is noted accomplishment on the effect of ionomer water uptake on electrode performance. Experimental results to improve durability, including catalyst detachment, are interesting and provide some insight. The steady-state voltage plot in slide 14 is another highlight. The data is impressive, as the electrolyzer ran at 1 A/cm^2. However, the data was obtained using 0.3 M KOH and PGM catalysts. Under such conditions, ionomer stability cannot be accurately measured. Demonstrating good performance and durability is critically important. More studies on the fundamental understanding of polymer effects on electrolyzer performance and durability are desired. There is very little, if any, work on PGM-free catalysts. Slide 3 indicated that the team accomplished the go/no-go point with performance <1.75 V, PGM-free electrolysis at 500 mA/cm^2, but all data presented uses PGM catalysts. Most accomplishment slides lack information. Some slides do not have catalyst information (slides 9, 10, 11). For slide 9's left-bottom plot, the legend is missing (not clear whether that red curve meant GT18 or GT38). Some slides do not have liquid electrolyte information. Other slides have the data using different liquid electrolytes (0.1 M KOH for slides 12 and 16, 0.1 M NaOH for slide 13, 0.3 M KOH for slide 14). On page 14, the title is confusing. It noted a non-conductive binder, but the information indicated GT32 and GT69 ionomers. It is unclear whether those are non-conductive.

- The project has demonstrated reasonable progress toward its targets, met the budget period 1 (BP 1) go/no-go milestones, and produced several publications from 2020 and 2021. Some good and interesting results are presented on stabilizing performance through ionomer/electrode optimization, including the ionomer swelling and adhesion properties. Not all results are clearly supported with evidence in the presentation. For instance, there was no clear evidence that poor adhesion of the electrodes is the principal stability challenge, as stated. Also, some results appear to have significant variability (e.g., the anode catalyst loading study) without a very clear trend visible, although a simple trend is claimed, raising concerns about the reproducibility of such results.
- There are good accomplishments regarding the membrane, but the project needs more work on understanding interfacial issues and electrocatalysis on both electrodes.
- There is good progress on membrane development. All the performance is obtained using KOH, so the AEM development becomes less significant.

Question 3: Collaboration effectiveness

This project was rated **3.1** for its collaboration and coordination with HydroGEN and other research entities.

- Collaborations between the team members are excellent. Each team member has different expertise, and several results were accomplished by the collaborative work. Non-core research activities can be supported by Energy Materials Network resource nodes as the project goes further.
- There are several partnerships with various laboratories, with each lab taking on responsibilities in which that lab is expert.
- The collaborations, such as those with the National Renewable Energy Laboratory, are just beginning at this point; it must have been a challenge, considering the circumstances.
- The project seems to have demonstrated good collaboration between project partners, but it is not clear that the HydroGEN nodes have been integrated into the project effectively yet. It appears that more collaboration with HydroGEN is planned in the next year, so one hopes that this will be remedied. Use of the HydroGEN Data Hub is not addressed in the presentation.
- This project has proposed a good collaboration with the HydroGEN consortium. The data from the collaboration with the HydroGEN consortium was not reported.

Question 4: Relevance/potential impact

This project was rated **3.0** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- The development of AEM electrolysis is quite significant because of the high scarcity and high price of Ir, which has been used in polymer electrolyte membrane (PEM) water electrolysis. The success of this project may enable meeting the DOE ultimate hydrogen production goal of $2/kg hydrogen.
- This project has excellent relevance, and potential impact is great. Collaborators have been carefully curated, and collaborations should bear fruit next year.
- The project aligns well with the DOE Hydrogen Program and DOE research, development, and demonstration objectives. AEM electrolyzers are a promising technology for green hydrogen production. The cost model output (slide 4) is reasonable. However, the project approach does not demonstrate how to get the target performance. For example, it would be very challenging to use a PGM-free cathode catalyst to get 1,000 mA/cm^2 at 1.85 V. Also, it has not been demonstrated that thin AEM (<50 micrometers) can produce hydrogen at 30 bars. Adding KOH solution into the system will also increase the cost, although it is unclear that the project is aiming for electrolyte-free liquid.
- The project's work on development of alkaline membranes and ionomers, as well as understanding and improving electrode stability and performance, has clear value for the field and advances the viability of AEM electrolysis. However, the project's impact is motivated with confusing cost analysis results. Several important assumptions relevant to the project are not presented clearly. It is unclear whether the analysis assumes the use of a supporting electrolyte. The support for the claim that AEM water electrolysis will have lower balance of plant costs than PEM water electrolysis is missing. The analysis assumes both very low-cost electricity ($0.02/kWh) and a 100% capacity factor; this is not clearly a realistic scenario, but it

may alter the relative priorities for lowering cost. It is not clear whether the results in the sensitivity analysis tornado chart are relevant to capital cost or levelized cost of hydrogen, and there are apparent contradictions about the importance of membrane and catalyst costs. The cost analysis seems to imply that these are not important, but then they are identified as major project focus areas.

- The progress made this year is good—but not out-of-the-ballpark good. For example, the principal investigator's (PI's) team did show stable AEM electrolysis stability, but only in the presence of a supporting electrolyte. It would have been interesting at least to hear about the AEM electrolysis durability in deionized (DI) water, especially since the PI did highlight the stability of sp^3 carbons. It looks like the electrocatalyst and ionomer durability will need to be supplemented with a supporting electrolyte. If that is not the case, there was no evident plan to overcome these issues.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The planned future work focus on continued research in stability and durability is good. Longer-term durability testing is a good next step and warranted by good results demonstrated by the project so far in durability tests now spanning about 100 hours or hundreds of hours. For electrode stability tests, some kind of cycled accelerated stress test (AST) would also be useful. For the planned scale-up activities, the electrode technology readiness level (TRL) seems low, but there is broader interest in commercially available AEMs, so demonstrating membranes at commercial scale is a reasonable next step. Further catalyst investigations are also reasonable; the project approach so far of not varying the catalyst too much is good, as it is preferable to have fewer variables in the electrode development work.
- Future work has been clearly outlined and is logical.
- Future work will be focused on long-time durability. Future work should be focused on electrode design to enable pure water operations.
- The future work is well-organized. However, the scope of work is little too broad. It seems that AEM and ionomer durability reach a certain level when low-concentration KOH electrolyte is used. Maybe it is time to investigate more on pure-water-fed conditions. Moreover, as the project's go/no-go decision criterion is <1.75 V PGM-free electrolysis at 750 mA/cm^2, the focused work for PGM-free anode and cathode catalysts is required. Demonstration of the stable membrane at a commercial scale may be less important, as those efforts can be leveraged with other projects.
- In the future work, the first bullet is that "there are clear pathways toward durable ionomers/catalyst/binder-based electrodes." However, this does not seem to be the case, as DI water electrolysis durability is not presented and it was mentioned that the OER catalyst has some stability issues. The ionomer direction is toward materials that are non-conductive. If that is the case, this project will need to focus on electrolyte-supported electrolysis. Whether that will be the focus is not clear, which is why the future work is rated as good.

Project strengths:

- There is good collaborative research. There is holistic research and development of membrane, electrocatalyst, and cost model development. There is promising materials development.
- The strength of the project is teaming. Georgia Tech (membrane) and the University of South Carolina (electrode) are capable team members for these efforts. Pajarito Powder has good resources on various hydrogen evolution reactions (HER) and OER catalysts. Nel Hydrogen has extensive testing experience. The high performance of AEM fuel cells using the Georgia Tech materials has been demonstrated. Therefore, the project team has a good chance to achieve high performance and durability for AEM electrolyzers.
- Work on development of alkaline membranes and ionomers and understanding electrode integration and durability are important priorities for the AEM electrolysis field, and the project appears to be achieving progress on these topics. The membrane/ionomer technology appears promising, and improvements to cell stability have been demonstrated.

- AEM development with high glass transition temperature is a strength. The project has a great team with complementary experience.
- The project strength is mainly on the development of a new membrane, though the PI has long experience with this class of polymer materials.

Project weaknesses:

- The main weakness is the seemingly ambiguous suggestion that focus will be on electrolyte-supported electrolysis (there is no DI water electrolysis durability, nor was there any mention that the anode catalyst is not stable in DI water). The PI did mention that the polymer chemistry is scalable, but it was not clear whether the production of the crosslinked membranes could be performed via large-scale membrane manufacturing, such as roll-to-roll or tape casting. Typically, crosslinked membranes are difficult to control from batch to batch, and this is especially difficult with square-meter-sized membranes.
- The project tasks are too diversified. The scope of the project is much larger than that of other HydroGEN projects, although the size of the project is similar. The team may try several catalysts, gas diffusion layers, membranes, and ionomers in MEAs. However, systematic studies on a focused area may be difficult. For example, in anode ionomer optimization, the team tried many ionomer combinations and concluded that the OER requires an ionomer with lower water uptake. However, the comparison between GT72-5, GT72-10, and GT72-15 suggested that the GT72-15 with the lowest water uptake showed the lowest voltage during the 2.5-hour test. Showing high performance and durability is critical, but a more systematic approach to understanding electrolyzer performance and durability may be necessary. Unfortunately, the resources to carry out such experiments seem to be limited.
- The cost analysis is confusing and not clearly adding value to the project. Some results presented appear to have possible issues with variability and reproducibility, and the project should be careful about validating such results. The project's approach to the use of supporting electrolytes is unclear.
- The $PbRuO_X$ catalyst has a hazard concern. Pb is a hazard material. RuO_X is not thermodynamically stable (from the Pourbaix diagram). The focus will be on electrode design without using KOH solution. BP 1 and BP 2 go/no-go milestones contain PGM-free catalysts, but actual data was obtained using PGM catalysts.
- A potential weakness is in electrocatalysis and the lack of a clear strategy for understanding interfacial issues both from an electrocatalysis point of view and from the transport aspect.

Recommendations for additions/deletions to project scope:

- The project needs to demonstrate baseline performance under standardized conditions first. The project should clearly define AEM, AEM thickness, ionomer, HER and OER catalysts, catalyst loadings, alkaline-electrolyte-fed conditions, temperature, pressure, and voltage degradation rate at a specified current density for a specified number of hours. This can be used as a progress measure. The project should also use non-PGM HER and OER catalysts (if those are proposed). The project should use differential pressure operation. The project should delete all Ir-based catalyst work (except for baseline performance).
- The cost analysis in its current form has unclear value to the project. This analysis should either be improved to clearly provide relevant guidance to the project or be omitted from future work. Some validation work to ensure that results are reproducible would also be very useful for the project and would be a good use of HydroGEN support resources. Durability testing should possibly also include dynamic operation/cycled ASTs to test electrode stability.
- The team should decide whether to focus on DI water or electrolyte-supported electrolysis to help gauge the TRL of the technology.
- It is recommended that the project shift the electrocatalysis focus to non-PGM materials; there is no purpose to moving to alkaline pH while using PGM catalysts.
- The project should focus on the testing without the KOH solution. Without the addition of KOH, the significance of this project has been compromised.

Project #P-186: Performance and Durability Investigation of Thin, Low-Crossover Proton Exchange Membranes for Water Electrolyzers

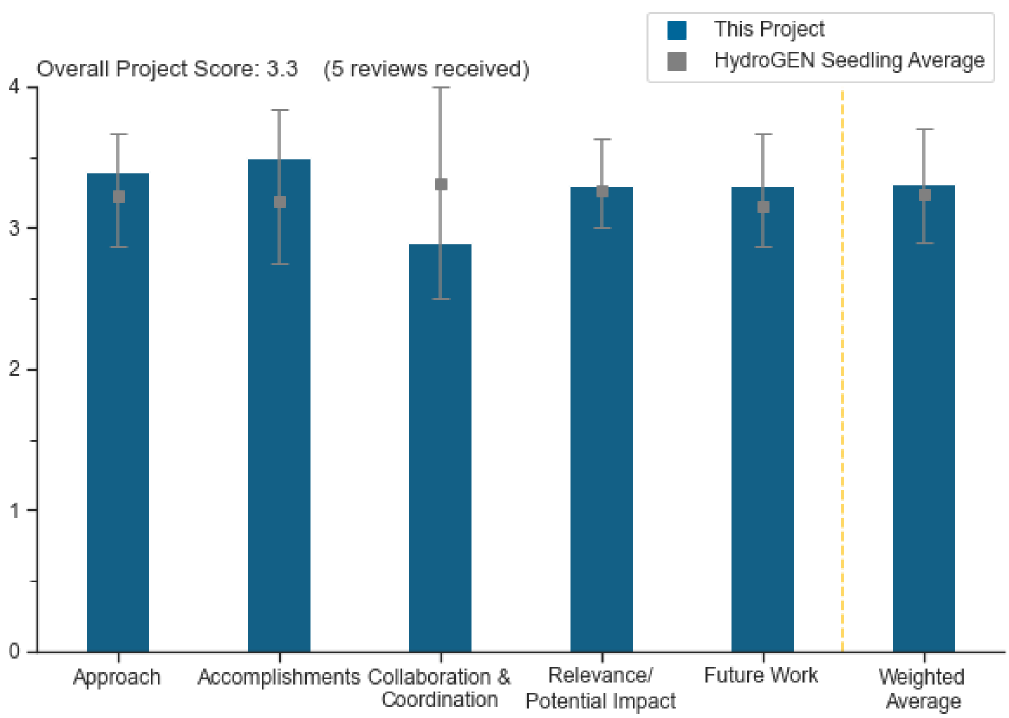
Andrew Park, The Chemours Company FC, LLC

DOE Contract #	DE-EE0008836
Start and End Dates	3/1/2020 to 2/28/2023
Partners/Collaborators	Los Alamos National Laboratory
Barriers Addressed	• Manufacturability: These membranes will be constructed on roll-to-roll systems for easy transition to the commercial scale • Durability: The additives envisioned to enable thin membranes can move, agglomerate, or leave the system entirely, which will be studied and mitigated

Project Goal and Brief Summary

The goal of this project is to develop next-generation membranes specific for polymer electrolyte membrane water electrolyzers (PEMWEs) with improved performance and durability. Thin, mechanically reinforced perfluorosulfonic acid (PFSA)-based membranes will include gas recombination catalysts (GRCs) and radical scavengers to reduce gas cross-over and increase durability, respectively. State-of-the-art roll-to-roll manufacturing technologies will be leveraged to fabricate the membranes on a commercial scale, where the placement and loading of the additives can be precisely tuned/distributed within the membrane structure. The critical factors for success include (1) integrating/optimizing additives within a thin, reinforced PFSA membrane, (2) understanding the additives' behavior (i.e., activity, migration, dissolution, and/or retention) within the membrane over a polymer electrolyte membrane (PEM)-water-electrolysis-relevant lifetime, and (3) validating membrane performance/durability using duty cycle and accelerated stress tests that are representative of dynamic electrolyzer operation.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- This project has a very strong approach, including the development of multiple distinct improvements to advance membranes for PEMWEs, following from successful approaches for PEM fuel cells but optimized for the PEMWE context. These membrane improvements are all useful in isolation and address critical challenges for PEMWE membranes, but the improvements also have the potential to be combined in an advanced membrane product. The project has a good structure, beginning with isolated modifications, verifying their effectiveness, and then moving to combined product and durability work in future budget periods. The HydroGEN partners are integrated from the beginning, providing characterization and modeling capabilities that complement the membrane development at the Chemours Company (Chemours), and can provide validation and guidance as the project progresses.
- This project aims at understanding the limits of PEM thickness using various strategies such as reinforcements and other additives. With this, the researchers expect to advance the membrane resistance from the current state of the art of 0.2 ohm-cm^2 to below 0.7 ohm-cm^2. They also plan to advance the state of the art in gas recombination catalysts and radical scavenging.
- The approach to making reinforced PEMs with GRCs is meaningful in lowering overpotential caused by ohmic loss. Thin membranes can also lower the capital cost. Hydrogen crossover characterization is quite comprehensive. More mechanical property testing of the developed membranes is necessary.
- This project tackles a very important opportunity for PEMWEs.
- There are reservations about this approach since it is still employing Nafion™, which is known to be fairly expensive, but now adding the additional process of including a GRC and radical scavengers will further increase the cost of this material. Furthermore, there was no discussion on exactly what this GRC composition is; one hopes it is an inexpensive transitional metal oxide, but this was not clear. In addition, adding additives have other consequences such as changing mechanical properties, leaching, and increasing materials costs.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- The project presentation demonstrates strong progress on all budget period 1 (BP 1) goals, with results and data very clearly presented and showing clear progress on critical metrics for crossover, mechanical properties, and processing of radical scavengers and the GRC. Durability progress has not yet been demonstrated, but this work is planned for BP 2. The project also demonstrated strong deployment of the characterization and modeling capabilities from the associated national laboratory HydroGEN nodes. The BP 1 milestones were met, with a short extension needed on BP 1 go/no-go milestones because of COVID-19-related delays on the lab work.
- The team made excellent progress on its initial milestones in the first year of the project. Uniformly dispersing the GRC in the membrane and demonstrating three-fold reduction in hydrogen permeation are good achievements.
- The project has made a great accomplishment in terms of reduced membrane crossover. The hydrogen crossover of the developed membrane is close to that of N117, but the membrane has a thickness of 50 µm..
- This project has made good progress with the homogeneous incorporation of both the GRC and radical scavengers. The resultant composite material had an electrolysis performance similar to N212 but hydrogen permeation around three times lower than N212. It is hard to gauge this advancement by itself; it would help if there were a cost model showing whether the cell could be run at around 1 A/cm^2 at 1.5 V in a real electrolysis system. It would also help to then see the equivalent cost savings for the current state of the art. Moreover, it would be beneficial to determine whether the higher performance would offset the higher cost of the membrane.
- The accomplishments have been very good, considering the challenges of the previous year's COVID-19 pandemic challenges.

Question 3: Collaboration effectiveness

This project was rated **2.9** for its collaboration and coordination with HydroGEN and other research entities.

- There is very strong collaboration with national laboratory partners and HydroGEN nodes, which provide characterization and modeling to complement the membrane development at Chemours. The collaborators appear well-integrated and are providing significant valuable contributions early in the project, providing validation and opportunities to guide membrane development as the project progresses. The collaborative activities are well-matched to partner capabilities and targeted to key project objectives. The use of the HydroGEN Data Hub and data sharing were not addressed in the presentation.
- There is a good workflow within the team that has addressed all important aspects of the research.
- The collaborations are just starting for this project, and they should be in good stead next year.
- There is good collaboration with key national laboratory experts, but what takes away from the feasibility of this project is that there is no original equipment manufacturer (OEM), such as Giner, Inc., or Nel Hydrogen, as a testing partner. If this project cannot get the OEM excited about testing these materials with the current progress, it is unclear whether there will ever be a viable end user.
- The only collaborator is Los Alamos National Laboratory. Collaboration with an electrolyzer company for further evaluation is highly recommended.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- This project has very high potential impact for PEMWE devices, the H2@Scale vision, and the DOE Hydrogen Program in general. If successful, the advanced PEMWE membrane developed by this project would combine multiple improvements to advance durability, cost, performance, and operational flexibility—all critical barriers for achieving the \$2/kg H_2 cost target for water electrolysis. The approaches pursued all appear highly promising based on their successful application for PEM fuel cell membranes and based on strong initial results from this project. Development and deployment of characterization and modeling tools with project partners and HydroGEN nodes will also be beneficial to the research community, as these tools will be transferrable to future projects.
- This project addresses a serious opportunity to enhance the efficiency and durability of PEMWEs.
- The development of reinforced PEMs may reduce the thickness of the membrane without much influence on the hydrogen crossover; therefore, it may bring down the overall cost of PEM electrolyzers. The cost of reinforced membranes with GRC needs to be determined.
- The project's relevance is good but not outstanding. The need to lower the membrane and interfacial resistance is well taken but is in the domain of optimization. The field of GRCs is also well-documented and not terribly new. Using Ce as a free radical scavenger is also well-known. However, success in this project will certainly offer greater functionality in a mature technology.
- This is interesting science, but it is difficult to see the breakthrough impact of lowering PEM electrolysis cost by essentially enabling use of thinner Nafion membranes. Moreover, the additives can potentially degrade and migrate out (there is already some evidence of this, seen in slide 14), and it seems that the additives open other problems with unknown consequences and seemingly little benefit.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- This project has strong planned future work, including integrating various membrane features developed separately into one advanced membrane and testing the resulting product. Planned testing includes durability testing to ensure that membrane additives are stable and provide expected improvements to membrane chemical durability. All future work appears reasonably planned and clearly targeted to achieve project goals and overcome critical membrane development barriers.
- The proposed future work properly builds on previous results to work toward achieving the overall goals.

- The proposed future work has been well-delineated.
- The proposed future work is detailed and reasonable.
- Testing efforts are planned in the future work, but it would make more sense if there were dialog between the project lead and OEMs, such as Giner, Inc., or Nel Hydrogen, to determine whether the performance metrics are of value to them. It is not clear whether a membrane that gives electrolysis performance similar to N212 and has three times less hydrogen permeation is a key hurdle in this technology space.

Project strengths:

- This project has a strong and clearly focused research effort to develop next-generation membranes for PEMWEs, including multiple promising pathways to improve the technology. There is high potential impact for the DOE Hydrogen Program if the project goals are met. Also, there is good integration with collaborators and effective use of support from the HydroGEN consortium.
- The project has good fundamental science. The approach includes homogeneous incorporation of additives, and the additives improved performance as predicted (lower area-specific resistance and lower hydrogen permeation).
- The reinforced PEMs with the GRC are a project strength, although this idea has already been adopted by major electrolyzer companies. Stringent hydrogen crossover measurements are commendable. The hydrogen crossover data are impressive. Also, the project has progressed well and met major milestones.
- The project has a great approach and an excellent team.
- This project aims at furthering the current state of the art of PEM electrolyzers. Some risk analysis, however, is important, considering the thinness of the membrane.

Project weaknesses:

- The project has provided little technical detail on the membrane modifications being developed. This is understandable because the project is working toward a proprietary product; however, it does limit the informational value for the broader community. One hopes that in a later stage of the project, more detail can be shared.
- The ultimate weakness of this project is that it is not clear whether the project is solving a real issue in current PEM electrolysis. The project might be introducing more issues with increased membrane cost and additive migration/degradation.
- The project's weaknesses are that the long-term mechanical testing has not been implemented and the cost of the developed membrane has not been analyzed.
- This project, as formulated, does not provide any advancement in the science of technology.

Recommendations for additions/deletions to project scope:

- There needs to be a partnership with an electrolysis OEM that can validate that the performance of this new membrane will lower system/operational cost and is a material the OEM can get behind once the lifetime testing and accelerated stress test are completed.
- The project should consider other possible failure modes that may fall outside membrane stress testing (such as anode catalyst dissolution and redeposition on the GRC) and inclusion of relevant testing for any risks identified.
- The project should complete the cost analysis of the developed membranes and add an electrolyzer company as a collaborator to validate the data.
- No recommendations are necessary at the moment.

Project #P-187: Pure Hydrogen Production through Precious-Metal-Free Membrane Electrolysis of Dirty Water

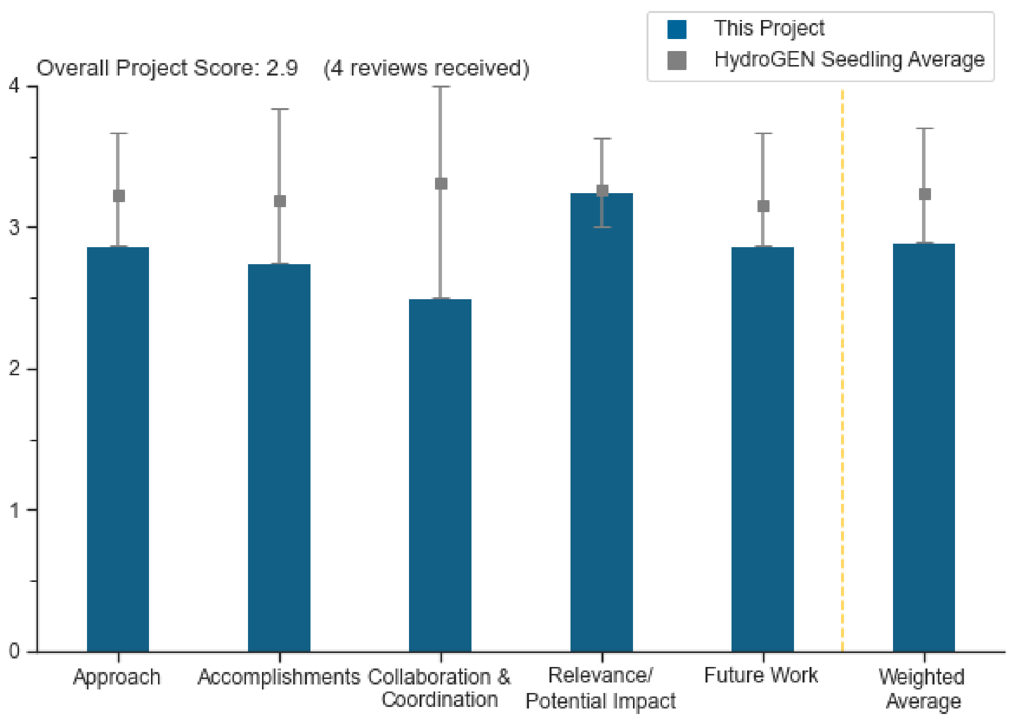
Shannon Boettcher, University of Oregon

DOE Contract #	DE-EE0008841
Start and End Dates	4/1/2020 to 3/31/2023
Partners/Collaborators	National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Sandia National Laboratories
Barriers Addressed	• Ion exchange in membrane(s): Minimize by controlling ion flow direction • Deposition of impurities: Use high loadings of low-cost catalyst, control location and morphology of deposits • Cl-oxidation: Maintain local basic anode

Project Goal and Brief Summary

The project team will develop a technical understanding of alkaline and bipolar membrane electrolyzers, specifically how their performance degrades in both pure and dirty water. Using this knowledge, the researchers will engineer impurity-tolerant systems. This project will improve the longevity of platinum-group-metal (PGM)-free electrolysis devices, make them more tolerant of input water impurities, and lower costs. The University of Oregon is collaborating with Lawrence Berkeley National Laboratory (LBNL), the National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL) on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **2.9** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- The project is following a good approach to begin with baselining and understanding the degradation and transport in pure-water-fed cells using PGM catalysts before proceeding to introduce added complexity from contaminants or PGM-free catalysts. The inclusion of baselining and validation work with HydroGEN to ensure reproducibility of results is a good feature of the project. This approach appears to give the project a strong position for addressing challenges for alkaline electrolyte membrane (AEM) and bipolar membrane (BPM) systems.
- The project aims to develop AEM electrolyzers using PGM-free catalysts. The project aims to deal with dirty water. The design of the reference electrode is impressive. It is unclear what the focus of the principal investigator (PI) is: catalyst development, electrode design, or impurities studies.
- The project is aiming to design more robust electrolyzers to produce hydrogen using "dirty" water. The project approach is to control ion flow using AEM and BPM electrolyzers. It is hard to capture what the unique approaches this team is trying to make are. AEM and BPM electrolyzer architectures are well known in the community. The only difference in this project is using unpurified seawater instead of the pure water used in other studies. In the approach section, there is no clear message on how impurities in the unpurified water are going to be dealt with. There are no specific pathways to deal with local pH change by seawater, which could be the key consideration to reach the proposed targets. No AEM material justification was provided. The choice of Sustainion or node-supporting materials for the project is unclear.
- There is a clear need to see the limits of alkaline water splitting electrocatalysis considering the larger overvoltage window in alkaline conditions. The approach is, however, missing key details such as thermodynamic limits based on the pH of "dirty water." "Dirty water" has not been clearly specified except that it contains NaCl; it is unknown if other components make sense in this regard. So, the approach would need more clarity, especially as to the basis for choosing 0.5 M NaCl and whether that choice has any relevance to "dirty water."

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- Good progress has been demonstrated toward meeting the project goals, including establishing testing capabilities and publishing project results. Work on the project so far has built a good foundation for future work, especially baseline development work and development of methods for the project, such as test stand construction, integrated reference electrodes, and analytical methods. The project appears on track to meet its milestones.
- The project demonstrated good AEM water electrolysis (AEMWE) performance using pure water. The project is unable to show long-term durability of the AEMWE. The catalyst $PbRuO_x$ might be highly unstable in alkaline media. The study on dirty water is not thorough, as there are many ions or impurities in saline water or wastewater.
- The project has been in place one year and had a possible delay due to COVID-19. Some progress was made using commercially available materials. The team accomplished measurement of the baseline electrolyzer performance, a water transport study, measurement of CO_2 effect, and measurement of ion crossover in NaCl solution. The PI talked much regarding the degradation via polymer oxidation, but this is a known fact from a previous study (see *Energy Environmental Science*, DOI: 10.1039/D0EE04086J [2021]). Likewise, water transport and CO_2 effects (NaOH vs. $NaHCO_3$) have been discussed in the community. It is okay to discuss those effects, but the PI should justify why these types of studies are related to the scope of the project. The project needs to define how to calculate the voltage degradation rate on slide 15. For the IrO_2 anode in pure water, the cell voltage increased from 1.87 V to 2.26 V for the first 100 hours. So, the voltage increase rate is 3.9 mV/h (0.39/100*1000), but it was reported to be 0.67 mV h^{-1}. Also, for the IrO_2 anode in 0.2 g $NaHCO_3$ case, the cell voltage increased from 1.9 V to 1.98 V during the first 110 hours, so the voltage increase rate is 0.72 mV/h, but it was reported to be 0.17 mV h^{-1}. The voltage increase rate during the first 20 hours shown on slide 12 seemed to be correct. The project needs to define

durability better. Electrolyzer durability should not be measured by voltage increase rate only. If the cell is stable only 10 hours before voltage goes to zero, then this cell is not durable. So, the project needs to add a minimum operation time (e.g., 1,000 hours) (please see what other HydroGEN projects are doing). The preliminary BPM electrolyzer performance shown in slide 18 is relatively poor, although the performance is approaching that of the AEM electrolyzer in pure water. The team should do a simple technoeconomic analysis that shows how much performance improvement is required to generate hydrogen at $2/kg. Any voltage over 3 V is not practical, but even the best-performing BPM electrolyzer has cell voltage >3 V at 2 A cm^{-2}. Adding dirty water and PGM-free catalysts will likely increase operating voltage. A few missing experiments the team probably should have accomplished in the first year of the project are the following:
    - Baseline electrolyzer performance using "dirty water"
    - Performance of PGM-free catalysts in rotating disk electrodes or electrolyzers
    - Planning for material design standpoint, as it is not clear what types of materials the team is trying to use for the proposed systems
    - Detailed planning for the modeling, ink formulations, and membrane electrode assembly fabrication.
- Accomplishments have clearly shown the risks, especially in terms of the choice of membranes and catalysts. Degradation rates are not acceptable. It is unclear what is causing this rapid decline in activity.

Question 3: Collaboration effectiveness

This project was rated **2.5** for its collaboration and coordination with HydroGEN and other research entities.

- The collaborations are yet to begin, and, hopefully, they will manifest themselves next year. It has been a challenge to foster collaborations in these circumstances.
- This project listed many node supports. The node supports seem to cover various areas of the project. However, no detailed tasks or accomplishments from the node collaboration are described. The node tasks listed in the presentation are general, except one from Weber. There are no plans or works with the benchmarking/protocols teams other than mentioning "ongoing collaboration with Nel Hydrogen."
- The project's integration with collaborators appears to be more in planned future work, without major collaboration demonstrated so far. However, the planned collaborative work does appear to make good use of HydroGEN node capabilities directed toward the project goals. The presentation made no mention of the project's use of the HydroGEN data hub or data sharing.
- Collaboration with HydroGEN is clearly presented. The project uses W7 membranes, but the role of SNL (Cy Fujimoto) is not clear.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- The impact of this project is high, if it succeeds. It can eliminate expensive and scarce Ir catalysts. It can also help develop strategies to mitigate impurities in water. The AEMWE can also enable other inexpensive non-active components. Long-term durability needs to be thoroughly studied for a higher impact.
- The relevance of this effort is very high, though there will always be a tradeoff between external water purifiers and inherent tolerance to salts and other species.
- The potential impact of AEM electrolyzers using seawater or dirty water is high. Also, the plan for using PGM-free catalysts for AEM electrolyzers is relevant and well aligned with DOE's research, development, and demonstration goal. One concern is that the actual content and current accomplishment is not well aligned with the project target. The PI indicated that ion exchange in membranes, deposition of impurities, and Cl oxidation are the major barriers, but the project's remaining challenges listed are ionomer degradation, comprehensive modeling, and model studies. It seems that the chance of high-performing AEM electrolyzers using seawater and PGM-free catalysts at the end of the project is very low. The work should be more focused and resolve some specific challenges related to the project objective.

- The project's focus on electrolysis of truly "dirty" water provides unclear value to the community, and this is not obviously a promising path to meeting broader DOE Hydrogen Program goals for low-cost hydrogen production. However, much of this project's work is more broadly impactful (for example, understanding degradation and transport in AEM systems generally and understanding and mitigating contaminants from steel or non-PGM cell components). It is good for the project to keep its focus on activities that provide broader value to the community and improve understanding of AEM and BPM systems in use cases other than dirty water electrolysis as well. The work focused on baseline performance, stability and degradation, and the impacts of supporting electrolytes (including after attempts to flush the cell) is very useful to the community and fits well within the project scope of understanding ion impacts and degradation mechanisms.

Question 5: Proposed future work

This project was rated **2.9** for effective and logical planning.

- The planned work continuing to understand baseline performance and degradation in pure-water-fed cells is good, as this area is clearly still needing more clarification. The planned validation work supported by HydroGEN is a good inclusion to ensure reproducibility of results. Planned support from HydroGEN on modeling and understanding ionomers and membranes is also reasonable for achieving the project goals. It is not clear if the planned work will include non-PGM catalysts as described in the project vision.
- The future work is clearly described. The dirty water study is interesting but challenging. Work has to be conducted to differentiate the impact on catalyst and on membrane. Advanced characterizations can help to understand durability issues caused by the interface.
- They are well delineated in slide 20.
- The future work section is filled with rosy targets. No clear pathways and specific approaches were discussed. For example, the PI indicated that oxidation of ionomer is the big issue. Then it is unclear what the appropriate experiments or designs to mitigate the oxidation of ionomer are. It is unclear what the specific plan to decouple the degradations by membrane, catalyst, ionomer, and impurities is. It is unclear what the pros or cons for PGM-free catalysts for AEM electrolyzers' performance and durability are. It is unclear what the strategy to prevent impurity crossover to the cathode is. Also, collaborative works with HydroGEN nodes are not well described.

Project strengths:

- The project is achieving good scientific work to understand performance, transport, and degradation in AEM electrolysis that is of broad value to the community. The project includes interesting innovative work in alternative cell design approaches, such as bipolar membranes and anode water feed. Strong baseline development work has been completed so far, as well as method and capability development, and the project is actively publishing its results. The project appears to have a good approach to understanding and overcoming key challenges for AEM electrolysis.
- The concept of the project is a strength. The conventional electrolyzer requires pure water or alkaline solution for high performance. The project is aiming to use "dirty" water for generating hydrogen. The team looks to be capable to analyze the data and has some background knowledge on AEM and BPM electrolyzers. Also, it was reasonable to test the electrolyzer in a practical current density (500 mA/cm^2) (slide 12). The team also has access to some commercial and non-commercial materials for the project. They are looking at various aspects to realize highly performing and durable water electrolyzers.
- This project and hopefully others will provide the general limits to how pure the water needs to be under alkaline pH conditions. This is a clear pathway toward the technoeconomics of running this unit with either seawater or seawater after partial desalination.
- Using PGM-free catalysts and dirty water are great ideas. Good progress has been made in a one-year time frame. The reference electrode design is very helpful.

Project weaknesses:

- The major project weakness is the broadness of the scope of work. Some of the works are largely overlapped with previous and other current projects. The project task should be refined and more selective to accomplish the project targets. Current data show some important information regarding performance and durability limits but lack strategy to resolve the problems. DOE Hydrogen and Fuel Cell Technologies Office projects are milestone-driven. Understanding degradation modes is useful to set strategies but does not necessarily bring the project to meeting the targets. It is not clear how controlling ion flow in AEM and BPM electrolyzers can improve the performance at the target level. The go/no-go milestone is not clearly defined. It stated "pure water/gray water/salt-water" feed, but it needs to provide specific information or definition of gray water and salt water. Also, it shows 1 A cm^{-2} at <2 V and 1 mV/h. Reaching the target at the end of the project (<2 V at 2 A cm^{-2}) and the durability target (<4 mV/100 h = 0.04 mV h^{-1}) seem to be very challenging. Also, there is no information regarding operating temperature, non-PGM catalyst, catalyst loading, etc.
- The catalyst $PbRuO_x$ might be highly unstable in alkaline media. This can be seen from a Pourbaix diagram. There is no plan to differentiate the impact of dirty water on the catalyst and on the membrane. The poor durability of AEMWE has not been understood.
- At the moment, durability is of concern.
- Electrolysis of "dirty" water is not clearly a promising path to meeting broader DOE Hydrogen Program goals for low-cost hydrogen production. Many of the project efforts are focused on more useful topics to improve general understanding of AEM and BPM cell degradation and performance and on contaminants from other sources. This is good in a way, but having this disconnect between the project vision and ongoing activities is not ideal. Significant collaborative work with HydroGEN is planned, but it is not clear how active this part of the project is at this point. Efforts should be made to integrate the collaborators into the project sooner rather than later.

Recommendations for additions/deletions to project scope:

- Work on contaminant mitigation through feeding water to the anode side should include clear comparisons to feeding water to the cathode (and possibly also both electrodes). Including investigations of supporting electrolytes with the investigation of contaminants would be useful as well.
- Dirty water study is time-consuming. In fact, dirty water has to be processed before entering the electrolyzer. This work can be less significant in this project. Focus should be given to PGM-free electrode design to improve the performance and durability.
- CO_2-related work is irrelevant, so that work should be deleted unless there is strong justification. The project should reduce all work with pure water feed. Those studies were largely overlapped with other studies. The project should expand PGM-free catalyst work under seawater-fed conditions. The project should do more AEM electrolyzer tests under dirty-water-fed conditions to identify performance and durability limiting factors.
- A clear strategy to understand the origins of poor durability is recommended.

Project #P-188: Advanced Coatings to Enhance the Durability of Solid Oxide Electrolysis Cell Stacks

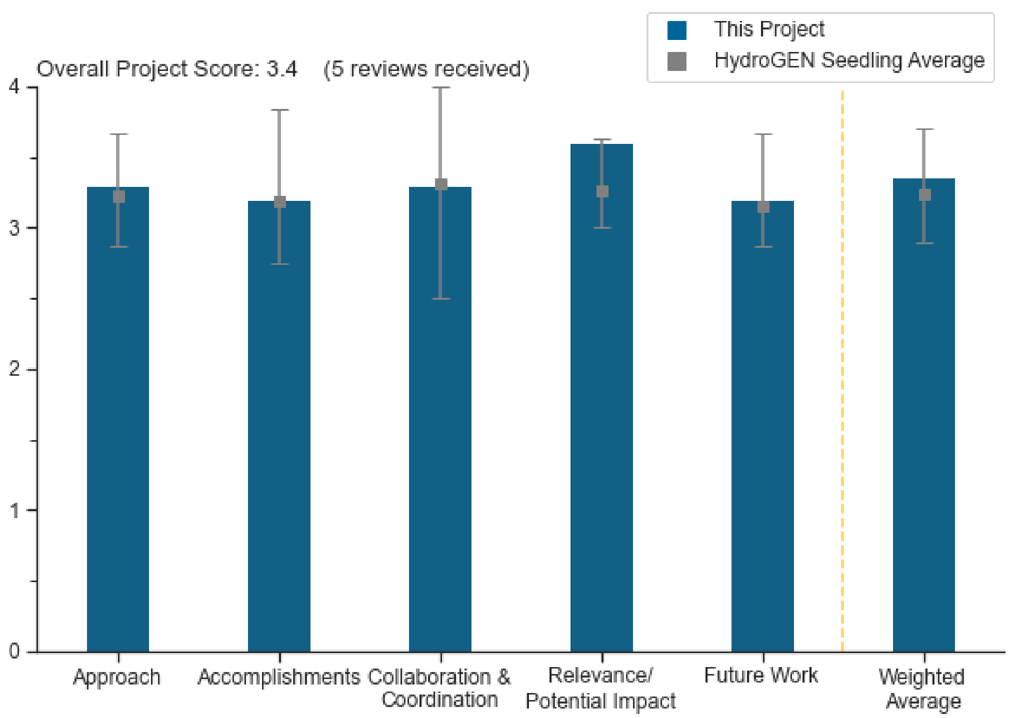
Neil Kidner, Nexceris, LLC

DOE Contract #	DE-EE0008834
Start and End Dates	4/1/2020 to 3/31/2023
Partners/Collaborators	University of Connecticut, Lawrence Berkeley National Laboratory, Idaho National Laboratory
Barriers Addressed	• Deconvolution of degradation mechanisms • Demonstration of coating technology at production-relevant scale

Project Goal and Brief Summary

This project will advance the technical and commercial readiness of solid oxide electrolysis cells (SOECs) by developing protective coatings and Cr getters to enhance system life. An integrated degradation mitigation strategy consisting of SOEC optimized interconnect (IC) coating, Cr getters, and a balance-of-plant (BOP) component coating will address the critical degradation mechanisms of metal corrosion and chromium evolution. These degradation mechanisms can be substantial, and mitigation strategies are essential to improving SOEC durability and achieving the U.S. Department of Energy performance and lifetime targets for SOEC systems. The efficacy of the coating strategy to reduce degradation will be demonstrated by testing on SOEC single cells and stacks, with a goal of achieving an equivalent (or better) reduction in stack degradation rate compared to single-cell testing.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- The objective of this project is to develop an effective coating strategy to minimize the degradation caused by metal corrosion and chromium evolution from metallic components in SOEC stacks. If successful, the project will significantly enhance durability and accelerate commercialization of SOEC systems. The technical approaches are scientifically solid and are appropriate for achieving the project objective. Several critical barriers are identified and are being effectively addressed. The experiments are well-designed and are integrated with other relevant efforts.
- This is a good approach for an industry project. Taking existing coatings Nexceris offers for yttria-stabilized zirconia (YSZ) solid oxide fuel cells (SOFCs) and running a gap analysis for SOEC operational conditions is an efficient way to begin the project from the basis of Nexceris's extensive prior work (and extensive work in literature on manganese cobalt oxide [MCO], on which the ChromLok coating technology is based). Also, the scalability of the coating approach is already validated, so if it works for SOECs, it is commercially viable. Some constructive criticism is offered: The presenter admitted to not realizing that MCO will degrade in reducing atmospheres (slide 9) (an unexpected admission). That is well-documented in literature, but there may be differences in ChromLok, so characterizing the coatings' degradation was useful. Also, much of the project's novelty lies in the data-gathering to understand the operational parameter space; the coatings and future getters seem to be selected from reasonably well-researched materials. Having access to these insights will benefit the community, but it is also plausible that some information will be withheld; Nexceris is encouraged to find a balance that allows for broad data-sharing, when possible. A reviewer mentioned the Data Hub, which would be a good avenue.
- This project tries to address an important issue in the SOEC, i.e., Cr poisoning. Half of the project focuses on evaluating existing coatings for interconnect, and the other half focuses on loading Cr getters in BOP. These two approaches are technically unrelated, although they contribute to the common goal.
- This project effectively builds on prior technology to meet the project objectives. Collaboration with HydroGEN is effective.
- It is indicated that the barriers of the approach are deconvolution of degradation mechanisms and demonstration of coating technology at production-relevant scale. However, no discussion or work plan on these barriers was given.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- The team has successfully completed the first go/no-go milestone, suggesting that the proposed coating is acceptable for further testing of SOEC stacks under typical operating conditions. Overall, good progress toward the outlined project objectives has been made against clearly defined and measurable performance indicators, such as required area-specific resistance and degradation rate. The accomplishments to date suggest that the researchers have made reasonable progress in addressing critical barriers to achieving DOE goals. It would be useful if the distribution of Cr and the Cr-containing phases in the porous electrodes could be characterized under different operating conditions, which could then be correlated with the performance of the test cells with and without the protective coatings.
- The positive is that the researchers met their Year 1 go/no-go targets. Some constructive criticism is offered: The existing coating has been determined to be adequate already, with minimal modification, for SOEC operation, and future milestones may necessitate much more significant modification to the coatings. Therefore, those should be evaluated early in Year 2 since they can take a good deal of time.
- The project exceeds the go/no-go criteria. It is not clear that the Year 2 go/no-go milestone will result in significant progress toward the <4 mV/kh degradation goal. Improvement toward the degradation goal relies instead on progress outside of the project scope (Generation 3 cells).

- From an interconnect Cr evaporation point of view, SOEC and SOFC operating conditions are similar to each other, so it is no surprise that the coating that worked under SOFC conditions also works under SOEC operation. It will be interesting to see more Cr getter results.
- Go/no-go decision point 1 was completed.

Question 3: Collaboration effectiveness

This project was rated **3.3** for its collaboration and coordination with HydroGEN and other research entities.

- Nexceris is adding to the company's baseline expertise with key partners at the University of Connecticut, Idaho National Laboratory (INL), and Lawrence Berkeley National Laboratory (LBNL). Prabhakar Singh's group is well-poised to contribute to the Cr getter work, as well as other Cr impact studies, based on the group's extensive experience. Some constructive criticism is offered: The INL and LBNL nodes are mentioned, but there was not much discussion of the laboratories' actual contributions to project goals. The presented work should communicate the national laboratories' roles more clearly, or descriptions of the work the laboratories contributed should be added. It would be interesting to know whether Nexceris participated in the 2B Benchmarking project activities.
- Valuable technoeconomic analysis is provided through collaboration. Collaborations appear to be effective.
- The team shows effective collaboration with Energy Materials Network nodes.
- The collaboration and coordination with the three partners, including the University of Connecticut, LBNL, and INL, appear to be reasonable. It would be helpful if the developed coatings could be independently tested by other HydroGEN team members.
- A more detailed description of the collaboration with INL and LBNL should be given.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- Efficient, durable, and low-cost SOEC systems will accelerate the transition to renewable, energy-efficient, and low-cost hydrogen. The project objective is to develop a critical coating that will enhance the durability of SOEC systems. The project aligns well with the Hydrogen Program and DOE research, development, and demonstration (RD&D) objectives and has the potential to advance progress toward DOE RD&D goals and objectives. The successful completion of this project will significantly advance the hydrogen production technology and the commercial viability. The project is also leveraging the resources and framework of the HydroGEN consortium. The project has good potential to advance the discovery and development of novel materials for efficient water-splitting systems, which will enable meeting the DOE ultimate hydrogen production goal of $2/kg H_2.
- The project is sharply focused on demonstration and development of SOEC corrosion coatings for commercial deployment. This sharp focus on a critical component will have a significant impact toward DOE goals.
- The Cr impact of steel components needs to be addressed in most SOEC systems in a way that is cost-effective, so the relevance for this project is very clear. The magnitude of the impact will be more apparent when the actual change in long-term degradation values is reported and acceptable stack lifetimes are calculated, but the project is off to a good start.
- This project addresses one of the most important issues in SOEC stability: Cr poisoning.
- The project includes evaluation of coating under electrolysis conditions. However, it is not clear how the project has leveraged progress and used relevant data under fuel cell (SOFC) conditions.

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- The project is well-planned-out.

- The proposed future work in budget period 2 includes further detailed studies and improvements of the existing ChromLok IC coating technology, identification of effective Cr getter materials, and the combination of IC coating and Cr getter materials.
- It is not clear whether the project covers any of the cell development. The presenter mentioned that Generation 3 will help get current densities and voltage ranges in the desired range. More detail on the coating and getter analysis plan would be helpful. The kinds of improvements being considered were not specified.
- The project should work on scaling up the coating technology.
- The effort should focus on the Cr getter development.

Project strengths:

- The project brings together a good team for the development of coatings at a major SOFC manufacturer. The coatings will be needed for most high-temperature electrolysis applications since Cr-containing steels are required in just about every design.
- The approach seems to be practical and effective in improving the durability of cell components susceptible to Cr poisoning. The probability of developing some effective protective coatings is relatively high.
- The project focuses on an effective low-cost coating technology and evaluates coating effectiveness under SOEC conditions.
- Thanks to leveraging previous technology, the project is likely to meet the project goals on schedule and within budget.
- The team’s expertise and the approach to addressing BOP are strengths.

Project weaknesses:

- Weight gain and lifetime studies would benefit from repetition of the trials. These types of data are prone to large sample-to-sample variability, so repetition would increase confidence that the results have not been influenced by spurious factors. Also, although Cr issues are undeniably important in solid oxide cells, it would be helpful to more explicitly highlight how these coatings will influence hydrogen production costs to help reach $2/kg.
- It is implied that meeting DOE's degradation rate target of <4 mV/kh is a project goal, but the project is narrowly focused on corrosion coatings. The degradation rate target is unlikely to be met by the project work alone.
- The project lacks microanalysis of the porous electrode surfaces contaminated by Cr or other contaminants. The project also lacks mechanistic understanding of Cr poisoning.
- The barriers identified for the project approaches are not addressed. The project activities are not closely coordinated (e.g., how the chromium getter work at the University of Connecticut has been incorporated into the project).
- Not much progress was demonstrated on the Cr getter approach in budget period 1.

Recommendations for additions/deletions to project scope:

- Thermodynamic analysis is mentioned, but there was no discussion of the approach to this type of analysis. It would be useful if the presenter would explain what he meant. Kinetics and electrochemistry analysis are clearer. If the existing ChromLok MCO coatings are deemed to perform well with minimum modifications, the scope should expand to evaluate more aggressive conditions. The time saved by not needing to make significant developments to the coating process would be re-invested into data-gathering for where the approach fails. That could provide information for future Office of Energy Efficiency and Renewable Energy decisions about Hydrogen Program goals and directions.
- It would be very useful to perform some microanalysis of the chemistry, phase, and morphology of the electrode surfaces contaminated by Cr or other contaminants. To gain some mechanistic understanding of Cr poisoning, it would be necessary to characterize the distribution of Cr and Cr-containing phases in the porous electrodes under different operating conditions.

- The IC coating effort should be reduced.
- No change to project scope is recommended.
- There are no recommendations for additions or deletions.

Project #P-189: Scalable High-Hydrogen-Flux, Robust Thin Film Solid Oxide Electrolyzer

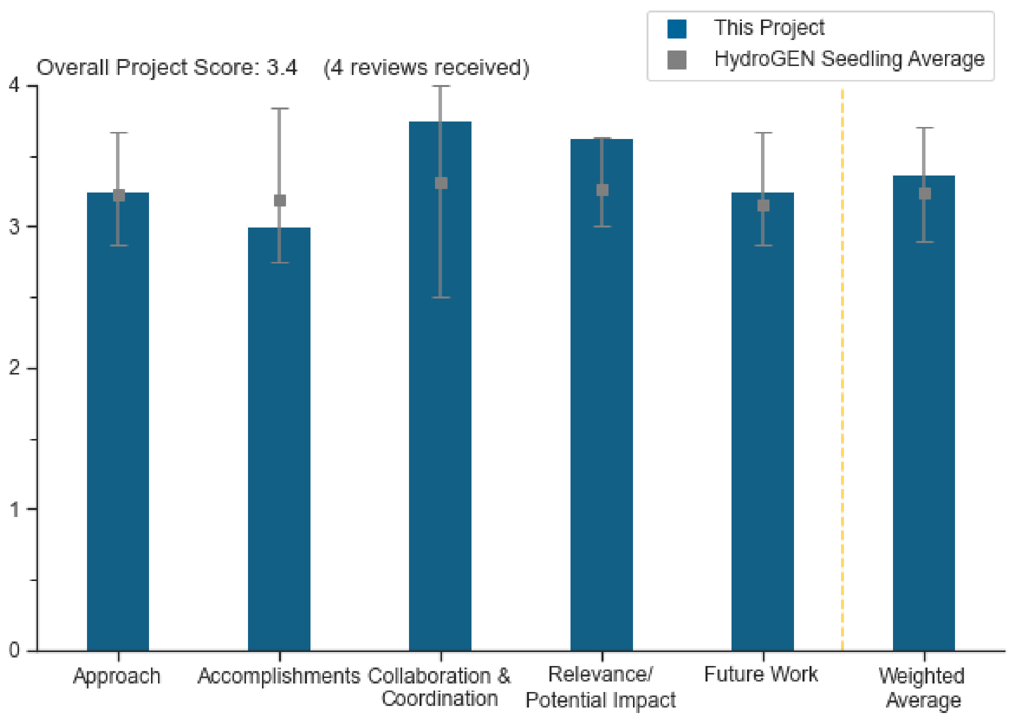
Colin Gore, Redox Power Systems, LLC

DOE Contract #	DE-EE0008835
Start and End Dates	5/7/2020 to 5/31/2023
Partners/Collaborators	Idaho National Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Optimizing stability, conductivity, or Faradaic efficiency in solid oxide electrolysis cell materials and devices typically requires tradeoffs in properties or processing

Project Goal and Brief Summary

The objective of this project is to demonstrate the technical and economic feasibility of solid oxide electrolysis cells (SOECs) based on a thin-film, multilayer, proton-conducting electrolyte. This project will develop a multilayer concept to block the electronic current with one layer, dramatically raising Faradaic efficiency (FE), and provide steam protection with the second layer, thereby mitigating long-term degradation and extending lifetime. The multilayers will be deposited by physical vapor deposition via methods scalable to high-volume manufacturing, overcoming high-temperature processing challenges that have hampered the development of conventionally processed high-performance proton conductors. The cost for H_2 production is expected to decrease significantly owing to a reduced stack size and decreased power consumption resulting from lower cell resistance of the thin film electrolyte layers and high FE.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- The scope of work appears to be appropriate. Significant integration of advances from HydroGEN consortium members into Redox Power Systems, LLC's (Redox's) commercial cell fabrication expertise is a plus.
- The main objective of this project is to enhance the stability and FE of SOECs based on proton-conducting electrolytes using multilayer electrolytes and functional layers. It is hoped that the proposed SOEC systems have potential to meet the U.S. Department of Energy's cost and performance targets. The technical approaches seem to be reasonable for achieving the project objectives. However, some critical barriers may be difficult to overcome. For example, it could be difficult to fabricate coherent bi-layer electrolyte composed of different materials. Sputtered films often need high-temperature annealing to get the desired phases; critical challenges associated with high-temperature annealing may include chemical reaction, inter-diffusion, and delamination between the two layers of different materials. It would be helpful to provide some description on how to determine e-, h+, OH-, and O_2 leaks versus temperature by varying pO_2 and pH_2O using a mass balance system.
- The project proposes a bi-layer approach to addressing the electronic leaking issue related to BZCY (ceria- and yttria-doped barium zirconate) proton-conducting electrolyte.
- The project approach should place more emphasis on optimizing cell stability and efficiency (key barriers) via tradeoffs between cell component properties and processing parameters.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- Some good progress has been made; preliminary results suggest that the protective coating material (the composition was not given) is relatively stable against high concentrations of steam at 500˚C for >200 hours. However, the claimed stability was based only on x-ray analysis of the samples, which may not be conclusive since x-ray diffraction is sensitive neither to surface change (the volume fraction of the new phases on the surface is too small) nor to non-crystalline phases (some of the hydroxides may be amorphous). It would be necessary to measure the conductivity of the samples after exposure to steam at 500˚C for >200 hours to confirm the stability against high-concentration steam. Overall, good progress toward the outlined project objectives has been made using measurable performance indicators. It would be useful to perform some careful microanalysis of the electrolyte surfaces (composition, phases, and morphology) before and after exposure to high concentrations of steam at 500˚C for >200 hours, which can then be correlated with the change in conductivity of the samples after the exposure to steam.
- Because of the coronavirus pandemic impacts, progress to date has been limited. Given the circumstances, the current progress is reasonable.
- It would be better if more bilayer data were presented.
- There is no significant progress on sputtering process development and scale-up.

Question 3: Collaboration effectiveness

This project was rated **3.8** for its collaboration and coordination with HydroGEN and other research entities.

- The team shows effective collaboration with Energy Materials Network nodes.
- Effective collaboration is a particular strength of this project.
- The collaboration and coordination with other partners of the project appear to be reasonable, including the HydroGEN consortium, with appropriate use of nodes.
- There is good collaboration with Idaho National Laboratory and the National Renewable Energy Laboratory but no collaboration or interaction with Lawrence Berkeley National Laboratory, Sandia National Laboratories, or Lawrence Livermore National Laboratory.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- The SOEC systems based on proton-conducting electrolytes have demonstrated very high performance in terms of current density and efficiency. The successful completion of this project will significantly advance the hydrogen production technology and the commercial viability. The project supports and advances progress toward DOE Hydrogen Program goals and objectives and also supports the HydroGEN consortium mission. The project has good potential to advance the discovery and development of novel materials for efficient water-splitting systems, which will enable meeting the DOE ultimate hydrogen production goal of $2/kg hydrogen.
- This project is significantly advancing the development of novel materials. The project is not advanced enough to determine the likelihood of significant impact on meeting DOE targets.
- Progress has been made on material development. More emphasis should be placed on demonstrating stability, especially the stability of large-area cells.
- Electronic leakage is the most important issue for the FE and stability of proton-conducting electrolyte.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The custom mass balance system developed by Redox is likely to be an effective tool to identify root causes of efficiency losses.
- The scope of approach for the proposed future work is good.
- Tasks proposed for budget period (BP) 2 (2021–2022) and BP 3 (2022–2023) appear to be reasonable. However, some details seem to be missing. For example, some specific description on how to enhance FE while reducing area-specific resistance would be very helpful. Also, it would be useful to explain how to determine the key performance degradation mechanisms and devise solutions to them.
- It is unclear why pulsed laser deposition (PLD) has been evaluated along with sputtering. If PLD is evaluated as an alternative to sputtering, then it is unclear when the down-selection is. It is suggested that the project focus on long-term stability and scale-up in the following budget periods, especially BP 3.

Project strengths:

- The proposed thin-film deposition methods seem to be practical and effective in exploration of the effect of protective coatings on cell performance, although a few key challenges are yet to be overcome to be successful in fabrication of coherent bilayer electrolytes. The probability of developing some effective protective coatings for durability and high FE is relatively high.
- Strong integration of the project with HydroGEN consortium members is a strength. Effective tools have been developed to significantly advance material development.
- The team members have the expertise to conduct the proposed work and leverage their strength in thin-film deposition in other solid oxide fuel cell systems.
- The project focuses on development of thin-film proton-conducting cells on hydrogen-electrode-supported substrates and evaluation of scalable and cost-effective sputtering processes.

Project weaknesses:

- There is a lack of detailed microanalysis of electrolyte surfaces exposed to high concentrations of steam at high temperatures and a lack of mechanistic understanding of steam–surface interaction or degradation mechanisms.
- More efforts (relative to the effort on performance improvements) are needed for evaluating material and cell durability and process scale-up.
- The early stage of the project makes it difficult to assess likelihood of success.

Recommendations for additions/deletions to project scope:

- To gain some mechanistic understanding, it would be necessary to perform some careful microanalysis of the electrolyte surfaces (composition, phases, and morphology) and to measure the conductivity of the samples before and after exposure to high concentrations of steam at 500˚C for >200 hours. The correlations between the changes in surface microscopic features and the changes in conductivity of the samples before and after the exposure to steam will be vital to gaining some critical insights into the mechanism of steam–surface interactions.
- It is suggested that the project team consider interdiffusion between the deposited layer and baseline electrolyte during SOEC operation.
- There are no recommendations for additions or deletions to project scope.

Project #P-190: A Multifunctional Isostructural Bilayer Oxygen Evolution Electrode for Durable Intermediate-Temperature Electrochemical Water Splitting

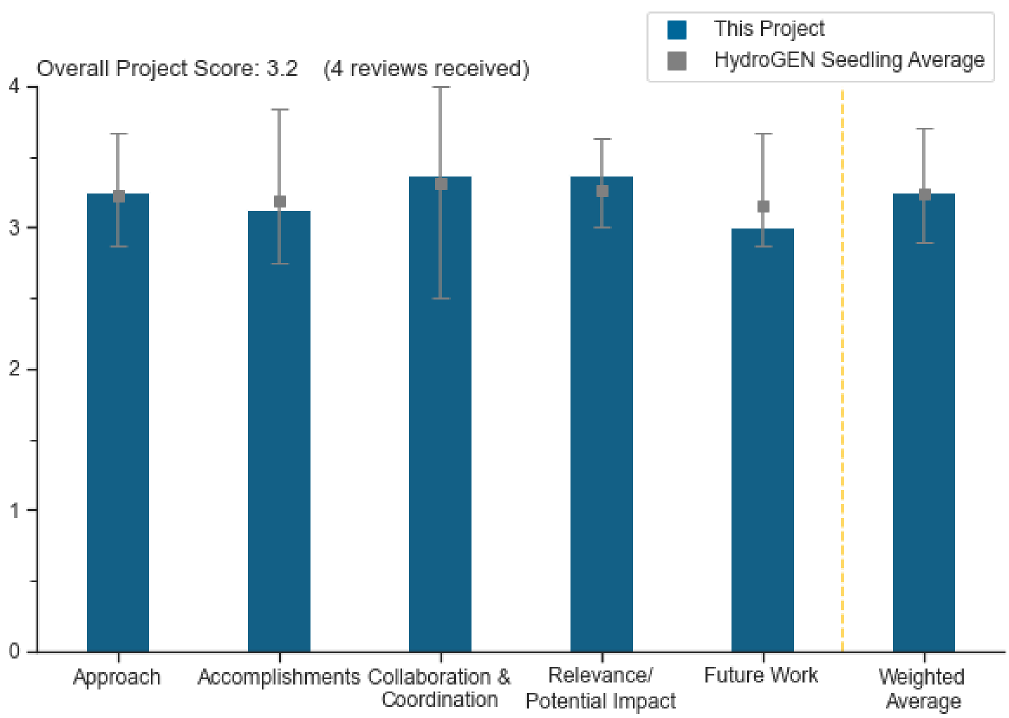
Kevin Huang, University of South Carolina

DOE Contract #	DE-EE0008842
Start and End Dates	4/1/2020 to 3/31/2023
Partners/Collaborators	University of South Carolina, University of Massachusetts at Lowell
Barriers Addressed	• Delamination and Cr-poisoning of OEs are the two leading causes for the performance degradation of SOECs. The new bilayer OE to be developed addresses these two critical issues at once.

Project Goal and Brief Summary

The two leading causes for solid oxide electrolysis cell (SOEC) performance degradation are delamination and chromium poisoning of oxygen electrodes. This project seeks to address these issues through materials innovation and theoretical modeling. The final product will be a highly active and chromium-resistant oxygen electrode for durable, high-efficiency, and high-rate hydrogen production via high-temperature SOECs. The University of South Carolina (USC) is collaborating with the University of Massachusetts (UMass) on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- The approach to this work seems very effective. USC is developing a unique oxygen evolution electrode, UMass is doing modeling work to explain the results, and Idaho National Laboratory (INL) is providing third-party testing to validate USC's results. The foundation of the experimental work seems solid; this material has already been developed by the USC team, so this project can focus on development more than materials research/discovery, which starts from a more mature position and reduces risk. It will be interesting to compare and contrast this work with that of Scott Barnett's HydroGEN project focused on overpotential and temperature impacts for different alternative oxygen evolution electrodes.
- The project aims at improving both performance and stability (against Cr poisoning) of SOECs via wet-chemical coating of the oxygen electrode.
- This is a good materials development project. It is unclear that building both planar and tubular cells is necessary to prove out the technology innovation.
- More emphasis needs to be placed on evaluating the interrelationship between electrode microstructure and electrode stability.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- The oxygen electrode performance is excellent. However, it is unclear how the team will address the delamination issue that can lead to rapid degradation. This discussion should be expanded in the future.
- The team's 25% of $SrCo_{0.9}Ta_{0.1}O_{3-\delta}$ (SCT) coating can significantly improve the performance (polarization resistance [Rp] reduction) of the SOEC. Considering the high costs associated with both Ta and the process (25% loading takes multiple steps to achieve), the team may want to conduct a preliminary techno-economic analysis (TEA) to understand the costs and benefits of the proposed approach.
- Progress has been made in the electrode overpotential study and modeling, but limited work has been done on manufacturing (task 3).
- It is hard to conclude that 25% loading and 950°C processing is an optimized set of parameters when it's also the maximum loading tested and minimum temperature. While it is understandable that infiltration to higher wt.% is challenging and hits a plateau as pore volume decreases so that 25% may be the maximum feasible amount, it would be helpful to see repeat experiments of the degradation percent at 25% loading to add confidence to the result that the 950°C value does indeed decrease in trend after increasing from 5 wt.% to 15 wt.% and plateauing at 20 wt.%. Also, the team could add confidence to the results by testing one or two lower temperatures (perhaps just for the 25 wt.% loading case) to prove the properties worsen or by showing x-ray diffraction results to explain that 950°C is the minimum calcination temperature with no secondary phase formation. This was a fair amount of experimental work already, and these minor refinements are suggested to help get the best confidence out of all that work.

Question 3: Collaboration effectiveness

This project was rated **3.4** for its collaboration and coordination with HydroGEN and other research entities.

- The collaboration for this work seems very effective. USC is developing a unique oxygen evolution electrode, UMass is doing modeling work to explain the results, and INL is providing third-party testing to validate USC's results. INL testing adds extra confidence to the results; their facilities are world-class, and they have many highly experienced researchers. Kevin Huang's group is also highly regarded in the field. Mistakes in characterization are always possible, so the agreement of results between the two facilities is critical in trusting the data with great confidence for the impact of this SCT. It's not clear, though, what the split in modeling effort is between UMass and the National Renewable Energy Laboratory (NREL). It is unclear if NREL is doing the multiphysics modeling guided by Professor Jin. Her role in the project needs to be clarified so that her contributions are not lost. She is identified as an expert in the modeling, so it is expected that she's playing a notable role.

- Effective collaborations with Energy Materials Network nodes were clearly demonstrated.
- The team is working effectively with HydroGEN consortium members.
- The project shows good collaboration with INL and NREL on modeling.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- Electrode material research is essential to improving the performance of SOEC systems. Results from this project are likely to inform the development of higher-performance stacks within the HydroGEN consortium.
- The main impact of this project is a better understanding of the oxygen electrode stability under high-temperature electrolysis conditions.
- Stability of the SOEC is a major issue for the life cycle cost of such systems. The project is trying to address such issues, especially the oxygen electrode, via coating.
- The coatings appear to help drastically reduce the overpotential at the oxygen evolution electrode. This is one of the largest challenges in the oxygen-conducting SOEC lifetime. The impact will be large if this is scalable and works on full cells. The impact on Cr tolerance will also be very important if it works at full scale since Cr poisoning is a major issue. If system components don't need to be coated, this could potentially decrease system costs. The conformality of the coating is very advantageous. It is unclear what the reason for it is and whether this is a benefit of low surface energy for the SCT. The usefulness of this infiltrated shell layer will depend on how it performs in full cells. It is understood that cell results are coming in budget period 2 (BP2), so those will be interesting to see. If new problems arise when not in symmetric cells and where current densities may be higher, the coating behavior may change. We'll stay tuned for more information next time. The scalability of infiltration processes is always a concern. Attaining 25 wt.% likely requires several repeat infiltrations and processing steps. It will be useful to know how labor-intensive these are at this stage so scaleup can be planned. Infiltration is possible at large scale, but it is still difficult. It was mentioned that SCT has very large coefficient thermal expansion, ~20, compared to that of lanthanum strontium cobalt ferrite–gadolinium-doped ceria, which is typically between 12 and 15. This could be problematic if there are larger thermal changes in large-scale cells during operation at high current densities or when changing from low load to high load, where rapid thermal changes are present.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- Proposed future work is reasonable.
- It would be good to also show the budget period 3 proposed work, even if in less detail than BP2. Perhaps the project should mention the partial pressure of oxygen ranges planned for the studies and the current density ranges.
- It is not clear how the future work that is proposed will address issues such as delamination.
- It is not clear when the work for task 2 (manufacturing of larger planar and tubular cells) and task 3 (performance demonstration at pilot scale) will be initiated and incorporated in future work.

Project strengths:

- The main strength of this project is to use the bilayer oxygen electrode approach to address the issues of electrode delamination and chromium poisoning.
- This oxygen evolution electrode coating impacts two of the largest issues in high-temperature electrolysis SOECs based on oxygen conductors (which is most SOECs at this time): the delamination at high currents due to high overpotential and the Cr susceptibility.
- The team has all the needed expertise to achieve the proposed work and goals.
- Innovative materials development is a strength.

Project weaknesses:

- The main weakness of this project is limited effort to evaluate the effect of electrode microstructure on electrode stability.
- It is unclear how delamination will be addressed to meet future project milestones.
- A primary concern is how scalable the infiltration-based process can be.

Recommendations for additions/deletions to project scope:

- The scope seems appropriate for this project.
- It is suggested to the team to conduct preliminary TEA to consider the cost of materials and process versus the proposed benefit.
- The project should down-select planar versus tubular cells for cell fabrication and testing.

Project #P-191: Perovskite–Perovskite Tandem Photoelectrodes for Low-Cost Unassisted Photoelectrochemical Water Splitting

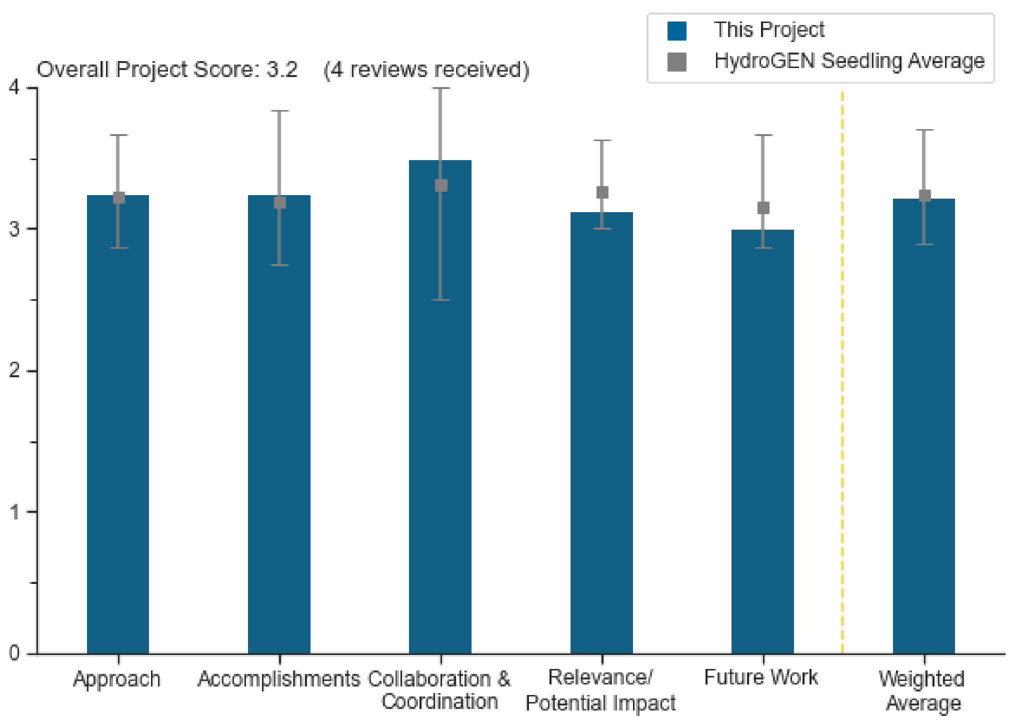
Yanfa Yan, The University of Toledo

DOE Contract #	DE-EE0008837
Start and End Dates	10/1/2019 to 9/30/2022
Partners/Collaborators	National Renewable Energy Laboratory, Lawrence Livermore National Laboratory
Barriers Addressed	• Materials Efficiency - Bulk and Interface: Identify absorber and interfacial materials for efficient hydrogen generation. • Materials Durability - Bulk and Interface: Investigate intrinsic stability; Develop durable protection layers Integrated Device • Configurations: Tandem cell and photoelectrode integration

Project Goal and Brief Summary

This project's goal is to enable cost-effective photoelectrochemical (PEC) water-splitting devices using monolithically integrated perovskite/perovskite tandem photoelectrodes, developed by the research team. If successful, the proposed PEC technology presents a significant technoeconomic advantage over the state-of-the-art spontaneous water-splitting devices. The team aims to demonstrate a high-efficiency and stable PEC system that shows potential to reduce PEC hydrogen generation costs to $2/kg. The University of Toledo is collaborating with the National Renewable Energy Laboratory (NREL) and Lawrence Livermore National Laboratory (LLNL) on this project as part of the HydroGEN consortium.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- The work centers on the important materials class on perovskite materials and the design of tandem perovskite photoabsorbers. The authors have shown which perovskite materials show sufficient stability to be processed into monolithic devices.
- The project seems to be very well balanced in its approach. It is logically laid out with each major aspect identified and appropriate numerical metrics applied to each.
- The pragmatic shift in approach to wider-bandgap materials and Pb-based perovskite/perovskite tandem to improve stability is good.
- The need to revise milestones so early in the project suggests the approach was not well thought out. The principal investigator (PI) indicated stability was the critical metric, yet the plan is to demonstrate only 100 hours of "stable" operation, the criteria for which is not given.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- The team showed that Sn/Pb-based photoabsorbers showed significant instability that was not able to be overcome. In addition, the team has identified the p-absorber water interface as the crucial next barrier to address; the reviewer agrees with this determination. Overall, the project progress has been very impressive, even in the presence of the global pandemic.
- The project has made substantial progress on a difficult and complex device structure. However, several of the numerical goals were revised downward. The reasons for the revisions were briefly mentioned but with insufficient details. Nonetheless, the revisions were generally slight and, if based on legitimate reasons, are acceptable. Identification of a suitable interconnecting layer is a big accomplishment. Demonstrating a working tandem device is also a significant achievement.
- The project is extending the community's understanding of the challenges associated with perovskite devices for water splitting.

Question 3: Collaboration effectiveness

This project was rated **3.5** for its collaboration and coordination with HydroGEN and other research entities.

- Use of HydroGEN node members NREL and LLNL is exactly on-point for the HydroGEN consortium vision. It rates an "excellent" collaboration.
- The project seems well integrated with HydroGEN.
- The authors showed excellent progress on the project and outlook toward budget period 2. Budget period 2 shows increased engagement with the LLNL nodes; however, it would be beneficial to more explicitly show the type of engagements that have been initiated with NREL in the current period.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- Perovskite materials have great potential for PEC hydrogen production. The construction and evaluation of effective monolithic devices are crucial to meeting the DOE targets.
- When the project goals are achieved, the project will have a meaningful impact on meeting the overall goals of low-cost PEC hydrogen.
- It appears the project had to scale back its ambitions around novel materials due to stability issues.

- The upside potential impact of this work seems low given the low stability of the perovskites. It's also tied to the potential impact of PECs in general. It is still a bit unclear how/why PECs will be advantageous in the future compared to photovoltaics plus electrolyzers from a cost, operations, and safety perspective.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The schedule for future work is reasonable and logically described.
- The project identified key challenges that need to be addressed, including hysteresis and durability, but did not articulate a clear plan to address them.
- The projected work for the next budget period was outlined. It is unclear how the project is going to proceed and which tasks and milestones will be continued or changed. The team showed that in situ x-ray experiments are planned, but, beyond that, it was not discussed.

Project strengths:

- The methodical breakdown and investigation of each component of the tandem device is a project strength. The excellent collaboration and use of the consortium team members are strengths.
- Perovskite monolithic devices are being investigated as an integrated solution for solar-to-hydrogen production. The proposed in situ experiments are of particular interest for the development and in defining areas of research going forward.
- This is an exploratory project that will help define the potential for perovskite PEC. There is collaboration with national laboratories.
- This project has a well-rounded team and research approach. The quick changes in plan to mitigate stability issues are appreciated.

Project weaknesses:

- The research activities seem particularly reactive. A more "develop a clear hypothesis, test hypothesis" approach is recommended.
- There isn't verification that achievement of the project goals will lead to the target $200/m^2 device cost. The downward revision of the metrics is a worrying trend.
- The stability of the perovskite device is still a concern. The team needs to have a more concrete plan on the possible degradation pathways and mitigation strategies.
- From what is described in the material, there is no plan for investigating the effect of the studies undertaken on hydrogen costs.

Recommendations for additions/deletions to project scope:

- Besides the work described, a preliminary investigation of the effect of the developments on hydrogen cost is suggested.
- The PI should better explain the reasons for the downward revision of milestone targets.

Project #P-192: Development of Composite Photocatalyst Materials That Are Highly Selective for Solar Hydrogen Production and Their Evaluation in Z-Scheme Reactor Designs

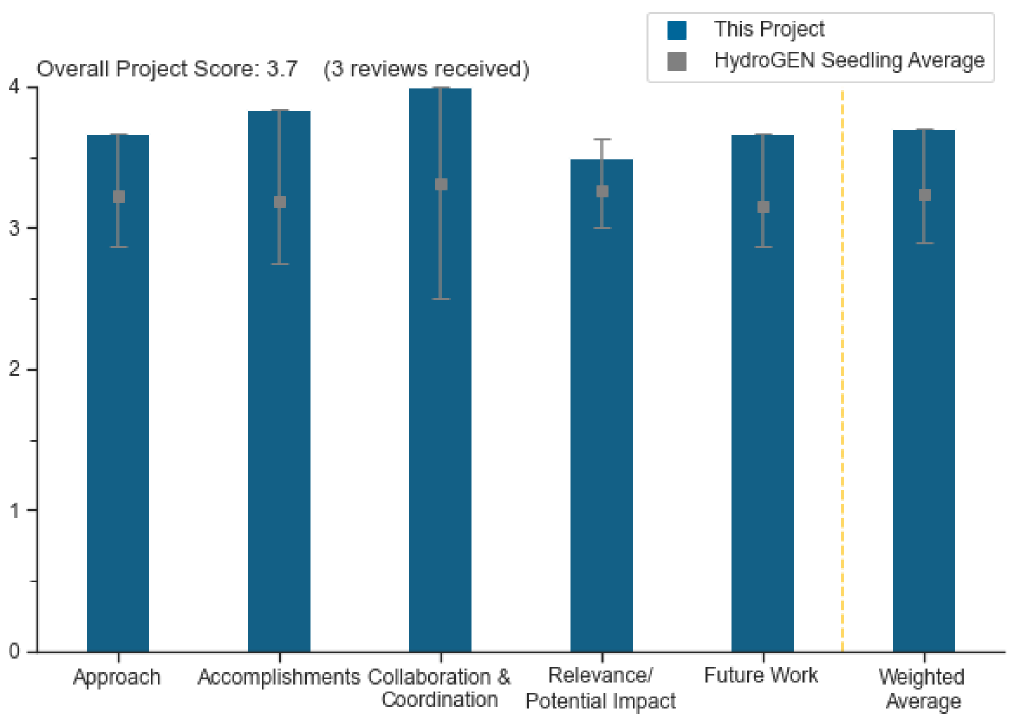
Shane Ardo, University of California, Irvine

DOE Contract #	DE-EE0008838
Start and End Dates	10/1/2019 to 3/31/2023
Partners/Collaborators	University of Michigan, Columbia University, National Renewable Energy Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratories, Tokyo University of Science, California Institute of Technology, Shinshu University
Barriers Addressed	• Few composite particles are known that selectively evolve H_2 and O_2 instead of performing undesired redox shuttle back reactions • Empirical and numerical results guide our design of ultrathin coatings for selective reactivity, and reactor dimensions for natural convective mixing

Project Goal and Brief Summary

This project aims to develop new photocatalyst particles and ultrathin oxide coatings for photocatalytic solar water splitting that can enable demonstration of the interim DOE target of 3% solar-to-hydrogen efficiency. The goal is to demonstrate a selective ultrathin oxide coating on particles that results in a ≥10 times larger hydrogen evolution quantum yield than for uncoated particles. Using an intrinsically safe tandem (Z-scheme) dual-bed particle suspension reactor design, the project also aims to validate high-efficiency and technoeconomically viable photocatalyst reactors for solar water splitting. The project team includes the University of California, Irvine; the University of Michigan; Columbia University; National Renewable Energy Laboratory (NREL); Lawrence Livermore National Laboratory (LLNL); Sandia National Laboratories (SNL); the Tokyo University of Science; the California Institute of Technology; and Shinshu University.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- The integrated approach of combining theory, experiments, materials science, and techno-economics is excellent, as it brings the PEC story into a broader context.
- This project is checking all the boxes: experiments, modeling, characterization to develop novel materials, and process concepts.
- The team is clearly guided by techno-economic modeling to target relevant barriers. This work represents an important alternative approach from conventional photoelectrochemical (PEC) systems. Novel catalyst coatings are investigated as a cornerstone of this approach.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- The project has shown excellent progress toward its goals. The team has investigated catalyst coatings that effectively avoid back-reaction of the Z-scheme redox shuttle. The team has also demonstrated the effectiveness of the approach using state-of-the-art photoabsorbers and has outlined how the next budget period will be leveraged to investigate new materials. Using techno-economic analysis (TEA), the team also shows that the project can achieve a significant impact on the cost of hydrogen. The project progress has been very impressive, even in the presence of the global pandemic.
- This project has hit all of the milestones, with deep scientific study behind each one.

Question 3: Collaboration effectiveness

This project was rated **4.0** for its collaboration and coordination with HydroGEN and other research entities.

- The team has been doing a pretty good job at collaborating across principal investigators (PIs) and the HydroGEN nodes.
- The team is clearly well connected with the HydroGEN nodes, as well as several other universities.
- The team has clearly shown how the various nodes have been engaged.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- The team has done a great job in demonstrating the potential of this technology and in advancing it.
- While the current technology readiness level (TRL) of the proposed designs is less advanced than other projects, it underlines the importance of keeping all options open in order to achieve the goal of sustainable and cheap hydrogen.
- The overall project work is good; however, from an industrial scalability perspective, as well as the $2/kg target (now $1/kg), it is a bit unclear on how this will beat photovoltaic–electrolysis (PV–electrolysis) systems that are a lot more mature. The statement holds for PEC projects in general. Hence, this is something to be mindful of when funding future work in this space.
- The project is a good model for how to leverage DOE funding to advance PEC; however, this reviewer is skeptical that this approach to PEC can be scaled up and therefore will have an ultimate impact on the cost of hydrogen. It is worth some level of DOE funding, but the ultimate impact may be in applying some of the materials concepts to other water splitting approaches.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- The project has a well-thought-out plan and is on schedule despite the COVID-19 pandemic.

- The team has outlined how new, more efficient photoabsorbers will be investigated in the next project period.

Project strengths:

- The project team works well across multiple team members and shows great progress. Furthermore, it demonstrated how powerful an integrated approach of experimental development with TEA analysis can be in identifying roadblocks early and mitigating them. An example is the elimination of active circulation of the system that clearly was a problem that was solved elegantly by employing natural convection.
- This project's breadth and depth of scientific inquiry are strengths, as it is not Edisonian. Its collaborations are also a strength.
- This is a strong team with strong collaboration. The project has a good approach that combines modeling, materials science, experimentation, and technoeconomic modeling.

Project weaknesses:

- The main limitation of the project is the TRL level, which is still low. This makes this project even more crucial in order to ensure multiple technologies have a shot at solving the problem of sustainable hydrogen.
- Although the project team is doing some nice fundamental work around PEC systems, the scalability challenges related to the use of rare earth materials, such as Ir or Sr, need to be addressed. In particular, given the rare availability of such materials, it is not clear if it is even possible to build world-scale green hydrogen facilities (10–100 kilo tons/year). If not, it is questioned if there is an envisioned pathway to a more scalable set of materials.
- The project has no plan to demonstrate stability.

Recommendations for additions/deletions to project scope:

- The team should demonstrate stability. Ideally, the team should comment on how material or modeling innovations might translate to other HydroGEN targets.
- The team's suggestion of moving to more efficient photoabsorbers, which can be accessed due to the progress made so far, is of high importance to achieve a more efficient system. Furthermore, the construction of a functional device as a demonstration in the next phase is also very critical.
- The work on the TEA is interesting. The team should consider looking at the different reactor designs from an operability and safety perspective, especially when compared to PV–electrolysis. This reviewer worries that due to low overall yields per unit reactor volume for PEC, a hazard is being distributed (H_2 and O_2 in stoichiometric ratios) over fairly large areas versus a polymer electrolyte membrane electrolyzer, which has a smaller hazardous area.

Project #P-193: Highly Efficient Solar Water Splitting Using Three-Dimensional/Two-Dimensional Hydrophobic Perovskites with Corrosion-Resistant Barriers

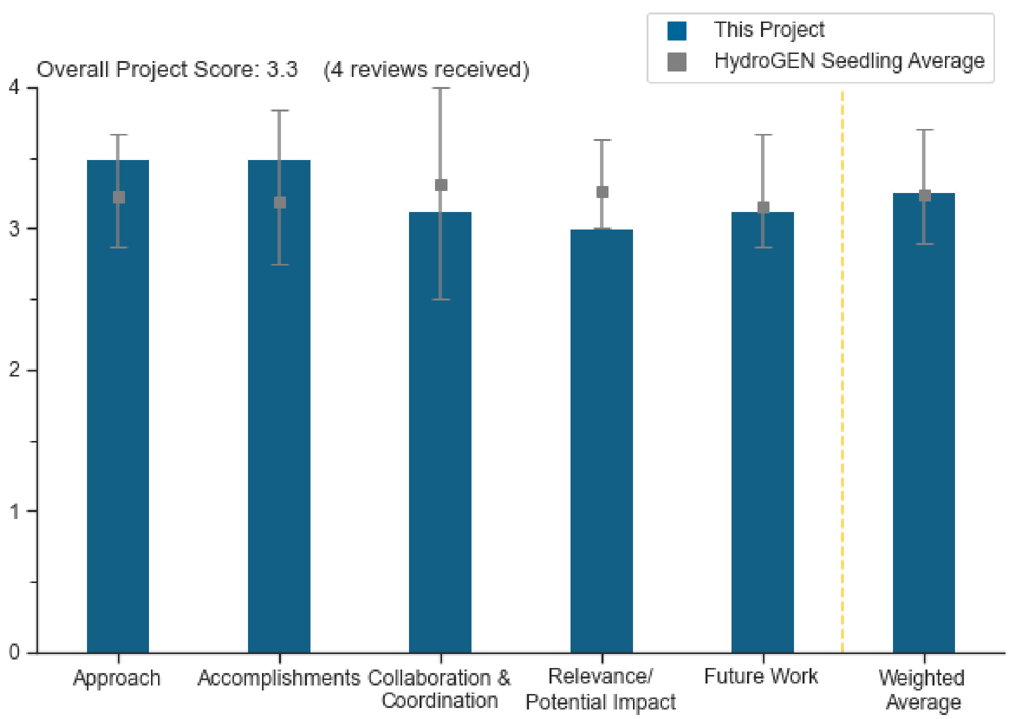
Aditya D. Mohite, William Marsh Rice University

DOE Contract #	DE-EE0008843
Start and End Dates	01/01/20 to 01/01/23
Partners/Collaborators	Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Hydrophobic polymers, carbons, atomic layer deposition oxides

Project Goal and Brief Summary

Rice University aims to demonstrate an innovative concept with advanced materials for photoelectrochemical (PEC) cells based on direct water splitting to produce hydrogen fuel. The project team is combining high-efficiency, low-cost halide perovskite (HaP) solar cells with hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) catalysts to demonstrate an integrated HaP-PEC cell with 20% solar-to-hydrogen efficiency and 500 hours of operational durability. If successful, this project, in collaboration with Lawrence Berkeley National Laboratory (LBNL) and the National Renewable Energy Laboratory (NREL) through the HydroGEN consortium, will demonstrate a water-splitting system that can produce hydrogen at scale using low-cost, abundant materials.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- The approach is well-considered and encompasses the main elements of the complete device. The selection of HaP-PEC cells is an interesting approach.
- The team has identified a neat approach that combines the best possible performance of tandem perovskite cells by making the top and bottom cell in parallel. This will allow the best evaluation of the performance in the absence of the practical issues of layering absorbers and catalyst; however, this will mean a minimum 50% loss in theoretical efficiency. While this trade-off was clearly identified, the practical limitation on the cost of hydrogen was not clearly identified in the presented work.
- The project is focused on the most important challenge for perovskite PEC. However, it is not clear what the potential is for the project's materials innovation to be useful in other HydroGEN strategies.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- Since the team chose a device design approach that utilized some of the state-of-the-art perovskite materials, the focus of the project and progress are on the stability of the system. The team showed significant progress toward a complete device operating under realistic conditions, as well as advances in the design of two- and three-dimensional perovskite materials that showed great promise. Owing to intellectual property considerations, the details of the protection layers strategy for the individual photoelectrodes could not be discussed, but the advertised properties were promising. During the stability measurements of the tandem device, the team showed a good initial performance, followed by a rapid decrease in performance. While the team could not share the experimental evidence showing that the stability issues were due to the OER catalyst, not the perovskite photoabsorber, the principal investigator provided detailed descriptions of the team's recent advances, which showed good progress on achieving higher stability. Most of the milestones set for this project period have been achieved or were described by the team as being under way; based on this, progress is on track to deliver on the targets identified. Overall, the project progress has been very impressive, even in the presence of the global pandemic.
- Demonstration of 12.4% efficiency with a perovskite PEC device is a very good Year 1 accomplishment. The evaluation of the four-barrier-layer concept and the down-select to one is a good achievement.
- The synthesis of the first-ever water-stable perovskite and identification of the patentable barrier are impressive.
- The team has been making good progress on the HER side of the reaction. However, challenges remain on the OER side. It will be interesting to see the innovative degradation mitigation strategies the team devises.

Question 3: Collaboration effectiveness

This project was rated **3.1** for its collaboration and coordination with HydroGEN and other research entities.

- Collaboration with NREL and LBNL is appropriate and worthwhile to the project.
- Rice University is collaborating with two national laboratories for benchmarking and characterization, but the impression was that these collaborations were only arms-length interactions.
- While the project showed great progress, it is unclear how the HydroGEN nodes have been leveraged and to what extent the team has an integrated approach.
- There are none in particular. The use of NREL as a collaborator, especially around benchmarking, is appreciated, but further use of NREL's capabilities is encouraged.

Question 4: Relevance/potential impact

This project was rated **3.0** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- A perovskite-based PEC device should be low-cost, and if efficiency and durability targets are achieved, the overall project will be a large step toward achieving overall DOE PEC goals.
- The team showed that the proposed strategy can achieve high solar-to-hydrogen efficiencies of 10%. The impact of high efficiency on hydrogen cost was not demonstrated by technoeconomic analysis at the time of the Annual Merit Review but was identified as a later milestone. Still, a top-level description of such an approach would have been beneficial for evaluating its impact.
- It is an innovative idea to explore and develop the potential of low-cost perovskites as a way to enable cost-effective PEC.
- The potential impact of this work is tied to the potential impact of PEC cells in general. It is still a bit unclear how and why PEC cells will be more advantageous in the future compared to photovoltaics (PV) + electrolyzers from a cost, operations, and safety perspective, especially if the solar PV materials are similar to the PEC options and anion-exchange-membrane-based water electrolyzers become mature.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- Budget period 3 not only continues the progress gathered in periods 1 and 2 but also expands into technoeconomic evaluation to determine the impact of the discoveries. Of particular interest is the work on stabilizing coatings for both anodes and cathodes that show functionality in both OER and HER catalysis.
- There are logical and clearly stated future work plans.
- It is strongly recommended that the team prioritize/focus on improving the durability of the device with regard to the OER side.

Project strengths:

- The clearly defined device concept is a project strength. Achievement of >12% efficiency is a strength. The examination and test of multiple barrier concepts is a strength. Demonstration of a water-stable perovskite is a strength.
- The project uses an innovative approach and has an effective problem-solving team.
- The team has shown excellent progress in developing novel protective coatings for perovskite photoabsorbers, as well as producing a demonstration device.
- The progress on stable coatings for the halide perovskite, at least for the HER half reaction, is quite promising.

Project weaknesses:

- Lack of any cost targets or analysis is a weakness. The claim "demonstrated a near-ideal corrosion barrier" is not supported by the slides. It is not clear which barrier layer they are referring to. The rapid deterioration during the 2.5-hour solar-water-splitting test is described as OER catalyst degradation, but no explanation is given for its rapid and precipitous onset just after two hours.
- The project relies on a strategy that immediately reduces the theoretical efficiency by 50% compared to a stacked device. In addition, the cost of materials (owing to a doubling of the device size) is also going to increase the hydrogen price.
- Durability of the OER half reaction is a concern. The team should prioritize improving that or at least create a mitigation plan around it.
- There is a lack of modeling to complement the experimental approach.

Recommendations for additions/deletions to project scope:

- The technoeconomic analysis proposed as a milestone for the next phase of the project is important and should be accomplished. This will be key to determining the full impact of this work.
- A modeling component focused on elucidating the fundamental degradation mechanism should be added.
- More discussion of failure mechanisms in the project presentation is recommended.

Project #P-194: New High-Entropy Perovskite Oxides with Increased Reducibility and Stability for Thermochemical Hydrogen Generation

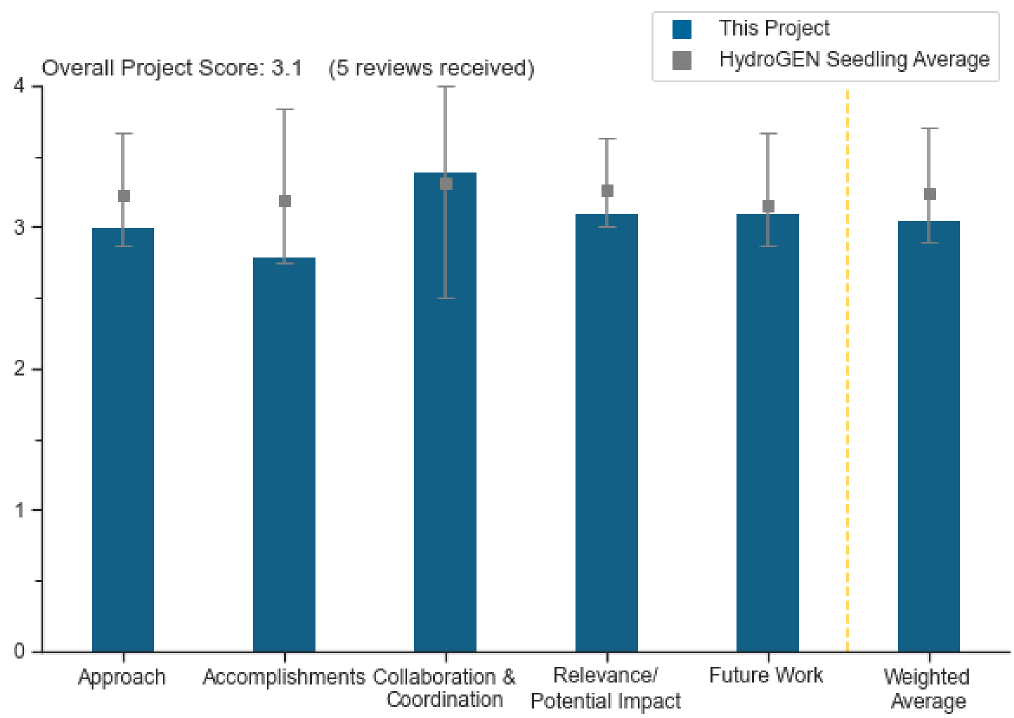
Jian Luo, University of California, San Diego

DOE Contract #	DE-EE008839
Start and End Dates	10/1/2019 to 1/31/2023
Partners/Collaborators	West Virginia University, Michigan State University, Brown University, Sandia National Laboratories, National Renewable Energy Laboratory
Barriers Addressed	• Extremely vast compositional space • Highly complex compositions and structures • Compositional controls in the synthesis of many-component oxides • Correlation of computation with experiment

Project Goal and Brief Summary

University of California, San Diego (UCSD), aims to design, synthesize, and test a transformative class of high-entropy perovskite oxides (HEPOs) as redox oxides to enable thermochemical hydrogen generation with improved stability, kinetics, and efficiency. If successful, this project will validate the usefulness of a new field of water-splitting materials and establish a new class of high-entropy redox oxides with a vast, unexplored compositional space. Along with project partners, UCSD will develop a HEPO that is able to deliver a H_2 yield of over 400 µmol per gram oxide and demonstrate high stability with less than 20% degradation after at least 50 cycles.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- Overall, the approach is outstanding. The high-throughput synthesis technique appears robust and has allowed for the successful synthesis of some very challenging compositions. The computation effort is also on very solid footing, although it is concerning to move away from tolerance factors (TFs) and into vacancy formation energy calculations, as they may become exceedingly costly from the aspect of computational time. It does appear that the calculations are only informing the cation selection process rather than driving it, so the risk may be mitigated. It is not apparent if starting oxygen stoichiometry is being taken into account or if all compositions are assumed to be stoichiometric with enough transition metal available to compensate for charge imbalances. The experimental screening is the only part that could use some improvement. The cycling between N2 and air is nominally sufficient; however, more information can be captured by beginning the reduction from room temperature rather than cycling only from the oxidation temperature in air. It is possible that this information is already being captured but not presented; however, the onset temperature for reduction is an important metric and is worthy of inclusion. Finally, some caution should be heeded when evaluating the oxidation kinetics with air rather than steam, as it is unlikely to be representative. The performance of most perovskites evaluated by the community thus far have shown significant kinetic limitations during water splitting that were not apparent in air oxidation.
- The approach in this project is to design, synthesize, and test a "transformative class" of HEPOs as redox-active oxides with the objective of enabling thermochemical hydrogen generation with improved stability, kinetics, and efficiency. The goal is to develop new enabling design strategies and methods, including the synthesis of HEPOs, which have a vast compositional space and tunability. The project identifies barriers to realizing the approach but stops short of identifying what barriers need to be addressed to advance the technology. Hence, the barriers are not well-identified, and therefore, it is not possible to tell whether they will be addressed well through this project's innovation. That said, the approach to investigating a "new class" of materials that increases the possible composition space is interesting and promising enough that the approach is good. The project is well-designed to find a large number of redox-active materials with large potential oxygen off-stoichiometries that are also cyclable and have fast kinetics. However, whether it is well-designed to identify optimal water splitters is less obvious, as no water-splitting experiments were shown, and the criterion of high off-stoichiometry does not imply good water-splitting potential. It seems the project is well enough integrated with at least one HydroGEN consortium node at Sandia National Laboratories, but there is still not a single water-splitting experiment. To validate the project's technology innovation, the project must show a capability to split water and should not have a singular focus on materials with large $\Delta\delta$ quantification and relatively low energy vacancy formation energies. The attempts at developing a theory that can explain the material thermodynamics are commendable; this effort seems at an early stage, and more development along those lines is expected by next year's review, and that might help sharpen up the design criteria. The researchers have relaxed their original criterion related to the stability of the structure relative to cubic, which seems appropriate; however, the new criterion is now "the predicted $\Delta\delta$ (with oxygen vacancy interaction and distribution) meets the HydroGEN requirement." It is unclear what this criterion means, and therefore, it seems too non-specific to meet the objective of being a useful design criterion essential to the approach to provide guidance moving forward.
- The approach to solving the problem of evaluating HEPOs as redox mediators for water splitting is generally very good. The biggest opportunities for improvement are to leverage approaches and results developed and obtained in the earlier HydroGEN Seedling projects. This would allow the team to focus on answering questions that have not yet been answered, rather than rediscovering much of what has already been learned from other seedling projects.
- The project aims to discover materials for thermochemical hydrogen production. The hypothesis appears to be that such materials could exist among perovskite oxides, specifically those with high entropy. From a computational and materials standpoint, the approach is strong and seems likely to identify many materials with the target properties. To have relevance to water splitting, however, the overall approach needs an improvement in direction and a deeper understanding of actual thermochemical cycles. First, the team is targeting materials with a vacancy formation energy of 2–3 eV (slide 7 and slide 14). With the enthalpy of water splitting at 2.5 eV, materials below this value would be unable to split water and are therefore not relevant to the project. The upper part of the target range is at least thermodynamically feasible but is

highly unlikely. For reference, the vacancy formation energy for ceria is ~4.5 eV. Second, materials seem to be evaluated under conditions that are not relevant to water splitting. Specifically, the reversible oxygen capacity (Δδ) is evaluated for reoxidation at 870□C in partial pressure of oxygen (pO2) of ~21,000 kPa. For comparison, the pO2 in steam (with no hydrogen) at the same temperature is ~0.15 Pa, or about 140,000 times lower. In the presence of hydrogen, this pO2 is lower still by many orders of magnitude. Therefore, reoxidation in air and the associated Δδ cannot identify promising materials for water splitting (slide 16), and it is unclear why such experiments were performed so extensively (perhaps they verify material stability). At best, the experiments can identify materials that are of no value (i.e., have a low Δδ, even under these highly favorable conditions, or decompose). It would have been somewhat more relevant to use the same gas (i.e., 10 ppm O2) for both reduction and oxidation.

- The team is using the Goldschmidt TF in its modeling. There are newer factors that are better and that should be considered. The researchers used computation to identify potential B-site elements. They had two series of suggestions. To get the second series, they increased the TF range from 0.95–1.05 to 0.9–1.05. It would be helpful to understand why this adjustment was made.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- The project has a number of notable accomplishments, especially in synthesizing a large number of compounds, doing a first-level screen on those compositions, identifying a number of interesting compounds, demonstrating redox activity and cyclability, and measuring some kinetics. In addition, there are efforts to produce thermodynamic models. All this is commendable, especially given that the compositional space is extremely large. The project has shown dual redox activity from cobalt and manganese in at least one combination, which is very interesting. Relative to the chosen milestones and go/no-go, the progress looks very good, and it is good to see a focus on the kinetics. What is not evident is whether the project is addressing barriers that will advance the technology. The researchers state that they have met the milestone BP 1 go/no-go target ($k \geq 7.5\times10^{-4}$ cm/s) and 90% of Δδ in an hour. What they do not state is why these are the right milestones to overcome specific barriers to advance the technology, and the team has not shown evidence that any of the materials that have been screened and used to meet milestones will split water.
- This group has a number of excellent accomplishments, from the large number of synthesized and screened materials to the modeling that produced oxygen vacancy formation energy calculations for quinary cation oxides. However, there are concerns that the project is pushing too hard on the goal of increased reduction (delta). With DOE's stated goal of solar thermochemical hydrogen materials that are viable at high conversion rates, it seems unlikely that a perovskite that reaches a delta >0.2 will be capable of splitting water under those conditions. The middle range of 0.1–0.2 seems more reasonable, and there may even be opportunities below 0.1. It would also have been helpful to see a list of any compositions the team could not synthesize, if any exist.
- It is not clear why the team increased the TF range for material identification. It seems the team increased it solely to give itself more materials to test (slide 13). High-throughput synthesis was thoughtfully done. On slides 18 and 19, phase stability is reported, but the conditions of the tests, including the number of cycles, were not given. Without knowing the experimental conditions, it is hard to determine whether the materials are indeed stable. The presenter did an admirable job of identifying where HydroGEN nodes were used. For the kinetics work, it would be helpful for the presenter to identify the kinetics goals—whether a 15-minute cycle is enough or it needs to be faster. The oxidation was done with oxygen gas. It is recommended that the project use steam to better match real operation. The team needs to show multiple cycles.
- The team is generally making good progress, but progress could be accelerated by not reinvestigating issues that have already been investigated by the seedling projects. Interaction with the seedling projects to learn the advances that have not yet been published, and using what they have already published, could greatly accelerate the project. For instance, using techniques developed within the HydroGEN consortium would have allowed the project to screen far more than the 100 compositions that it has currently screened. It was not clear whether progress had been made on screening for kinetics (or how this would be done).

- The project is making good progress toward goals but would benefit from aligning with DOE goals.

Question 3: Collaboration effectiveness

This project was rated **3.4** for its collaboration and coordination with HydroGEN and other research entities.

- There is clear evidence of collaboration with the HydroGEN consortium nodes at Sandia National Laboratories. The team has engaged with the benchmarking/protocols (2b) project by participating in the workshops. It is unclear whether the team has engaged with the HydroGEN Data Hub. It is hard to tell whether the partners are well-coordinated.
- The institution collaboration appears to be working well, with contributions coming from all three members. The groups also participated in the latest benchmarking and protocols workshop. The reviewer is unable to judge contributions to the Data Hub, however, as the public-facing count of zero datasets does not consider all submissions. The consortium nodes have provided meaningful contributions that directly support the project's successes.
- The project's internal collaboration is outstanding, while the use of the nodes is very good. Interactions with other teams within the consortium is limited but could greatly add to the success of the project.
- The team appears to be effective and making good use of HydroGEN research infrastructure.
- The presenter did a good job identifying what nodes were used and what was learned. The use of HydroGEN nodes is consistent. The team should have used the HydroGEN team to refine its experiments prior to doing the experiments.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- By looking at HEPO materials and synthesizing these complicated systems, the project has already made contributions to the discovery of new materials. Going forward, the large number of materials and the data collected about them will help not only this project but others who want to mine the results to glean possible underlying principles.
- This project has the potential to make a significant impact toward the DOE HydroGEN consortium goals and objectives.
- The project supports the HydroGEN consortium mission of theory-guided materials discovery for redox-active metal oxides that can split water. The project has significant potential to advance the discovery and development of novel advanced water-splitting materials when the project establishes the appropriate screening criteria. An improvement over the state-of-the-art water-splitting material is necessary, although not sufficient to enable meeting the DOE ultimate hydrogen production goal of $2/kg H2. Project aspects align with some of the DOE Hydrogen Program and DOE research, development, and demonstration objectives, and the project is leveraging and contributing to the resources and framework of the HydroGEN consortium to some extent.
- The project would benefit from a realignment that would make otherwise excellent materials work relevant to DOE goals.
- It is too early to tell the potential impact of this project.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The future plan should be effective and should contribute to overcoming most of the identified barriers to the success of the project. Additionally, the project appears to be on track to meet most, if not all, of the end-of-project goals and to advance the materials research mission of the HydroGEN consortium. The researchers have proposed some challenging new efforts, including trying to develop a new thermodynamic model for the relationship between partial pressure of oxygen, temperature, and, and most importantly, the team will be doing some water splitting, ideally in collaboration with the nodes. In addition, the intent to move beyond equimolar compositions will make the composition space much larger, thereby making it a challenging undertaking but potentially that much more interesting.

- Plans are in place to address one of the main project weaknesses, namely cycling conditions. This is a positive development and should be prioritized.
- The future work appears both ambitious and conservative. This is especially true for some of the new efforts. Expanding the compositional space to explore more non-equimolar compositions could be a very large rabbit hole to traverse if sufficient direction is not involved. There does not appear to be a plan for using the vast results from the earlier budget periods to guide this work. Some of the characterization work, on the other hand, seems interesting, but it is unclear what contributions it will provide, considering the overall thrust of the project. It would have been good to see a more concerted effort to produce water-splitting results on a large cross-section of the discovered and synthesized HEPO materials and attempt to make correlations to better guide both the theoretical modeling work and further synthesis.
- In addition to the proposed improvements to the model, the researchers should use a factor different from the Goldschmidt. For the foam samples, the team needs to include some tests on the mechanical strength. The project needs to clearly identify its performance goals.
- The sequence of looking at A-site mixing and then B-site mixing in the subsequent budget period does not seem effective. There is significant potential for coupling the effects caused by the separate alloying on the A-site and B-site sub-lattices. Learning this later in the project could lead to a much less successful materials discovery effort.

Project strengths:

- The approach of exploring the rich compositional space of high-entropy perovskite oxides is a strength. The high-throughput synthesis capability is a strength, as this team seems to have been able to screen a large number of compositions. Having demonstrated dual cation redox activity (cobalt and manganese) is a strength.
- The work division is a strong suit of this project. Each institution has a manageable scope of work and appears to be leveraging its individual strengths. The synthesis and initial characterization throughput is impressive.
- This is a strong, well-organized team with complementary abilities. The project has a generally good approach and methods, as well as good theoretical concepts to explore.
- This is a well-rounded team. The researchers are using good high-throughput production methods. The project is using the HydroGEN nodes well.
- The strength of this project is the strong computational materials basis and the effective team.

Project weaknesses:

- It seems that the project did not have the right equipment for the tests it was running. It seems it is building the test stands and will be able to use them in future tests. It would be helpful if the team included more description of the test conditions and what success looks like.
- The non-stoichiometry and kinetics experiments could use work. Too much importance is being conferred to the extent of reduction over other metrics, and the fitting of kinetic parameters for oxidation in air is of limited usefulness. It appears that not enough effort is going into leveraging the existing results to guide further development. The project is producing a treasure trove of results that should be utilized to a greater extent.
- There is a limited number of compositions evaluated to date. There is no screening for kinetics. The team is not using the lessons learned from previous HydroGEN efforts, and it was not clear how the project would determine which phase to use for predicting vacancy formation energies.
- The team has materials to characterize and yet has not demonstrated water splitting. The researchers have not given a rationale for their guiding criteria.
- The team does not appear to have a firm understanding of the nuances of the actual application, water splitting. Such understanding would significantly improve the project's effectiveness and impact.

Recommendations for additions/deletions to project scope:

- The approach is sound and needs only a better focus to significantly increase the impact.
- Nothing formal needs to be changed, but some slight adjustments to the approach are likely sufficient.
- The scope is appropriate; one addition should be to determine design criteria with a clear, understandable rationale for the design criteria.
- The team did not have the right equipment for the tests the project was running. It seems it is building the test stands and will be able to use them in future tests. It would be helpful if the team included more description of the test conditions and what success looks like. It may be useful for this team to consult with HydroGEN and the Benchmarking/Testing Protocol project for the tests they run. Since the goal of the project is water splitting, it is recommended that the team test the material oxidation with steam and not oxygen.
- The project needs to be explicit about its plans for screening kinetics.

Project #P-195: A New Paradigm for Materials Discovery and Development for Lower-Temperature and Isothermal Thermochemical Hydrogen Production

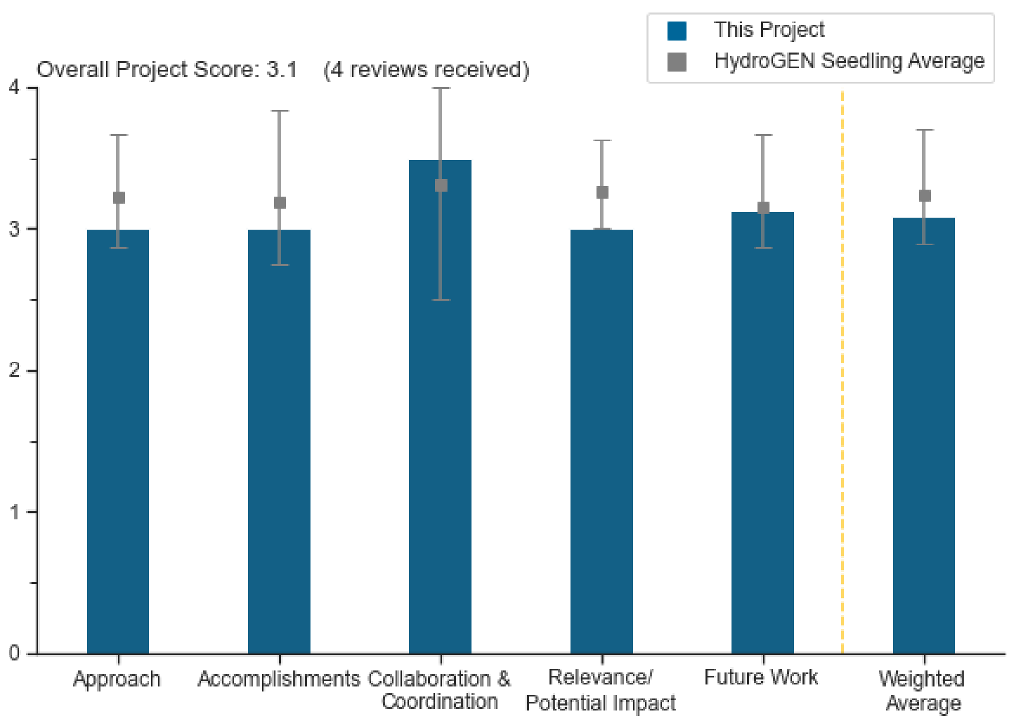
Jonathan Scheffe, University of Florida

DOE Contract #	DE-EE0008840
Start and End Dates	1/1/2020 to 1/1/2023
Partners/Collaborators	National Renewable Energy Laboratory, Sandia National Laboratories
Barriers Addressed	• Computational accuracy coupled with high throughput • Material stability and kinetics – phase stability and redox capability. Does it work? • Scale-up synthesis and stability – porous structure synthesis and characterization with simulator and laser heating

Project Goal and Brief Summary

University of Florida aims to combine computational and experimental efforts toward the development and demonstration of novel materials for efficient solar thermochemical hydrogen (STCH) production under isothermal operation. If successful, this project will provide a pathway to scalable and STCH hydrogen production with a solar to fuel efficiency > 26%, allowing STCH producers to reach the U.S. Department of Energy target of less than \$2/kg H_2.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying barriers and addressing them through project innovation, as well as for project design, feasibility, and integration with the HydroGEN consortium network.

- The team is trying to lower the operating temperature and/or operate isothermally. Lowering the operation temperature for STCH is a worthy task. Isothermal operation may result in higher system efficiencies. The researchers are trying to develop foams instead of powders. This could result in some improvements. The foams the team is making should include mechanical strength testing, which is missing, or at least not reported, in this work.
- The main hypothesis of the project is that lower temperature and isothermal thermochemical hydrogen production will overcome the engineering difficulties of high-temperature, thermal swing thermochemical cycles. Although the hypothesis is highly questionable, not supported by thermodynamics, and contrary to approaches in highly successful fields (such as turbines), the team has undertaken a comprehensive and well-structured materials search under it. Assuming performance metrics omissions is addressed in future work, the project is highly likely to conclusively disprove the original hypothesis and help focus the field onto more promising directions.
- The approach is generally good, but there is not sufficient detail to know whether the team is using the lessons learned from previous HydroGEN materials discovery projects. From the information that was presented, it appears that there is significant opportunity to leverage advances made from the HydroGEN Seedling efforts.
- The approaches being taken by the three efforts within the project appear reasonable. However, they do not all seem to align with the broader goals of the project, nor the approach that is proffered on slide 4. Specifically, while the computational effort is looking for new manganates with higher oxygen vacancy formation energies, this does not address the stated goal of finding combinations of enthalpy and entropy that will make isothermal splitting viable. In fact, there is no mention of entropic effects being modeled at all. While the foam development is well designed, it seems better utilized on compositions that are already identified as viable, but the powder testing to identify those candidates is lacking in detail.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals, as well as the HydroGEN consortium mission.

- The project describes a number of accomplishments and has met most of its milestones. The foam development has produced excellent results, and it will be interesting to see how well it translates to newer compositions. With the help of the nodes, the project has also highlighted some of the challenges with working with strontium-containing perovskites, so the computational work that has investigated alternative A-site compositions could be very beneficial. The existing cycling work is also a good start on quantifying whether the surface issues seen in the lanthanum–strontium–manganite (LSM) family are a large concern. The project's accomplishments on milestones makes it clear that the team is poised to achieve the budget period 1 (BP 1) go/no-go target. Considering the early deadlines on the Annual Merit Review slides, perhaps the team has since tested the new compositions.
- The research team was able to synthesize and test foams. The results on slide 14 were obtained at a very high temperature of 1350°C. This is higher than other STCH materials and is in the opposite direction of the project's stated goal of lowering operation conditions. The researchers should be commended for showing experimental error in their data (for example, on slide 14). This is a best practice that should be encouraged. The data reported in slide 14 indicated that there was no difference in performance when the water hydrogen ratio was changed. It is unclear whether this was a product of the high test temperature. The team was able to cycle for 50 cycles, but only 10 cycles are shown. It would be helpful to show all 50, or at least the first 10 and the last 10. On slide 15, the cycle time appeared to be about 30 minutes. It is unclear whether this was the target. Slide 16 shows an x-ray photoelectron spectroscopy (XPS) graph. It would be helpful if the researchers stated what we are to learn from the graph. It would also be helpful if they would explain why the temperature used for this experiment was a different from those used for other experiments. Perhaps this was an equipment limitation.

- The team is making excellent progress toward meeting project goals, especially in terms of material identification, synthesis, and characterization. It must be noted, however, that the main technical performance metric (page 14) omits key elements and that, in its current form, it is difficult to evaluate the relevance of project outcomes to practical thermochemical hydrogen production. Recalling that no useful work can be performed by a cycle without a temperature difference (also the Second Law), the only useful work in the process, as proposed, must come from external work input. In this case, that work appears to be in the form of separation (of H2 from a H2/H2O(g) mixture and of O2 from an O2/N2 mixture). If such input is ultimately derived from heat, then conversion efficiencies should be accounted for. However, these key energy inputs (and associated parasitics, such as conversion of heat to separation and pumping work) are completely absent from the proposed metric (page 14). It is absolutely vital to include these inputs in the performance metric in future work.
- The project appears to be making good progress; however, it was difficult to evaluate how many materials have been screened, what lessons/principles were learned (specifically from the computational screening), and how those principles are guiding the continuing effort.

Question 3: Collaboration effectiveness

This project was rated **3.5** for its collaboration and coordination with HydroGEN and other research entities.

- The project has utilized several node resources and achieved meaningful results. The interactions with the nodes and with the broader advanced water-splitting community are excellent. Professor Scheffe is an active participant in the benchmarking efforts, both in developing protocols and in overall discussions during workshops.
- The team is collaborating with other team members and HydroGEN nodes effectively. There is an opportunity to increase the amount of interaction/collaboration for other projects funded by HydroGEN that would make both this project and other HydroGEN-funded projects more effective and successful.
- The team appears well-coordinated internally and in work with the HydroGEN infrastructure.
- The research team effectively used the HydroGEN nodes. The research team worked with the benchmarking team to develop protocols. The research team was composed solely of professors from the same university. The project may have benefited from some additional collaborators. For example, the team could have examined additional materials.

Question 4: Relevance/potential impact

This project was rated **3.0** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN consortium mission.

- The relevance and impact of the project on DOE goals are twofold. First, as indicated earlier, the main premise of the approach is not supported by thermodynamics. It has, however, enjoyed periodic popularity, largely driven by difficulties in addressing truly hard engineering challenges. This project presents an excellent opportunity to conclusively disprove the premise and help focus the field. To do so, performance metrics must be revised to address key omissions. Second, the project is reasonably likely to create methods and capabilities that can be useful in the future.
- If successful, this project has the potential to discover new materials that can dramatically improve upon the hydrogen production capacity of existing materials. However, it is unclear from the report how quickly materials are being evaluated and whether the approach will be sufficiently directed and efficient to evaluate enough materials, and materials in the right chemical space, to discover superior materials.
- The larger impact has yet to be realized. It depends on the efficiency arguments, and those efficiencies lean heavily on hydrogen separation techniques, which are not included in any analysis. By the project’s own results, steam-to-hydrogen ratios lower than 200 realize dramatic penalties in yield. This means active separation and recirculation will be critical, regardless of the hydrogen produced. Higher production will require commensurate increases in steam, which cannot just be condensed out of the product stream. The parasitic losses to the separation process could be difficult to keep below the heat exchange improvements afforded the isothermal process.
- It is too early in the material development to determine the potential impact.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The proposed future work is both appropriate and relevant. One possible exception is the proposed fabrication of ceramic foams and their subsequent characterization.
- It is good that the researchers will be looking at additional materials. The work on the foams seems well-thought-out. The team needs to consider mechanical strength considerations.
- The proposed future work was not sufficiently detailed to enable understanding of what will be explored and how results and lessons learned are guiding adjustments to the work plan. If the project is successful, it should uncover principles that will motivate revising the future proposed work toward materials that are more likely to be successful, but the report does not provide information about what the lessons are and how they will be used and, in some cases, how what was discovered repeats lessons learned from previous work on STCH redox mediators.
- The proposed and planned future work is acceptable. It builds upon the finding from earlier budget periods and is in line with the initial roadmap. It is unclear whether the existing workflows will be capable of keeping pace with an increase in candidates to be synthesized and tested, however. The realistic solar testing seems premature/unnecessary, considering the effectiveness of the other testing proposed, but it could be valuable to know if there are large discrepancies between the in-laboratory testing and more real-world scenarios.

Project strengths:

- Perhaps the biggest strength is investigating isothermal cycles at all. It is still important work, and there are many unanswered questions that need to be either answered or marked as unknowable. The foam synthesis work has shown itself to be quite strong. The testing reactor is excellent and is providing beautiful data.
- The project has good collaboration and a well-thought-out materials development approach.
- The project is looking at a process different from others. The team is utilizing the HydroGEN nodes well. The work is a good combination of theory and experiments.
- The team is strong and experienced. The methods and approaches used are appropriate. Collaborations within the team and with the nodes are extensive.

Project weaknesses:

- By not addressing the hydrogen separation issue, the project loses impact. This is critical, considering there is also no investigation into reducing the higher steam-to-hydrogen ratios needed for isothermal splitting of perovskites found to date. While the DOE target of 10:1 or lower may be unrealistic for all materials but ceria, the efficient utilization of ratios 20–50 times higher seems equally so.
- It is recommended that the researchers consider additional material classes. Whenever foams are used, mechanical strength needs to be considered. A task characterizing the foam mechanical strength would be recommended.
- The reported results are vague, so it is difficult to access the progress and to provide suggestions. The project does not use many advances made from previous STCH efforts funded by HydroGEN, which is essential to accomplishing the ambitious goals of the project and exploring such a large composition space.
- There is a fundamentally flawed basic premise, with performance/outcome metrics constructed in a way that cannot reflect the actual potential (or lack thereof) of the approach.

Recommendations for additions/deletions to project scope:

- As nice as it would be to add an investigation into hydrogen separation and/or decreases in steam-to-hydrogen ratios, the scope increase is too great. Perhaps there are smaller analysis efforts that could be done to identify the impact of the problem and incorporate the results into a modified performance metric. The whole community would probably be overjoyed to hear that it is a non-issue.
- A stronger technoeconomic component would be beneficial, as it would help bring to light omissions in the efficiency metric and the likely real-world productivity.
- A task characterizing the foam mechanical strength would be recommended.

INFRASTRUCTURE

Project #H2-061: Innovating Hydrogen Stations: Heavy-Duty Fueling

Michael Peters, National Renewable Energy Laboratory

DOE Contract #	WBS 8.6.2.1
Start and End Dates	8/1/2019
Partners/Collaborators	Air Liquide, Honda, Shell, Toyota
Barriers Addressed	• Hydrogen safety, codes and standards: insufficient technical data to revise standards • Hydrogen delivery: other fueling site/terminal operations • Targets for Class 8 tractor–trailers: hydrogen fill rate

Project Goal and Brief Summary

This project aims to develop both digital and physical models of hydrogen fast-fill systems that can fill heavy-duty vehicle (HDV) hydrogen tanks at a rate of 10 kg/minute. This work will address a lack of data on fast hydrogen filling into representative medium- and heavy-duty storage systems.

Project Scoring

The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is the only project that is directly tackling the question of what kind of equipment is required to achieve the desired performance for HDV fueling. The objectives are timely, and if the project is successful, it will provide valuable insights for several stakeholders. The approach is well-constructed to collect the necessary details, providing significant and reliable demonstrations of equipment performance and capability as applied to HDVs.

- This project is very much in line with what is happening in the industry regarding fueling for HDVs. That, coupled with the publicly available tools and data, makes this an extremely valuable project.
- Having hardware to generate real data and rapidly validate both the one- and three-dimensional models is a great value to the industry.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The work is progressing very well and is exceptional, given the pandemic-related circumstances of the past year. The ability and opportunity to test some new equipment (the micro heat exchanger) are also advantageous. The project can work with and add to some good historical data (the 116 L and 36 L tank data). The team seems very tuned into the needs of those who are developing the protocols and who will be implementing this technology (HDV fueling) in the near future.
- Given COVID-19, the fact that the project has progressed to commissioning equipment installation—in less than two years—is remarkable.
- Several significant milestones have been crossed in the project, especially with respect to station equipment installation and testing equipment fabrication. Some of the final steps remain outstanding for the station equipment commissioning, though it does not appear that there should be any remaining roadblocks. The amount of time left in the project may be a little bit of a concern, especially given the desired scope of the outcomes. It appears that only six months are left in the project and that may be a strain on full-station testing and the ability to collect enough data for full characterization of station performance, while also collecting enough data to inform and validate computational fluid dynamics (CFD) and the one-dimensional model.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project includes a wide range of collaborators, spanning industry members, academic institutions, regional and state government, and even an international partnership with a similar technical focus. In addition, this project leverages accomplishments from another DOE-funded project, the HDV simulator. The industry project partners are also appropriate, given the interests and expertise of those organizations.
- The project has a good deal of input from the industry and collaboration with other entities and projects, which enables receipt of comprehensive input. The monthly update meetings and the review of key details allow for a consistent exchange of information.
- The project has a good network of industry, academia, and standards organizations in the United States and internationally.

Question 4: Relevance/potential impact

This project was rated **4.0** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project's outcomes are absolutely necessary to ensure the viability of applying hydrogen fueling technology to HDVs. The work completed through this project appears to be a unique effort, or at least one without very many existing parallels. DOE has recently launched the Million Mile Fuel Cell Truck (M2FCT) initiative. As has been learned from the example of light-duty vehicles, success in vehicle design and development will not mean much without preceding success in fueling infrastructure. This project directly addresses some of the most pressing information needs in the critical, prerequisite scope of fueling infrastructure.

- The hydrogen industry has pivoted strongly toward HDV transportation, with large complex compound hydrogen storage systems (CCHSSs) as a second wave—after forklifts—of commercial fuel cell applications. Fueling those applications safely and quickly will be critical to enabling commercial success.
- This project is extremely relevant to the emerging, yet very fast-paced, HDV hydrogen fueling market.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- Future work is happening currently and is all excellent and timely.
- As presented, the project looks to be on track for completing and commissioning the test facility and for updating and releasing the revised Hydrogen Filling Simulation (H2FillS). It would be helpful to clearly explain how the industry and companies that are working on HDV fueling can access the tools to test and validate their protocols and systems, clarifying both the access to and support for H2FillS and the use of the National Renewable Energy Laboratory (NREL) site for validation.
- The proposed future work is well-aligned with the project objectives and follows logically from the accomplishments to date. One suggestion is to develop a more complete solution for how the CFD model could be shared with stakeholders outside of the national laboratories. At the least, a proposal could be developed for how organizations could collaborate with NREL to have the model available for further investigations in the future. Based on the latest state-of-the-art tools, it does appear that there are still several important design considerations for HDV tanks that need to be explored. The CFD model developed through this work appears to be quite powerful and accurate, so it should be leveraged significantly by future investigations, even outside of the national laboratories.

Project strengths:

- A major strength of this project is the combination of practical demonstrations—including some advancements being made in novel test equipment design—with detailed, multiple-scale modeling. This methodology and the project's wide scope of research seem effective at helping the project self-direct the necessary investigations to respond completely to the questions being asked by the project objectives.
- The upgrade of the testing site at NREL with "real" HDV hardware and testing capabilities is a huge strength of this project. This is a resource that does not really exist anywhere else, at least in a form that can be accessed widely by industry. This installation will provide safety and commercialization benefits and accelerate the development of infrastructure for fueling vehicles with large CCHSSs.
- Overall, this project is one of the most useful in terms of the "real time" aspect, which means working in parallel with industry as the technology comes along. The original H2FillS model was very useful, and expectations are that this version of it will be the same.

Project weaknesses:

- There are no apparent weaknesses with this project.
- The timeline is the only identifiable and significant concern; however, it appears that this project has simply been affected by the COVID-19 pandemic, like many other projects and the global economy in general. If the project does end up time-constrained, DOE should find some way to provide flexibility for the project's completion date.
- It would be good to see more information on how a developer of HDV fueling protocols and equipment can access the resources that the project is putting in place, especially with regard to support for modeling and validation.

Recommendations for additions/deletions to project scope:

- As mentioned in the presentation, HDV nozzle, hose, breakaway, and receptacle standards and hardware are under development and should be considered for integration into the project as soon as possible, as those elements will play a significant part in the safety and reliability aspects of HDV fueling infrastructure and there are many lessons to be learned by including them in both the hardware and modeling elements of the project.

- If any progress is made on protocol development within the timeframe of this project, the team should run some tests and incorporate them into the model. That being said, it might be a given with the level of coordination within the industry.

Project #IN-001a: Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Metals

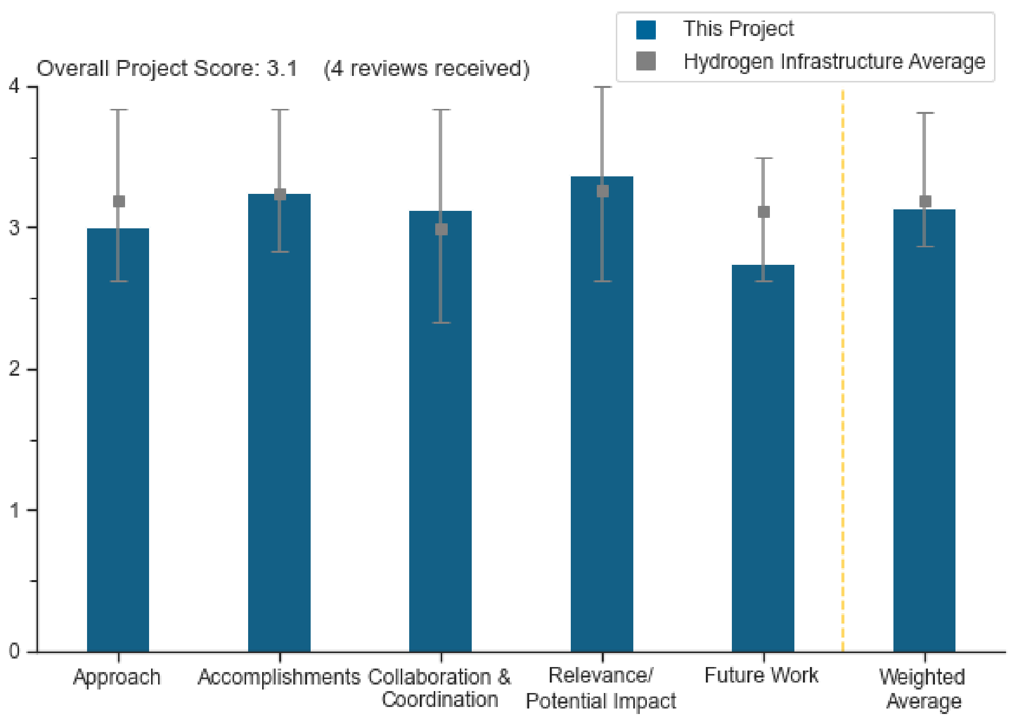
Chris San Marchi, Sandia National Laboratories

DOE Contract #	8.7.0.1
Start and End Dates	10/1/2018
Partners/Collaborators	Colorado School of Mines, University of California, Swagelok, HyPerformance Materials Testing, Massachusetts Institute of Technology, University of Alabama, UIUC
Barriers Addressed	• Reliability and costs of gaseous hydrogen compression • Gaseous hydrogen storage and tube trailer delivery costs • Other fueling site/terminal operation

Project Goal and Brief Summary

The primary objective of this project is to evaluate the potential for modern, high-strength steels to facilitate reductions in the cost of hydrogen pipelines. Specific goals are to (1) characterize fatigue performance of high-strength girth welds in the presence of hydrogen gas and compare performance to that of low-strength pipe welds, and (2) establish models that predict pipeline behavior as a function of microstructure in hydrogen to inform future development.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The work provides useful information in some areas of the project, and it should be focused on well-determined objectives to improve cost efficiency. The reviewer supports the following:
  - High-strength ferritic steel microstructures
  - High-strength aluminum alloys
  - Transferability of damage and crack nucleation
  - Microstructurally resistant, austenitic stainless steels
  - Materials for cryogenic hydrogen service.
- To approach this question, one must start with what is (somewhat) negative about the project. This is actually five projects being funded under a single contractual vehicle. One can see this on pages 2 and 4 of the presentation (under the Tasks heading), as well as in the size of the budget. It is odd to say that this is a bad thing, except that the presenter was provided the same amount of time allotted to single projects. In this case, each individual task (project) was provided two to three slides and not nearly enough presentation/ discussion time. As such, delivery of the important bits during the presentation and in the slides is sorely lacking. This is an unfortunate outcome, given the apparently excellent work being performed. It is strongly suggested that future U.S. Department of Energy Hydrogen Program Annual Merit Reviews view this grant as five projects and allot presentation time for each. With the above in mind, yes, the barriers were sufficiently defined, but the project design and feasibility were not communicated well. There was simply no time.
- This is a very broad program. It is challenging to have a rigorous critique of the approaches based on the abbreviated descriptions in the slides and the short talk. This is not the fault of the principal investigator but rather just a structural constraint of the review format. Generally, the approach is sound. In some areas, the goal/objective is very broad, and the link between the specific actions described is not self-evident. While in many instances the reported results seem useful, they would fall short of conclusively informing the very broad objective.
- The project would benefit from having more visible input from folks who are experts in specific material classes or test methods.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- It appears that, to date, the project has performed a considerable literature review, a decent-to-considerable number of molecular dynamics simulations, a decent-to-considerable amount of high-strength steel fracture testing, in situ hydrogen slip experiments, and some cryo-temperature testing. While it is certain that the project has performed more work, the above is clear from the slides. This is quite a bit of work for a project that started in October 2018 and endured COVID-19. Having said that, more/supporting information is warranted for each task, given the claims that are stated in the slides.
- The testing and analysis could result in a breakthrough for achieving the identification of ferritic steel microstructures with tensile strengths up to 1,100 MPa and a 50% increase of fracture resistance in high-pressure hydrogen.
- Evaluation of the progress is difficult owing to the abbreviated material. That being said, all indications are that significant progress has been made; this is an achievement, given the COVID-19 environment of the past year and a half.
- It seems like much effort is being put toward modeling, and more should be placed in developing well-planned experiments.

Question 3: Collaboration and coordination

This project was rated **3.1** for its engagement with and coordination of project partners and interaction with other entities.

- It appears the project is collaborating relatively well within the hydrogen community. The project is strongly advised to look toward collaboration in the damage, damage parameter, and crack initiation community.
- There are extensive collaborations that are not just "on paper" but are actually being realized.
- The projects are all focused within DOE or at select universities. There could be much more progress in this area with more diverse participation.
- The project's collaborations are somewhat limited. It is likely that this limitation is a function of the project's being new, and collaboration is anticipated to grow. The team needs to establish a higher degree of collaboration for achieving goals common to the delivery and storage of high-pressure hydrogen.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- One could not overstate the relevance or potential impact of any one of the five projects being studied in this grant.
- The posed questions/goals/objectives are highly relevant, and the work will make advances toward these goals. While the progress toward these goals will be tangible, it seems that there will be incremental progress rather than the more comprehensive solutions that would be inferred by the objective statements.
- The research and development relating to high-strength ferritic steel microstructures and high-strength aluminum may be a breakthrough for efficient pressure vessels that are used in delivery and storage.

Question 5: Proposed future work

This project was rated **2.8** for effective and logical planning.

- This project was marked fair because the detailed future work was not elucidated in the presentation or slides sufficiently such that someone could comment on the project's worthiness of future funding.
- The commentary on remaining challenges and the associated barriers is well-stated but a bit vague. However, some of the statements may be neglecting the significant work aimed at understanding and integrating nucleation behavior into linear elastic fracture mechanics predictions and environmentally assisted cracking in high-strength Al alloys.
- The project would benefit from having more visible input from experts in specific material classes or test methods, and more effort should be placed in developing well-planned experiments.
- The result of this ongoing project will determine the need for expanding it.

Project strengths:

- The current project and testing protocols should provide guidance with regard to applicability of high-strength ferritic steel microstructures or high-strength aluminum for suitable pressure vessels or pipelines that provide adequate strength and ductility for resisting hydrogen embrittlement.
- Project strengths include the collaborations, breadth of effort, the multiscale nature of the efforts, integration of testing and modeling, and identification of important knowledge gaps.
- The projects have good participation of DOE laboratories and some academic institutions. The folks working on the projects are experienced in effects of hydrogen on ferrous materials.
- This is a well-rounded approach that includes experimentation and modeling for all the projects in the grant.

Project weaknesses:

- There was not enough time for the presenter to provide enough information to elucidate any real strengths or weaknesses in the current and proposed work. This is unfortunate, as, in all review processes (e.g., peer-reviewed journal articles), reviewer feedback can help to open a line of thinking that may have been missed. While project teams may seem broad and diverse in their expertise and thorough processes, no team is sufficiently equipped with both depth and breadth. Once subsequent year funding is decided upon, this project would benefit from a more thorough peer review to support its path forward. The review should include people outside of those commonly involved with hydrogen.
- There are very broad objectives (that are likely not to be fully realized), intermittent disconnects between the broad objective and targeted modeling, and, in some instances, a lack of integration of work from other fields (could simply be due to the abbreviated format of the review).
- There is a lack of collaboration, mainly involving experts in specific materials classes who can propose new ideas with respect to the materials, microstructures, and mechanical behaviors of those specific materials. The project uses ferritic steels, austenitic steels, aluminum alloys, fatigue crack nucleation, and alloy development. It is unclear who the experts who are helping to guide the work are.
- There should be an extensive literature search to avoid repeating expensive testing. There were several tests of low and medium ultimate tensile strengths of ≤950 MPa for steel, so the results did not provide any new information.

Recommendations for additions/deletions to project scope:

- There was no chance to ask questions after the presentation, so the reviewer emailed the presenter afterwards. The recommendations here are somewhat based upon the email communication between the presenter and the reviewer. The images chosen for the "project goal" slide would lead one to believe that the project has interest in elucidating the effects of notches and/or cracks. The images also lead one to believe that the project is interested in the micromechanisms leading to the particular morphology of crack paths. The images are not congruent with an understanding of the project focus, as elucidated via email. The project would benefit from an explicit definition of what is sought from the "transferability of damage crack nucleation" project. Email communication made this clear, but the presentation did not. Along those lines, the term "critical damage accumulation leading to a crack of interest to fracture mechanics" (or something similar yet less convoluted) would be more apt, rather than the terms "nucleation" or "initiation." Those two terms have specific meaning to a sect of mechanicians. The project team is cautioned against the sole or primary use of monotonic deformation accumulation when going for a critical damage accumulation formulation. The components of interest for hydrogen use experience repeated loading, even if only hundreds of cycles. Materials of interest experience considerable kinematic and isotropic evolution, cyclic stress and strain redistribution, and cyclic load magnitude-to-cyclic damage accumulation rate dependence, all of which may occur in the first hundred to several hundred cycles of loading (even under R=0). To this end, load-controlled tests are unable to capture the material's history-dependent deformation response.
- It is recommended that this project continue with a new objective and goal to use the resource and strength toward achieving a new material that is better suited for hydrogen embrittlement.

Project #IN-001b: Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Polymers

Kevin Simmons, Pacific Northwest National Laboratory

DOE Contract #	L062-1502
Start and End Dates	9/1/2018
Partners/Collaborators	Argonne National Laboratory, Sandia National Laboratories, Oak Ridge National Laboratory, Savannah River National Laboratory, Pacific Northwest National Laboratory, Swagelok, Takaishi Industries, Arlene, Zeon, Top Sector Energy, Chemours, Kyushu University
Barriers Addressed	• Limited access and availability of safety data and information • Insufficient technical data to revise standards • Limited participation of business in the code development process • No consistent codification plan and process for synchronization of code research and development • Reliability and costs of gaseous hydrogen compression • Gaseous hydrogen storage and tube trailer delivery costs • Other fueling site/terminal operations

Project Goal and Brief Summary

The project objective is to fill a critical knowledge gap in polymer performance in hydrogen environments. Investigators are gathering and assessing stakeholder input about the challenges, materials, and conditions of interest for hydrogen compatibility. Findings inform the project's development of standard test protocols for evaluating polymer compatibility with high-pressure hydrogen, characterizing polymers, and developing and implementing an approach for disseminating the information.

Project Scoring

The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **2.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach addresses key knowledge gaps with respect to failure mechanisms in polymer systems commonly used in hydrogen service and should provide useful feedback to make improvements. That said, the specific questions that are being investigated in the U.S. Department of Energy Hydrogen Program (the Program) are a small subset of the large range of materials and approaches that could have been assessed. It was not clear how these specific materials and improvement approaches were selected for evaluation, whether by the investigators themselves or with input from the broader research and commercial community.
- The project objective is clearly identified as demonstrating, by September 2022, an elastomer formulation with 50% less swelling compared to similar off-the-shelf materials. Regarding critical barriers, since this project purports to develop science-based strategies to design material (micro)structures and morphology with improved resistance to hydrogen degradation, it is expected that the project is identifying and addressing specific science-related barriers. However, such science-related barriers are not clearly established and are not linked to the technical accomplishments. Rather, there is more emphasis on particular modeling and experimental tools than on resolving specific knowledge gaps by applying the tools in a targeted fashion. To illustrate this impression, the titles of slides 7–11 all emphasize the tool applied, as opposed to the science question or knowledge gap that is motivating the application of the tool.
- The project objectives and critical barriers have been clearly identified. It is difficult to understand how all of the different pieces of work are tied together and pointing toward addressing the barriers and achieving the objectives. The relationship between the Hydrogen Materials Compatibility Consortium (H-Mat) website, Data Hub, and the technical work is not clear; they seem like many individual efforts.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The results generated by the project team during the last year have provided useful insights into the behavior of compounded polymeric elastomers when exposed to high-pressure hydrogen. The accuracy of the molecular model as a predictive tool for a hydrogen pressure failure point is especially impressive, and its value in directing research toward new, more degradation-resistant formulations has already been demonstrated. Further progress could be made in having tools and conclusions more broadly available, especially with respect to the H-Mat and Data Hub.
- The project objective of demonstrating an elastomer formulation with 50% less swelling compared to similar off-the-shelf materials is clearly identified; however, it is not clear how the technical accomplishments represent progress toward that objective. Since the project does not identify specific science-related barriers and knowledge gaps that are linked to the goal, it is difficult to judge how the accomplishments represent progress toward achieving the goal. For example, in reference to slide 7, it is unclear whether it was postulated that swelling could be related to hydrogen accumulation at the silica–polymer interface, and thus these results would confirm the posited relationship and inform a pathway to mitigating swelling.
- The project has made significant progress, but it is difficult to see how the progress will lead to reaching project objectives.

Question 3: Collaboration and coordination

This project was rated **2.7** for its engagement with and coordination of project partners and interaction with other entities.

- The partners include DOE laboratories and a few companies, and among those partners, there appears to be sufficient collaboration. Participation by a broader group of organizations, including standards development organizations, pre-normative groups focused on materials, and the National Institute of Standards and Technology might help accelerate this work. This reviewer recalls the Hydrogen and Fuel Cell

Technologies Office director making a statement about all canoes rowing in the same direction; however, that approach is not seen here. It is not clear how the team knows that it has the right partners for success.

- The strong collaboration between national laboratories is a key component of this project and has been readily demonstrated through the technical results obtained by geographically and organizationally diverse teams. That said, while multiple commercial organizations are listed as team partners, their degree and form of involvement are unclear. Achieving DOE goals for the project will hinge on the near-term commercial impact of findings, so this linkage should be emphasized going forward.
- The project clearly identifies industry partners and research collaborators; however, it is not apparent how these relationships are enabling the accomplishment of the project goal (for example, how the collaboration with Kyushu University's contributes to accomplishing the project's goal).

Question 4: Relevance/potential impact

This project was rated **3.0** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project's goal, "By September 2022, demonstrate an elastomer formulation with 50% less swelling compared to similar off-the-shelf materials," seems pretty conservative and achievable. The project objectives are aligned with DOE's goals and will help realize the goals if the project achieves those objectives.
- The project is intended to enable a more robust and reliable infrastructure, which is certainly in alignment with the Program goals.
- The broad goals of this project will have a high impact on the overall Program goals and objectives through the reduction of unanticipated maintenance events and hydrogen losses. However, it is unclear what percentage of the overall problem is addressed by the specific technical projects the investigators have selected to pursue. A broad survey of the materials in use and the impact of solving the specific issues as a percentage of the commercially deployed hydrogen seal market would assist an assessment of how impactful the project will be, assuming its technical success.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The focus of investigators on broadening the applicability of technical results generated so far, and making them accessible to the community, is exactly the right direction for the project to go. Close collaboration with industrial partners will be necessary to ensure near-term impact of the work. Further thought may be necessary to determine the best approach to making H-Mat and Data Hub useful repositories for Program results, though this, too, is planned through beta testing by the team.
- There does not seem to be a plan to generalize the technical approach more broadly. It looks like the team is addressing a solitary problem. There does not appear to be a plan to engage stakeholders with the H-Mat site and Data Hub widely. A plan to ensure that the resources are what stakeholders need and to evaluate their use could help target the resources to address these needs.
- It is not clear how the proposed future work is informed by the reported accomplishments. Furthermore, it is not apparent how the proposed future work represents a pathway toward satisfying the project goal (by September 2022, demonstrate an elastomer formulation with 50% less swelling compared to similar off-the-shelf materials).

Project strengths:

- This project shows a high level of collaboration between multiple national laboratories, which has led to the generation of impressive technical results and predictive modeling tools. Providing these results to hydrogen seal manufacturers should yield near-term benefits in the design of more hydrogen-resistant materials and a reduction in seal-related unplanned maintenance events. By building in communication and dissemination tasks in the later portion of the project, sharing the findings from this work, as well as the subsequent positive impacts, is much more likely.

- The project's science-based approach can be fruitful toward the goal of improving the performance of materials when they interact with hydrogen gas.
- Establishing mechanisms, such as consortia, to enhance collaboration could be valuable in accelerating progress toward reaching DOE goals. The technical collaborators on the project are making good progress.

Project weaknesses:

- The breadth of the problem that this project hopes to address makes any reasonable workplan fall short with respect to addressing all the potential technical questions related to elastomeric materials for hydrogen service. The team has done excellent work on the technical problems selected for evaluation, but it is unclear how large a percentage of the underlying technical issues are being addressed. As the project moves into its final years, it will be challenging to broaden the findings to enough different materials to truly serve as a complete database.
- It is not clear how all of the pieces of the project are related or how they are driving toward the same goals. The engagement with key stakeholders for codes and standards development could be improved. A plan for how the team will address the stated barrier of "limited participation of business in the code development process" could be helpful.
- The team needs to explicitly identify science-based issues and knowledge gaps that must be resolved to meet the project goal (demonstrate an elastomer formulation with 50% less swelling compared to similar off-the-shelf materials). The suite of theoretical and experimental tools seems intended to give the impression that the project is science-based, but the purpose of each tool for answering a targeted science-based question is not clear.

Recommendations for additions/deletions to project scope:

- The original scope of this project is exceptionally broad and has not necessarily been narrowed down by the investigators. To maximize the relevance of the project results, it would be useful at this point in the project to resurvey commercial partners to ensure that their most pressing needs are being addressed by the selected technical activities. Further industry input on the specific list of elastomeric and thermoplastic materials that are investigated will maximize the project's near-term impact on DOE performance goals.
- It is recommended that the project consider whether all of the theoretical and experimental tools are necessary. The priority must be to pose the critical science-based questions that represent barriers toward the project goal, and then identify and implement the right tools to address these questions.
- No additions or deletions are recommended at this time.

Project #IN-004: Magnetocaloric Hydrogen Liquefaction

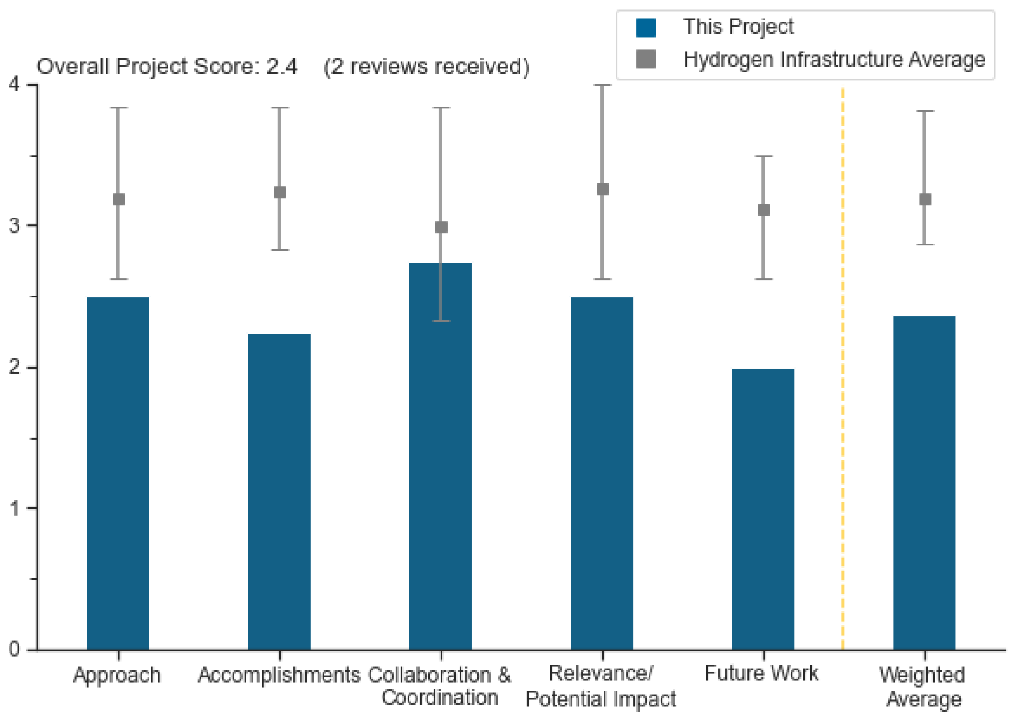
John Barclay, Pacific Northwest National Laboratory

DOE Contract #	3.1.0.2
Start and End Dates	10/1/2015
Partners/Collaborators	AMES Lab, Iowa State University
Barriers Addressed	• Low hydrogen liquefier efficiency • High liquefier capital costs

Project Goal and Brief Summary

The Pacific Northwest National Laboratory (PNNL) magnetocaloric hydrogen liquefaction system is expected to be considerably more energy efficient than the Claude cycle. At 30 tons per day, the latter shows 40% efficiency, while the former is projected to be 70%–80% efficient. In this project, investigators will demonstrate the PNNL system liquefying ~25 kg/day of hydrogen. At industrial scales, the concept is expected to have a figure of merit (FOM) >0.5 (as compared to the Claude cycle system's FOM of <0.3). The project will also identify a pathway to a larger-scale system with an installed capital cost of less than $70 million.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Because of late reviewer withdrawals and conflict of interest notifications, the minimum number of reviewers for a complete review panel (three reviewers) was not achieved for this project. The results are included here to inform future work and reviews, but the scores for this project are not included in the subprogram average.

Question 1: Approach to performing the work

This project was rated **2.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Critical barriers (FOM, capital expenditures, operations and maintenance, energy input) are clearly identified and addressed. They are also consistent throughout the years, which is good to see. The way the project is self-designed and whether it is commercially feasible are more difficult to quantify or qualify. There is obviously a good mix of modeling and experimental investigation, but it looks like a large amount of work has been devoted to characterizing and manufacturing the materials rather than looking at the system itself.
- This is the fourth year of reviewing this project. The fundamental premise is interesting; however, the lack of progress over the past two years suggests that it is time for the U.S. Department of Energy to provide other potential technologies the chance to prove their value. Much of the material in the presentation appeared to be very similar to what was presented in 2019. Furthermore, current commercial technologies in hydrogen liquefaction have reduced their energy input to levels approaching the project's goal of 6–7 kW/kg.

Question 2: Accomplishments and progress

This project was rated **2.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Since the last presentation in 2019, this project appears to have made very little progress in the area of materials development and testing, although the impact of the pandemic over the past year must be acknowledged.
- There were only three slides on accomplishments and progress (the fourth one is actually a response to reviewers). Granted, the third slide has many bullet points, but it is difficult to judge the level of effort (such as whether accomplishments listed in slide 8 have required as much effort as those listed in slide 10).

Question 3: Collaboration and coordination

This project was rated **2.8** for its engagement with and coordination of project partners and interaction with other entities.

- Many industries are listed. However, they are merely possible prospects, not active collaborators. For instance, it may be a long time before the technology readiness levels (TRLs) presented at the DOE Hydrogen Program Annual Merit Review (AMR) are acceptable enough to be of benefit to Raytheon Technologies and Nikola Corporation. There are no onboard liquid hydrogen (LH2) storage technologies available yet, and the hydrogen business model that Nikola Corporation must demonstrate is such that it is unlikely that the AMR is on the top of their list for another five years or so.
- It was good to see collaboration with Nikola Corporation, Woodside Energy Ltd., and Raytheon Technologies, but at the end of the day, none of these companies will develop liquefiers on their own.

Question 4: Relevance/potential impact

This project was rated **2.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Relevance and impact are excellent. This is typically the type of work DOE should support; it is innovative, high-risk, high-reward, and low-TRL. There is one note, though: the claim that this project is a game-changer is a little far-fetched, as it does not address the cost of hydrogen production, which is central to the consideration of hydrogen production pathways and zero-emission transportation.
- Progress is slow, and convincing results are not available. Now that hydrogen consumption for mobility is ramping up, organizations that build hydrogen liquefaction plants are ramping up their investments to achieve energy-efficient liquefaction processes to compete in the market. Today, the three industrial gas organizations have commissioned, or are building, hydrogen liquefaction plants with capacities of over 30 tons per day. Chart Industries has invested in liquefaction technology and is likely working on

improvements. As demand grows, so will proven and reliable designs that adopt efficient technologies for a competitive edge.

Question 5: Proposed future work

This project was rated **2.0** for effective and logical planning.

- It is uncertain that the concept of proposed future work is relevant since the project is on a no-cost term extension, ending in September 2021. Work left to be performed until then seems challenging. The related slide shows very interesting mapping of technology options.
- It is suggested that DOE allow the project to end and look for other concepts to fund in the future.

Project strengths:

- This is a very innovative project, with a strong science basis and high potential of generating LH2.

Project weaknesses:

- There is a lack of clarity on cost, material selection, fabrication, and overall plant design. Producing well-shaped spheres seems to have been a challenge throughout the six years.
- Any innovative technology must face the reality of commercialization, which means productivity and reliability. This technology is interesting but has not demonstrated the potential to be commercialized. For that reason, when the funding is finished, there should not be a renewal.

Recommendations for additions/deletions to project scope:

- The project should be clearer on challenges and how difficult and unforeseeable they have been.
- No changes to the current project are recommended.

Project #IN-015: Optimizing the Heisenberg Vortex Tube for Hydrogen Cooling

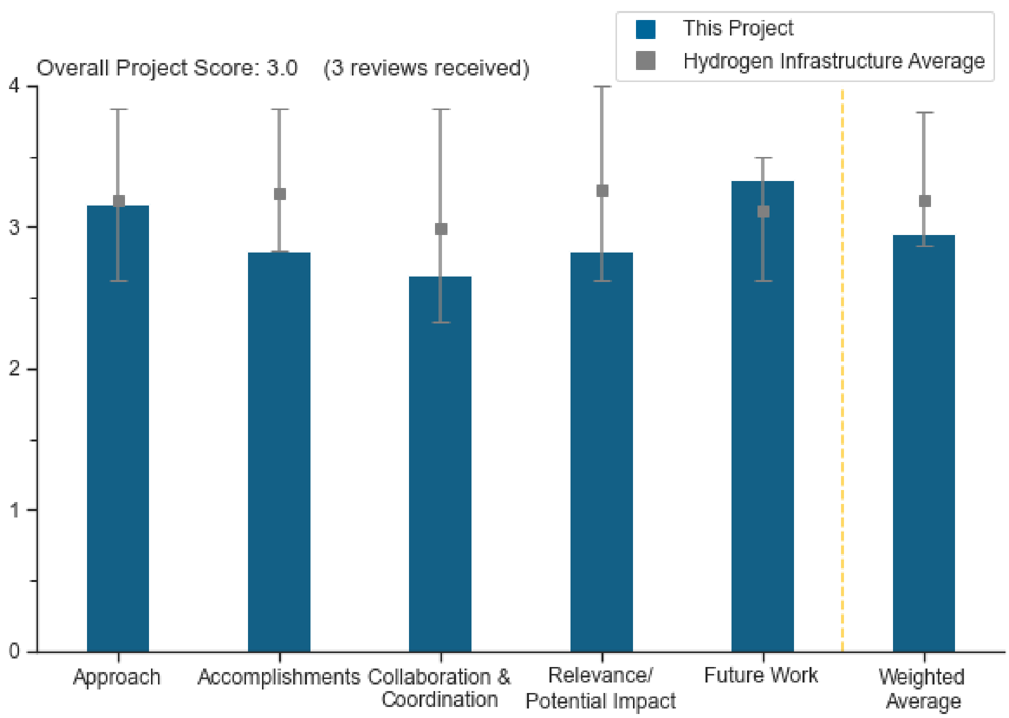
Jacob Leachman, Washington State University

DOE Contract #	DE-EE0008429
Start and End Dates	1/23/2019 to 9/30/2021
Partners/Collaborators	Washington State University, Plug Power Inc.
Barriers Addressed	• Reliability and cost of liquid hydrogen pumping • High cost and low efficiency of liquefaction • Other fueling site/terminal operations

Project Goal and Brief Summary

This project aims to establish that Plug Power Inc.'s (Plug Power's) Heisenberg Vortex Tube (HVT) cooling system can effect the following improvements to cryogenic hydrogen systems: (1) a 20% increase in liquid hydrogen (LH2) pump volumetric efficiency through vapor separation and subcooling, (2) a 20% decrease in LH2 storage tank boil-off losses through thermal vapor shielding, and (3) an increase of supercritical hydrogen expansion from 31% to more than 40% through greater isentropic efficiency.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The reviewer has tracked this project for the past three years and is happy to see that the concept has evolved in a productive manner and found an application that may result in its productive use.

- Due diligence has been performed to identify the best application case. This looks like a great utilization for the HVT. Also, stratification is a key issue for stationary LH2 storage systems.
- The work to validate the science behind the concept of refrigeration provided by para-orthohydrogen conversion is sound. The project is about to enter the testing phase. This will test the efficacy of the project plan to meet its goals. There will be inherent challenges with this testing because of the number of variables involved. The three barriers listed on slide 3 do not seem directly applicable to the project for the following reasons: (1) the reliability and cost of LH2 pumps is not directly affected by the thermodynamic performance of the LH2 system (e.g., tank vent losses), (2) the high cost and low efficiency of LH2 liquefaction is not addressed, and (3) it is unknown what is meant by "other fueling/terminal operations."

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The work on material selection and material shape is admirable. It was good to see the adoption of the catalyst in the HVT.
- The project has made progress in validating the technical concept of para-orthohydrogen conversion. There is no progress yet in terms of calculating or comparing the refrigeration effect to achieving the stated goals on slide 2. For example, it is not clear how the pump volumetric efficiency improvement of 20% and the reduction of vent losses will be achieved and measured reliably. It would be helpful if the project provided the baseline for both of these goals, to which the results can be compared later. It is also not clear why the same loss-reduction benefit could not be achieved by simply improving the operation of the LH2 pump and/or increasing the size of the boil-off compressor. The goals of this project are relatively narrow and apply only to the specific Plug Power systems. As such, it is not clear that the HVT will provide significant benefits to other systems or markets. For example, there are other cryogenic pumps on the market today that demonstrate performance that already exceeds the stated goals, even at the relatively small system size. As systems increase in size for the heavy-duty market, the benefit of a modest amount of in-tank cooling will diminish rapidly.
- There were few details on Task 2.1.2, which lasted 12 months. If this is proprietary to Plug Power, then public money should probably not pay for this, nor should there be any evaluation. Although Task 2.2.3 is interesting in principle (nice block diagram), it is difficult to estimate the progress there. It is unclear how many runs were completed or what the error bars on each result were. The team can perform uncertainties well. It is not clear why it was not done to compare experiments versus computational fluid dynamics. Also, it is not clear whether 1 K of cooling (53.7 K to 52.7 K) is enough for the process. Finally, it would be good to know what the accuracy of the sensor is. Objective 3 seems to have been well met.

Question 3: Collaboration and coordination

This project was rated **2.7** for its engagement with and coordination of project partners and interaction with other entities.

- It is a good choice to work with Plug Power, which utilizes installations that are ideally suited to adopting the HVT and utilizes the molecules vented from the process. Upon completion of the late 2021 testing, the results should be shared with the broader industry to gain greater visibility of the technology.
- Coordination between the two project members, Washington State University and Plug Power, seems to go well. However, there are no collaborations with outside members.
- Working with Plug Power and a tank vendor offers the ability to deploy and test the technology. The collaboration with Plug Power limits the ability for broader use, testing, and validation, though. As a result, the applicability might be relatively narrow and will help with only a subset of applications using specific equipment. The equipment of the entire system has not been described to help with understanding the HVT's effect on other systems and when used by other vendors.

Question 4: Relevance/potential impact

This project was rated **2.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The work is well-aligned with DOE objectives of reducing costs for LH2. Boil-off is a challenge for many applications. The implementation is realistic and backed up well by analysis.
- As the demand for LH2 for mobility and stationary applications grows, the potential value of the HVT will expand significantly.
- The underlying technology is sound, but the question is whether it will have enough of an impact to be commercially feasible for this market or for other markets. The nature of the work lends itself to a relatively narrow subset of applications where it would be helpful. For example, the project states that this technology is projected to be feasible for only 50% of Plug Power material handling sites, which is already a fairly narrow portion of the DOE Hydrogen Program. There are also other technologies and equipment that already meet the goals of improving pump efficiency and reducing vent loss on LH2 systems and that serve the same and comparable markets.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The plan to proceed with a tank vendor to deploy this technology for further testing is good. Given the number of variables inherent in the design, use, and manufacturing of the equipment, it might be challenging to get useful results. The catalyst's degradation is critical to the HVT's overall long-term success since the catalyst is inaccessible after the manufacturing of the tank. It is good to see that this is a priority.
- The project team has developed a good plan for future work. With that in mind, the researchers will need to begin thinking about how to commercialize the technology for wide use.
- It is great to see a proof of concept in a real full-scale system.

Project strengths:

- The concept of using the para-orthohydrogen conversion process to recover refrigeration is one that has potential. Progress in this area is useful for future LH2 system optimization. There is a lack of data concerning the actual temperatures within an operating LH2 tank, particularly with regard to stratification of its contents. This project and its testing will provide additional insight in this area. While it will help the existing project, it also will benefit future research. The project has a good plan, and the plan is being executed.
- The project has adequately performed both the theoretical and practical testing to position the technology for a real-life demonstration.
- This is a down-to-earth application that has a great academic background and is partnering with a leading LH2 company.

Project weaknesses:

- The validation of the concept will be challenging because of the relatively small benefit when compared to external factors that may affect the overall heat leak and operation of the system. The modeling shown for the internal temperatures of an LH2 tank appears to be for relatively static conditions and does not reflect the dynamics inherent with the operation of the cryogenic pump (and its condition), the boil-off compressor, the tank autovent, and the pressure-build system. The relatively modest refrigeration, provided by the HVT, may get lost within these conditions. For example, slide 15 shows the relatively small temperature impact. The lack of ability to share key technical and economic information (because this information is proprietary) makes it difficult to truly validate the technology's performance and future viability. It is not clear how the goal of a 35% increase in boil-off compressor flow will be obtained from the HTV's use. The efficiency and output of the boil-off compressor are unlikely to be unaffected by modest refrigeration inside the tank. Additional detail should be provided on this point.

- Clearer communication is needed to explain what delta T (ΔT) is needed, what the rough energy balance is, and how the HVT improves it.
- There are no serious weaknesses.

Recommendations for additions/deletions to project scope:

- The team should provide a rough order of magnitude on what makes the technology relevant (e.g., ΔT, balance of energy).
- The project could add commercialization planning.
- There are no recommendations for additions or deletions to project scope.

Project #IN-016: Free-Piston Expander for Hydrogen Cooling

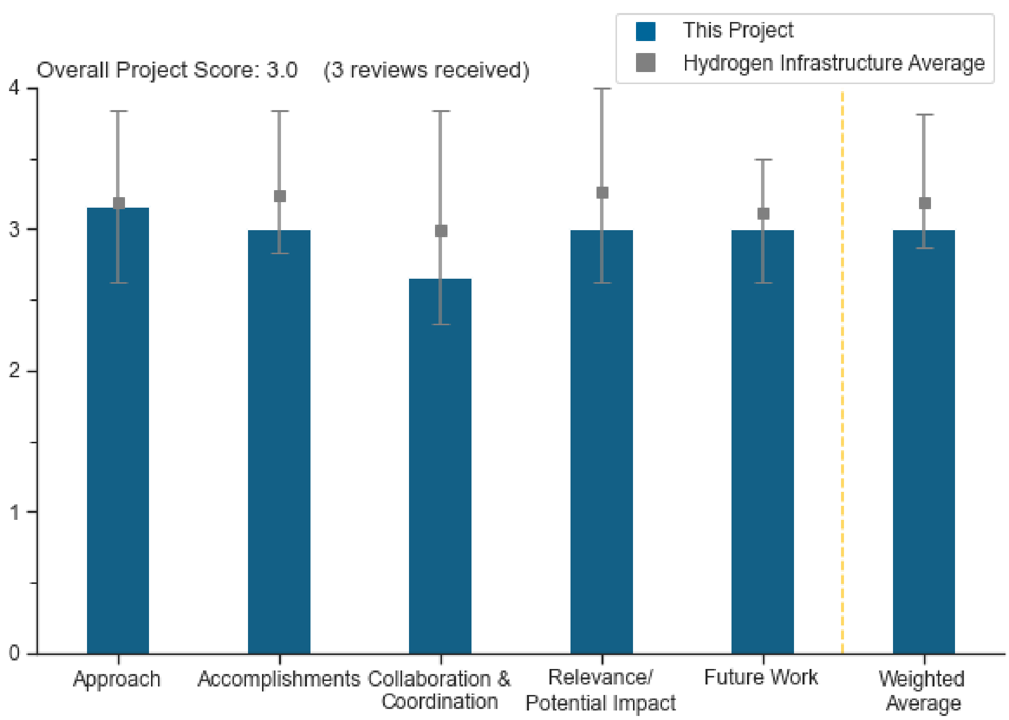
Devin Halliday, Gas Technology Institute

DOE Contract #	DE-EE0008431
Start and End Dates	1/2019 to 6/2022
Partners/Collaborators	Center for Electromechanics (University of Texas at Austin), Argonne National Laboratory, Quantum Fuel Solutions
Barriers Addressed	• Other fueling site/terminal operations

Project Goal and Brief Summary

The project team is developing a free-piston linear motor expander that can conduct hydrogen pre-cooling for light-duty hydrogen fueling, while producing energy that can be used to offset compression energy consumption. Pre-cooling units represent 10% of the capital cost of hydrogen fueling stations and impose significant operating costs as well. Replacing conventional pre-cooling units with expanders could reduce these costs, removing a major barrier to hydrogen fuel adoption.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The concept is very interesting and, if successful, will be a major contributor to diminishing the cost of hydrogen fueling. The team appears to be analyzing both the theoretical and physical constraints of the concept.
- There is a linear approach from modeling to design to proof of concept.

- The project is attempting a new method of providing cooling for dispensing applications. No meaningful barriers are listed on slide 3, although several were apparent in the presentation and from observation of the project review. In particular, some significant barriers might exist regarding long-term operation and longevity (e.g., maintenance costs):
    - Long-term longevity of the expander seals. No information was provided regarding the expected life of these seals, despite their being a limiting aspect of many reciprocating designs. This applies both to internal seals (affecting efficiency and performance) and to external seals (affecting safety).
    - Valve life. Some information was provided, but there were no details to back up assertions as to cycle life of the valves, especially when modifications were made and they are in service that exceeds the manufacturer specifications.
    - Maintainability of the unit, especially a unit of this size. This will be critical in terms of the technology's ability to be used commercially.
    - Ability to stay within the closely defined SAE International fueling protocol targets, particularly over a wide range of flows and pressures. For example, it is unclear whether the equipment can meet the cooling requirements for partial fills with low differential pressure. There is no mention of being able to vary flow as needed to meet varying flow conditions.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There is good work on evaluating valve speed and considering improvements. More modeling of ground storage dynamics is required, and the fact that the researchers acknowledged that they had not considered cascade dispensing is appreciated.
- The proof of concept is under construction.
- Good progress is being made on the basic function of the machine. However, development of similar machinery has typically shown that units such as these will need extensive prototype testing after initial function is proven. The competitive cost targets used are relatively high compared to current designs. The system shown on slide 5 is dated and does not fully reflect the current technology available, and the long-term targets are above competing technologies. For example, the cooling costs are not consistent and are higher than those shown in other DOE Hydrogen Program Annual Merit Review presentations.

Question 3: Collaboration and coordination

This project was rated **2.7** for its engagement with and coordination of project partners and interaction with other entities.

- This is a great mix of public–private partnership.
- The project collaborators have limited station operating experience fueling H70 (70 MPa) vehicles. It would be helpful to get the support of and partnership with a sizable station operator that could provide meaningful feedback on operating and installation issues, in addition to a platform for the long-term testing needed to validate long-term viability.
- The collaboration is focused on academic evaluation. The team needs to expand its reach to organizations offering commercial solutions and maybe even look outside the hydrogen fueling environment to applications such as helium cooling or other products.

Question 4: Relevance/potential impact

This project was rated **3.0** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Pre-cooling is a key challenge for LH2 refueling, and this looks like a worthwhile approach.
- Developing a lower-cost, lower-power refrigeration option for fueling activities has an impact on DOE goals. The costs shown in the presentation appear dated (2015) and for station sizes that are significantly

smaller than those being deployed and proposed today. Costs and technologies for dispenser cooling have advanced beyond the state of the art in 2015. In particular, this expander is required for each dispensing point, as opposed to systems that might be leveraged across multiple units for cost-effectiveness, so this technology may not scale well to larger systems (capacity and multiple dispensers).

- It is too early to tell, but the concept may have relevance to numerous applications.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- There is demonstrated functional hardware in various applications that target real-life applications.
- The next steps are logical.
- For those barriers identified, the future work is appropriate. The challenge is that unidentified barriers run a high risk of interrupting progress. Additional consideration should be given to those barriers, particularly long-term operation and reliability. The future work does not specifically address needing to stay compliant with very prescriptive fueling protocols that are critical to its success. There is no capacitance in the device to level out performance and transients.

Project strengths:

- The project looks to be relevant and has potentially broad applications.
- There is a realistic approach and great application.
- A properly designed expander can operate to provide the cooling required for fueling vehicles. The project team has developed a prototype.

Project weaknesses:

- The concept requires that all gas be compressed to high pressure to reliably provide enough refrigeration energy. This might be problematic for direct filling and for multi-pressure cascade pressure stations, which account for the majority of station designs. Effectively, the system relies on additional compressor energy and equipment to provide the cooling energy to then provide power back to the compression, but there will be losses inherent to the process. The maintenance costs have not been evaluated as part of the economics. The physical size of the machine (12'), its orientation (linear), and its relatively small capacity (light-duty) make it challenging for deployment in current form. Matching power generated with compression power required will be challenging because of different usage profiles and timing.
- The project needs to account for real-life technology scenarios.
- There are not enough details (see next section).

Recommendations for additions/deletions to project scope:

- After the basic function has been demonstrated and once the technology has been assessed for commercial viability, a long-term test program would be needed to assess long-term performance, particularly regarding maintenance intervals and cost. If not already completed, a hazard and operability study should be performed to evaluate potential safety risks of mechanical operation close to a dispensing operation, as well as potential for unanticipated leakage either within or external to the machine.
- The project could use more details: examples of how the work could be really recovered, especially during regime fluctuations of the station; the size of the system; and major technical challenges.
- The team should keep working.

Project #IN-019: Ultra-Cryopump for High-Demand Transportation Fueling

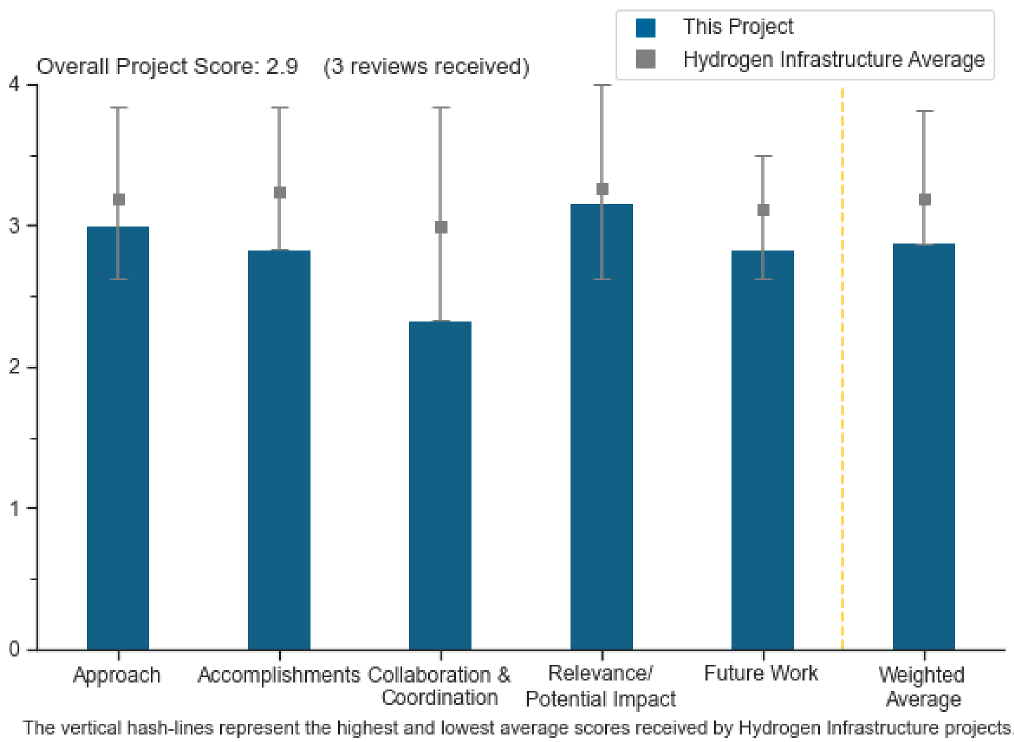
Kyle Gross, RotoFlow/Air Products

DOE Contract #	DE-EE0008819
Start and End Dates	2/1/2020 to 5/1/2023
Partners/Collaborators	N/A
Barriers Addressed	• Reliability and costs of liquid hydrogen pumping

Project Goal and Brief Summary

This project aims to help advance hydrogen refueling infrastructure for heavy-duty transportation by designing, building, and testing a liquid hydrogen pump with the flow and pressure necessary for bus and truck refueling. The work addresses challenges caused by refueling operating conditions (e.g., extreme pressure), in part by upscaling existing technologies by RotoFlow and making improvements to pump design, seal design, and motor–drive configuration. The intended final product is a cost-effective, reliable, high-flow, high-pressure reciprocating liquid hydrogen compressor system.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The overall approach seems reasonable, and the tasks in the current budget period are showing good progress.
- This project's approach is methodical and measured.

- The project's challenges to overcome were not really addressed adequately. The elephant in the room is seal life and maintainability. While these topics were mentioned, there was no proof provided that the issue of >350 bar cryogenic pump seal reliability has been addressed, nor was there at least an explanation of what is different about this approach compared to prior designs.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- This project has made good progress with developing the necessary material to move toward actual deployment and demonstration that will happen later in the project.
- It is expected that component testing will be conducted to validate the design approach planned, such as accelerated life testing of seals on a bench rig. The mechanical design of a cryopump is not novel; the team should focus on the high-technical-risk elements and address that risk first.
- Direct articulation (a page or two) of the specific technical barrier(s) that must be overcome to meet the DOE technical targets for the cryopump should be provided, as comparable pumps that meet lesser targets already exist. This will help others in perhaps adjacent fields to offer potential solutions that could advance the technology but that would otherwise go undiscussed.

Question 3: Collaboration and coordination

This project was rated **2.3** for its engagement with and coordination of project partners and interaction with other entities.

- The collaboration within Air Products is well-coordinated and significantly benefits the project, but there are no external collaborations. Perhaps working with vendors is a possibility for the project. Also, it may be useful to engage a group (e.g., the National Renewable Energy Laboratory) that could help model the duty cycle of the pump as a function of station usage, particularly across different usage scenarios. That might help establish the best design.
- There is no collaboration and no voice of the customer.
- No external collaboration or coordination exists for this project.

Question 4: Relevance/potential impact

This project was rated **3.2** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Heavy-duty (HD) transportation is a clear target for hydrogen. The refueling infrastructure needs to be convenient and reliable. A cryopump that enables HD refueling is a key link in the chain.
- While this project focuses on the modification of existing commercial pump technology, if successful, the technology could have an immediate impact on the HD application market.
- High-pressure cryopumps that are reliable and have low operating expenses are a key limiting factor in high-capacity refueling and cost-effective distribution.

Question 5: Proposed future work

This project was rated **2.8** for effective and logical planning.

- This project's proposed future work seems to logically follow the next steps for where the project's schedule and budget period currently is.
- The future proposed work seems to be on target.
- There is no component-level derisking or clear communication of the high-risk elements. If the investigators really have no concern, then it is unclear why this project is considered research and development (R&D).

Project strengths:

- Building off of internal company experiences and knowledge—particularly encouraged by engagement with Air Products experts for hydrogen refueling station designs—is a project strength.
- This project fits a gap in the current market.

Project weaknesses:

- The development plan does not credibly identify key risks or form an R&D strategy to focus on those risks before building a unit and testing it in a representative environment.
- Having no external interactions is a weakness.

Recommendations for additions/deletions to project scope:

- The mechanical design capability of the principle investigating entity is without question. It is recommended that the project focus on iterating seal designs quickly at a component level to prove they can last for durations that are commercially relevant, at full speed and full pressure.
- The pump capabilities should be evaluated against performance needs under different HD refueling station scenarios, with the help of a partner.

Project #IN-020: Self-Healable Copolymer Composites for Extended-Service Hydrogen Dispensing Hoses

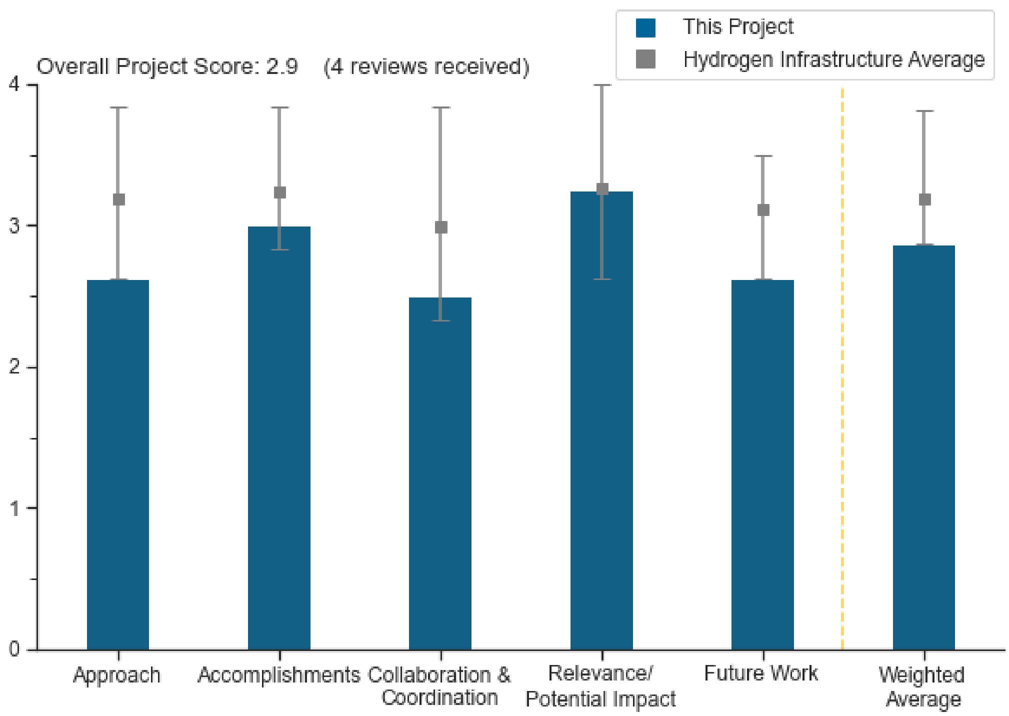
Marek Urban, Clemson University

DOE Contract #	DE-EE0008827
Start and End Dates	1/1/2020 to 2/28/2023
Partners/Collaborators	Savannah River National Laboratory, Sandia National Laboratories, Pacific Northwest National Laboratory
Barriers Addressed	• Fueling site/terminal operations • Reliability and cost of hydrogen fuel pumping

Project Goal and Brief Summary

This project aims to design, develop, and pre-commercialize a low-cost inner layer for hydrogen dispenser hoses that integrates a self-healable copolymer matrix with polypropylene fibers. Currently, hydrogen dispenser hoses develop microcracks after around 1,000 fueling cycles. This project could extend the service life of hydrogen hoses to over 25,000 cycles, making them far more cost-effective.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **2.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The concept is extremely innovative and could be a real game changer for realizing reliable and cost-effective hydrogen fueling. It seems like some potentially useful blends might be screened out prior to environmental testing. Fundamentally understanding how the different environments affect self-healing could be an important aspect of the work. It is not clear whether the measurement of self-healing is reproducible or whether it is measuring the key properties. It is not clear whether scratches are the same as cracks. It would also have been helpful to understand how a damaged material would behave during a tensile test. Slide 14 shows undamaged vs. self-healed specimens, prompting questions of how a damaged specimen would behave.

- The principal investigator (PI) has taken a novel approach to solving an issue that is a key cost driver in hydrogen dispensing. A solid team of national laboratory experts is on board to perform materials evaluations, and the technical bar set—with respect to durability of a developed solution—is such that if the material can be deployed effectively, the self-healing attributes of the polymer should affect long-term hose durability. However, the omission of an overall scheme for how this polymer will be integrated into a full hose assembly makes it difficult to know whether the results can be translated into a deployable product.
- Ultimately, the project team would benefit by defining several key metrics that can be used to direct the project moving forward. These metrics should explain concepts such as the following: (1) what self-healing is, (2) whether self-healing includes restoration of strength and ductility or just hydrogen permeability/ ability to seal hydrogen, (3) what the success level of self-healing is, (4) whether a scratch at 50% through thickness would be expected to self-heal more so than a completely severed membrane, and (5) how the properties and functionalities recovered through self-healing are defined (i.e., quantifying factors such as a membrane's ability to seal hydrogen, a specific measure of strength, or the elongation-to-failure measure). Each should be defined, and each metric should be quantified.
- The overall approach listed on slide 5 seems all right. From the subsequent slides in the presentation, it is not clear which of the work was done as part of U.S. Department of Energy (DOE)-funded Hydrogen Fuel Cell Technologies Office work versus what was already accomplished before this project started. It seems like many of the items listed in the approach were already known/published (e.g., design, synthesis, and characterization). Hence, it appears that the approach is repeating some of the prior work. Slide 3 describes a key barrier that this project is addressing as "reliability and cost of hydrogen fuel pumping." What is missing in the presentation is an explanation about the barrier associated with the "reliability" (of the hose, presumably) and whether it is attributable to the failure of the inner lining (that this project is trying to heal) or some other component of the hose (joints, crimps, cracking in outer layer, etc.).

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The work has shown good progress to date. The results are promising. Once metrics are defined, it is believed that the DOE Hydrogen Program (the Program) can provide even more quantifiable support for the work that has already been performed.
- The project appears to be making good progress and is meeting its milestones.
- The PI has demonstrated multiple polymeric compositions that meet the cost, self-healing, and durability targets set at the beginning of the project. All of these successes are commendable; however, the order of tasks in the work plan, and the difficulty in translating the damage mechanism used to test the self-healing properties, make it difficult to determine whether these results can be translated to solve the issue of cracking of hydrogen dispensing hoses.
- The PI's work that was funded by the National Science Foundation (published in *Science* 2018, 362(6411) 220–225, 10.1126/science.aat2975) shows that the team had already developed self-healing chemistries prior to this project's start date in 2020. The stress–strain curves (slide 9) and molecular dynamic simulation (slide 10) are both taken from this *Science* article. Therefore, it seems that some aspects of the work described here have already been published, and new work is not clearly identifiable. The distinction between the prior work and that performed under current funding needs to be made. A self-healing response in the presence of moisture, temperature, and pressure (slide 27) was determined. These are useful experiments. Slide 10 states a high cohesive energy density (CED) is desirable for self-healing, and slide 27 shows that CED decreases with an increasing number of hydrogen molecules. It is unclear whether that means that the "healing action" will occur only when hydrogen is not being dispensed.

Question 3: Collaboration and coordination

This project was rated **2.5** for its engagement with and coordination of project partners and interaction with other entities.

- This project has a good team approach overall.
- The PI has assembled an excellent team of experts from national laboratories to perform accurate and detailed materials property testing. However, the team is very much in need of input from an industrial partner, ideally a hydrogen dispensing hose manufacturer, to assist in ensuring that the selected test metrics are the most relevant to the material properties necessary for the application. An industrial partner could also provide insight into the integrated design of a hose using these self-healing polymers and into additional materials testing that might be required to ensure the developed materials meet the required technical specifications of a polymer that could easily be utilized in such a design.
- Slide 16 lists three national laboratory partners. Gas permeability test data from one of the national labs was presented, but data from the contributions of the other two labs were not immediately obvious from the slides. Most of the work seems to be done at the PI's institution. The project could benefit from initially reaching out to national laboratories to learn about damage/failure mechanisms in hydrogen dispensing hoses in previous funded research, and then determining how the self-healing phenomenon could address those damages/failures.
- The collaboration and coordination taking place in this project were not explained well. From the review, it is not clear whether the appropriate collaboration is in place for success.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Developing inexpensive, self-healable copolymer fiber-reinforced composites to extend the hydrogen hose service life is critical to increasing the reliability and decreasing the cost of hydrogen fuel pumping. Resolving this issue would be a big win for the Program and would have a widespread impact.
- If successful, this project would provide great impact on hydrogen storage, transportation, and fitting applications. The work is very exciting, given its potential impacts.
- The project's high-level goal of developing a self-healing hydrogen dispensing hose would have a significant impact on the overall goals of the Program through cost reduction and elimination of unscheduled maintenance. However, the approach selected to try to meet this goal, and the order of tasks, waits until the end of the project to determine whether the developed materials will be able to perform in the intended environment. As such, the overall impact of the work will not be known without testing the self-healing ability of composites formed with these polymers.
- In general, the project has identified its main goal as improving hydrogen dispensing hoses so they can survive many cycles, which is aligned with the Program goals. The project goal is to use a "copolymer matrix with Innegra™ fibers," according to slide 2. However, all the experiments were done on damaged "neat" polymer, and it seems likely that the reinforcing fibers, Innegra, are unlikely to heal if cut or damaged. Therefore, an important question arises: even if the project were wildly successful, it is not obvious that a healed copolymer with damaged reinforcing fibers would still be a viable inner lining of a hose. Some information on the type of damage in hydrogen dispensing hoses currently used would have been useful to provide the context for this work and determine the value. The project assumes that it is the inner lining that is the limiting feature of a dispensing hose. It would be useful to know whether prior DOE-funded work on dispensing hose damage can validate this assumption.

Question 5: Proposed future work

This project was rated **2.6** for effective and logical planning.

- The proposed future work appears appropriate. The proposed future work can be made far more impactful if the team immediately determines the criteria for success (defining self-healing, defining metrics for recovered properties, defining successful recovery kinetics, etc.).

- A planned demonstration of self-healing for a reinforced composite mat, including polypropylene fibers, will help to resolve concerns that these materials will either not exhibit the mechanical robustness required for the application or will not provide the same self-healing durability within a strong composite. However, additional work is necessary to understand how such a mat could be integrated into a dispensing hose assembly and whether it could operate as intended. If the hydrogen permeability of the composite mat is too high, the external casing of the hose will experience cyclic exposure to high-pressure hydrogen, eliminating any benefit that the composite mat self-healing properties could provide.
- Several proposed tasks (slide 18) seem focused on tensile testing and increasing the number of damage–repair cycles, even though (1) the tensile strength does not seem to be a required property for the inner lining and (2) the relationship between a hose's duty cycle and the level of damage are not known. Slide 17 indicates effort to install a micro-scratcher to enable repetitive cuts. Since tensile failure is not the key failure mechanism, the project can consider some other means to impart damage repetitively (e.g., fatigue loading/unloading to a fixed number of cycles, followed by permeability testing). The Innegra fibers in the matrix are an overlooked part of the equation. The project can consider demonstrating the retention of required properties if the overall composite—and not just the copolymer matrix—is damaged.
- It is not clear how these polymers will perform in composite systems. This work seems to address the matrix material but assumes that there will be no loss due to fiber damage. It is unclear if this is the expected mode of failure. An understanding of the damage and healing mechanisms is essential for long-term manufacturability, reliability, and safety. Unfortunately, the project does not appear to have a plan to gain this understanding.

Project strengths:

- This project takes a novel approach to the long-standing, difficult problem of materials failure in hydrogen dispensing hoses. The PI has demonstrated the ability to synthesize multiple self-healing polymers that can be cast as films. These formulations exhibit the ability to restore their mechanical properties after damage due to a high enough number of cycles to be relevant in hydrogen service use. In addition, the materials have been developed with an eye toward cost, and their integration into a dispensing hose assembly would be financially viable.
- An excellent scientific basis, as well as chemical and modeling analyses, has been provided for a self-healing phenomenon.
- The project appears to be progressing very nicely with regard to materials processing. This will allow the team to build a solid foundation on which to move forward.
- This is innovative and potentially game-changing work to enable low-cost, safe, and reliable hose liners.

Project weaknesses:

- This project suffers from a lack of industrial input on how the materials would be integrated into a dispensing hose assembly. The composites developed need to be assessed for hydrogen permeability, as this is crucial in understanding whether they can be integrated into a hose in such a way that the self-healing properties will provide a benefit. The project also would have benefited from earlier testing of the self-healing performance of the composite mat, perhaps after the first polymer was synthesized, to see whether the self-healing properties of the pure polymer system will translate to the composite without further modification.
- (1) It is difficult to distinguish between pre-existing work and the new work being done. (2) Self-healing is expected to maintain the inner lining's permeability, but it is not clear that permeability of the inner lining is indeed the reason for failure in hydrogen dispensing hoses. (3) It is not clear whether any damage to the reinforcing fibers will render the lining (and thus, the hose) unusable even if the matrix is able to self-heal. (4) It is not clear who is providing the cost-share on slide 3. (5) The glass transition temperature seems to be close to room temperature or near 0°C on slides 6 and 7. It seems possible that such a transition temperature would make the copolymer brittle when filling in pre-cooled hydrogen and, therefore, more susceptible to widespread damage than the total number of healing cycles to which it is being tested.
- Understanding the damage mechanisms that are seen in liners today and matching the damage mode evaluated by the project to these mechanisms will be important to realizing the project's goals. There does

not seem to be a plan to accomplish this. Understanding the role of the fiber in the composite and how the self-healing matrix interacts with the fiber is largely ignored.

- The one weakness that is recognized in the project is that the project lacks detailed explanations for important concepts of self-healing and would benefit from defining and quantifying these components of the project.

Recommendations for additions/deletions to project scope:

- The project should clearly demarcate pre-existing work (experiments, modeling) from new work. Although self-healing in general is a very desirable material property for engineering applications, the project should focus on identifying the weak link in the hydrogen dispensing hoses and determine whether self-healing of the polymer matrix is the right property to be addressed.
- The project scope should be expanded to examine the hydrogen permeability of the composite polymer mat compositions. A commercial hose supplier should be added to the project team to assess whether additional materials property testing is required to meet the technical specifications necessary for dispensing hose integration and full commercialization.
- The team should consider focusing more on gaining a fundamental understanding of the damage and healing mechanisms. It will be difficult to gain the trust needed for code development and market penetration without a fundamental understanding of these mechanisms.
- The team would benefit from defining several key metrics that can help to direct the project moving forward.

Project #IN-021: Microstructural Engineering and Accelerated Test Method Development to Achieve Low-Cost, High-Performance Solutions for Hydrogen Storage and Delivery

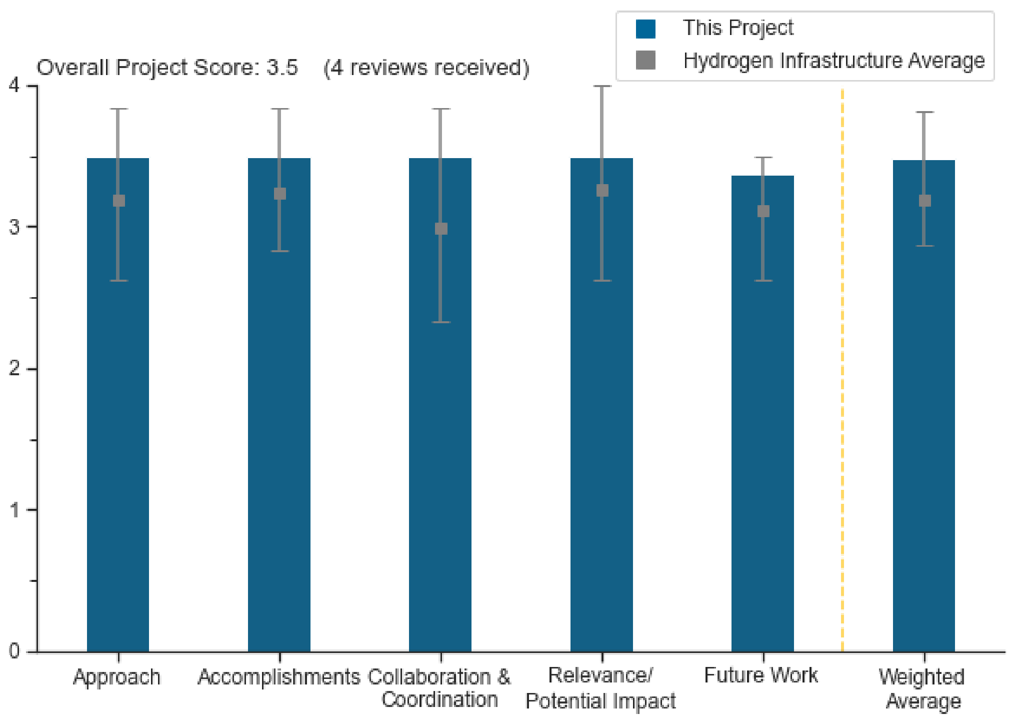
Kip Findley, Colorado School of Mines

DOE Contract #	DE-EE0008828
Start and End Dates	2/1/2020 to 2/28/2023
Partners/Collaborators	Los Alamos National Laboratory, National Renewable Energy Laboratory, WireTough Cylinders, LLC, United States Steel Corporation (U.S. Steel), General Motors Company, Hydrogen Materials (H-MAT) Consortium, Chevron Corporation, POSCO
Barriers Addressed	• Reliability and costs of gaseous hydrogen compression • High as-installed cost of pipelines • Gaseous hydrogen storage and tube trailer

Project Goal and Brief Summary

This project aims to use novel microstructural design techniques to develop lower-cost, high-performance steel alloys for use in hydrogen refueling infrastructure. The project will also develop and validate accelerated test methods for efficiently evaluating variations in alloy and microstructure design, enabling broader accessibility and lower-cost testing in hydrogen environments. The work could accelerate the implementation of hydrogen fueling infrastructure.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project clearly presents two objectives: (1) developing lower-cost steel alloys for use in hydrogen refueling infrastructure and (2) developing and validating accelerated methods to lower the cost of testing in hydrogen environments. These objectives focus on recognized barriers related to structural materials in hydrogen fuel infrastructure.
- The work provides very useful potential in development of infrastructure and acceleration of test methods to efficiently evaluate variations in alloy (austenitic steels [POSCO and commercial stainless steels]) and microstructure design to enable broader accessibility and lower-cost testing in hydrogen environments.
- There is a sound approach to the work. Comparison between electrochemical and gas in situ charging may be a little narrow, but it is a good first step toward being able to compare results from most labs that are able to do electrochemical and the few labs that have gas in situ testing capabilities. Going forward, it would be good to see a little more emphasis on the microstructure of the various steels—and specifically on enumerating the similarities and differences between them and how those may affect the steels' performance.
- The principal investigator (PI) nicely outlines the objectives and the approaches used to achieve these objectives. This is particularly true for the first two materials development tasks. The knowledge gaps and uniqueness of the third effort (the linking between electrochemistry and hydrogen charging) is less well-developed, and it is not clear that the approaches are going to provide clear insights. The fatigue crack growth testing methodology development is interesting but seems disjointed from the rest of the project.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project formulates a clear and reasonable series of goals and milestones related to the two primary objectives of alloy development and materials test method development. The reported accomplishments represent progress toward these stated goals and milestones.
- The work on cost-effective austenitic steels (stainless steels) has great potential for design and construction of pressure vessels and pipelines that are suitable for hydrogen embrittlement performance of austenitic steels and lower-cost ferrite–austenite alloys that have intermediate hydrogen embrittlement performance, i.e., between austenitic stainless steels and lower-alloy ferritic steels.
- Progress is reasonable, given that it is early in the project and especially considering barriers due to the pandemic. Preparation work has been performed in designing and fabricating the alloys.
- Considering the effects of the pandemic on the last year, reported progress is excellent.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The industrial involvement is solid. To date, it does not seem like all of the benefits have been fully realized. This is simply due to the stage of the project; the feedback loop and early engagement with steel producers will ensure that candidate alloys are scalable and cost-effective.
- Great collaborations have been established with a number of highly qualified laboratories, industries, and institutions that will be essential in achieving the goal.
- The project is productively engaging with its partners to accomplish goals and milestones. One notable example is the relationship with U.S. Steel, which is producing experimental alloys that are designed to meet cost and performance targets.
- It looks like collaboration and coordination will increase as recovery from the pandemic continues, and it seems that the amount of collaboration, while good at the moment, will improve as the project moves forward.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The research and development relating to high-strength austenitic steels and commercial stainless steels could be a breakthrough for efficient and reasonable-cost pressure vessels that are used in delivery and storage of gaseous and liquefied hydrogen.
- The potential impact will depend largely on the ability to make a cost-effective alloy that meets the design criteria. (The PIs should be cognizant of how the data were collected with regard to the loading rate and that other important parameters will have strong impacts on the results.) Growth kinetics, other metrics of susceptibility to environmental degradation, and other property variations should be incorporated (and the PI has stated that the team plans to account for these). The impact and potential for success of the testing methods is questionable.
- This project aligns directly with the DOE Hydrogen Program's (the Program's) need for lower-cost materials that meet performance requirements in hydrogen service.
- The relevance to the Program goals is clear. The potential impact to relevant industries, if the project is successful, is clear. The relevance to the wider hydrogen embrittlement/testing community could be greater, though that would require expanding the scope of work. For example, while the current plan will allow comparison between the electrochemically charged and gas-charged in situ results with the specific sharp-notched sample geometry, it is not clear that it would be relevant for other conditions, which would be of great interest to the wider hydrogen community. However, extensive study beyond the stated scope of this project would be needed to answer that particular need.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The proposed future work extends reported accomplishments and is consistent with the milestones and goals outlined for the project.
- The proposed future work shows a clear path forward.
- The results of Year 2 of this ongoing project will determine the potential for expanding the project to Year 3.
- The work is in its infancy, so future work will just execute the proposed work. Statements of the remaining challenges are broad, vague, and weak.

Project strengths:

- The current project for Year 1 and testing protocols provide potential for development of an accelerated testing for austenitic steel and commercial stainless steels that are suitable pressure vessels or pipelines that provide adequate strength and ductility for resisting hydrogen embrittlement. The highlight of this project is the development and implementation of an "electrochemical hydrogen charging setup utilized to evaluate fracture toughness of steels in the presence of hydrogen-containing environments."
- The alloy design strategy has a sound technical basis for its performance target, i.e., stacking-fault energy. The active roles of partners such as U.S. Steel, the National Renewable Energy Laboratory, and Sandia National Laboratories enhance the prospect that results from this project can have impacts on technology and concretely advance Program goals.
- Project strengths include collaboration with industry partners, logical material design strategy, and building on well-known literature to improve hydrogen embrittlement resistance by modifying stacking-fault energy.
- There is a strong technical metallurgical approach to solving a clear engineering problem.

Project weaknesses:

- This is somewhat of an informed Edisonian alloy design strategy with disjointed alloy design and testing efforts, and it is seemingly weak on determining knowledge gaps and a plan to address the electrochemical/hydrogen charging issues.
- The project needs to reduce the cost and speed the testing in Year 2, which will be a major factor in whether to continue the project.
- It is not clear that activities associated with partners Los Alamos National Laboratory (LANL) and WireTough Cylinders, LLC (WireTough) align with project goals. The need for permeation experiments at LANL to meet the two project objectives (alloy design and accelerated test method development) has not been demonstrated. In addition, the implication is that WireTough may consider the alloys developed in the project as alternatives to the incumbent liner material (A372 Grade J) in Type 2 pressure vessels. From a cost perspective, the idea that the highly alloyed steels proposed in this project could replace the A372 Grade J may not be realistic.
- More basic science aspects, such as neutron scattering analysis to determine mechanisms, feel tacked on to the project. If the project is successful, good insight could be obtained, but as presented, it has the feel of "Let's try it and see what we get."

Recommendations for additions/deletions to project scope:

- This project should continue with a new objective and goal to use the resources and strength toward the selection of new cost-effective austenitic steels (commercial stainless steels) that are suitable for delivery and storage of high-pressure gaseous and cryogenic hydrogen.
- Fatigue efforts seem tangential. Improvements to the electrochemical/hydrogen charging evaluation approaches are recommended.
- It is recommended that the project critically evaluate the roles for LANL and WireTough in the project.

Project #IN-022: Tailoring Carbide-Dispersed Steels: A Path to Increased Strength and Hydrogen Tolerance

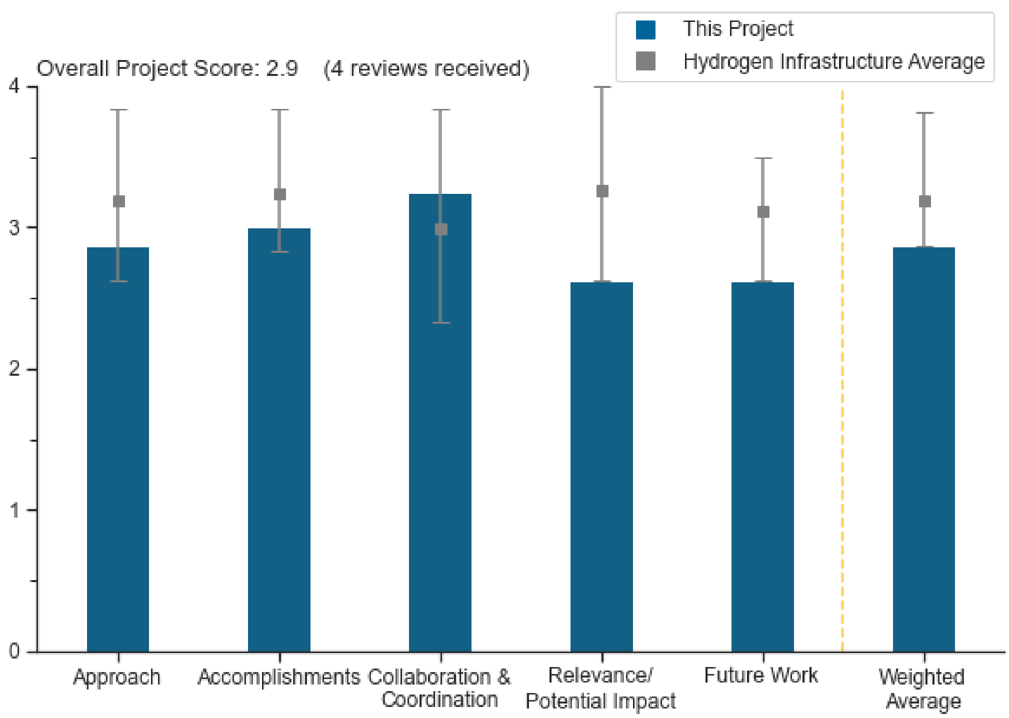
Gregory Thompson, The University of Alabama

DOE Contract #	DE-EE0008831
Start and End Dates	1/7/2020 to 1/31/2023
Partners/Collaborators	Colorado State University, Exothermics, Inc., Ames Laboratory, Army Research Laboratory, Hydrogen Materials (H-MAT) Consortium
Barriers Addressed	• Identification of the most sustainable transition metal carbides for a hydrogen trapping mechanism • Uniform dispersion of the trapping carbide particles • Forming metal-rich-carbide (hemicarbide particles)-dispersed steel alloy • Achieving the required compact steel alloy while retaining the target phase structure

Project Goal and Brief Summary

This project is developing a new carbide-dispersed austenitic/ferritic steel for hydrogen storage and dispensing. The alloy will have higher strength and hydrogen tolerance, which will increase the service life of hydrogen storage equipment, facilitating the expansion of hydrogen infrastructure while reducing its cost and environmental impact.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project addresses a critical need within the hydrogen technology community. The novel approach to avoid hydrogen embrittlement is well-thought-out and combines experimental and modeling approaches to the best use of both. There is a practical team in place to provide the input necessary to allow this technology, if successful, to transition to commercial use. The only potential gap in the approach is that long-duration hydrogen exposure experiments may be necessary to determine whether the hydrogen sequestration sites developed will become saturated and what effect this will have on the steel's mechanical strength (the presentation did not address the duration of proposed experiments).
- This project feels high-risk, high-reward. If successful at creating results and discovering how to transfer these results to conventional structural materials, this project could prove a fantastic advance in design. Otherwise, some fundamental science may be advanced, but the application will be minimal.
- The project proposes a combined experimental/first principles computation approach to disperse transition metal nano-carbides in ferritic/austenitic steels in order to improve hydrogen embrittlement and strength. The applications are directed toward hydrogen storage and hydrogen dispensing. The main thesis of the project is that the insertion of carbide nanoparticles in a steel microstructure increases the resistance of the alloy to hydrogen embrittlement. The idea is drawn from a similar approach to use oxide dispersoids to strengthen creep resistance of metallic alloys. Two critical barriers—the need for increased notched tensile strength and the need for high-yield strength—have been identified, but there is no specific quantitative objective. For instance, in the case of stationary gaseous hydrogen storage or dispensing, there is no reference to operating or refueling pressures at which these carbide-incorporating microstructures—achieved through powder metallurgy—are aimed. The statement that the proposed steel microstructures will have "comparable or better fatigue strength" is vague. There is not even a single reference or motivation in the proposed plan as to how dispersed carbides will bring about "better fatigue strength," specifically in the presence of hydrogen. The project uses density functional theory (DFT) to identify the most effective stoichiometric and non-stoichiometric carbides in trapping hydrogen, and the team will then use powder metallurgy to disperse the most promising carbides in a metal matrix. However, metrics of what constitutes promising carbides are not referenced. In the end, the project will use atom probe tomography to identify the location of hydrogen in the carbides. Incidentally, the project does not mention how it will quantify the overall trapping capability and distribution of the carbides because, in the end, it is this capability and density of the carbides that matter vis-à-vis resistance to degradation.
- It is not apparent why it is necessary to develop carbide-dispersed steels (CDSs) with optimized hydrogen trapping characteristics since the project does not identify the shortcomings of incumbent technologies or how the proposed solution represents an advancement. For example, it is unclear whether the incumbent SA-372 Grade J steels in the stationary hydrogen storage vessels are inadequate in their cost or performance or whether the CDS alloys can be demonstrated as the solution to such shortcomings. It is also not clear that the cost or performance of incumbent Grade 316 stainless steels in hydrogen distribution systems is a barrier to the deployment of refueling stations—or that the CDS alloys are a potential solution to this barrier.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The principal investigators (PIs) have demonstrated significant progress toward their stated goals, including developing multiple practical approaches to producing test samples. Future experiments will determine how effective the proposed solution is and how broadly applicable, but all tasks to date have been successful.
- The researchers made good decisions to maximize modeling and planning with collaborators during the limited-lab-access period due to COVID-19. The early stages have clearly been picking up speed as access has opened.
- DFT calculations were used to establish trap-binding energies for a number of stoichiometric and non-stochiometric carbides with calculated energies ranging from 10 to 100 kJ/mole. Interestingly, the

calculations indicate that as hydrogen is filling out the trap sites of a titanium carbide, its trapping capability reduces; in fact, it reduces drastically, as shown in the figure on slide 8. In addition, DFT calculations have been set to explore the activation energies for diffusion in the carbides. In summary, although trap-binding energies have been computationally determined, there has not been any reference to how such binding energy magnitudes underlie the project's goal, which is the mitigation of hydrogen embrittlement. On the experimental side, sufficient progress has been reported on dispersion and sintering of Fe with ZrC, ball milling of Cr into solution, and a route of rapid spark plasma sintering (SPS) dispersing of ZrC nanoparticles in Fe and 304L stainless steel. In general, within the project scope of developing carbide-strengthened microstructures, the project has made sufficient progress, in collaboration with the NASA Ames Laboratory SPS project.

- It is not clear how the performance indicators for the project were established. For example, the apparent metric for optimizing the hydrogen-trapping characteristics of the CDS is trap-binding energy exceeding 75 kJ/mol. An explanation is needed as to how this value was determined. In addition, trapping characteristics depend not only on binding energy but also on trap density, but it is not clear how trap density is being considered in the objective to optimize hydrogen-trapping characteristics. Other performance indicators are maintaining 95% of the notched tensile strength after hydrogen charging and yield strengths above 500 MPa. It is not clear how these performance indicators were established, particularly in the absence of any reference to incumbent technologies.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The PIs have assembled an excellent team with the right mix of expertise in fabrication, modeling, and property testing of materials. The team also includes multiple potential end users, including commercial end users, to ensure their input in the development process and to increase the chances of transitioning to becoming commercial if the approach is successful.
- The relationships with Ames Laboratory, Exothermics, Inc., NASA, and Sandia National Laboratories appear productive. Hydrogen technology stakeholders, such as Praxair, must be engaged to ensure the project is designed to address particular barriers and is guided by relevant performance indicators.
- For the experimental approach of carbide dispersing in Fe and austenitic matrices, it seems that the collaborations with Ames Laboratory, Exothermics, Inc. (processing through hot isostatic pressing), and NASA are effective and serve as a solid pathway for the project to synthesize the microstructures it promised. The computational aspects of the project seem to be uninformed of the existing understanding of hydrogen interactions with vacancies and carbides.
- It seems that the project's collaborations experienced limitations due to COVID-19, moving focus toward in-house activities. Future work appears to use collaborations heavily, which looks promising for producing progress.

Question 4: Relevance/potential impact

This project was rated **2.6** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- If the approach to reducing hydrogen embrittlement is proven successful experimentally, the impact could be significant. The approach, as detailed, should provide conclusive answers in the second year of the project. It remains to be seen how broadly applicable this technology can be; if the hydrogen sequestration sites quickly become saturated, hydrogen embrittlement may still occur. That said, there may still be short-term exposure applications (i.e., compression and dispensing) that could make use of the technology even if the protection from embrittlement is transient.
- Again, because this appears high-risk, high-reward, the potential impact is high if good results are achieved and processes to apply results to industrially relevant materials are found. The current status suggests less impact in the short term.

- Given the absence of references to incumbent technologies, it is not clear what impact the project will have on DOE Hydrogen Program goals and objectives. Specifically, it is not clear how the project will reduce costs or improve performance relative to incumbent technologies.
- The project addresses a classic and thoroughly investigated aspect of hydrogen embrittlement, namely, the trapping of hydrogen at microstructural defects. However, the trapping of hydrogen mainly affects the amounts and the spatial and temporal distribution of hydrogen in the material. Specifically, with the proposed carbide-dispersed-strengthened steel, the project's outcome may be that it can deliver carbide-strengthened steels in which hydrogen is all trapped at carbides and no hydrogen is available in the rest of the lattice to initiate embrittlement. However, this mitigation strategy needs to be analyzed relative to specific and targeted closed-system applications. It does not work for open systems in which hydrogen uptake is continuous.

Question 5: Proposed future work

This project was rated **2.6** for effective and logical planning.

- The team has outlined a solid plan to provide experimental evidence that the modeling work will translate to significant material property gains. The only additional work that may be required is long-term hydrogen-exposure testing to ensure the durability of the approach.
- Clear steps forward have been lined out to next steps, though not to long-term goals. "Discussions under way with industry partners," is a good statement but does not necessarily give concrete steps forward. The characterization techniques were not as clearly laid out in the presentation (although there were some answers in the question-and-answer period). Emphasis on the atom probe feels like the team is emphasizing the in-vogue technique, while ignoring other techniques that could provide the researchers with good characterization information (thermal desorption spectroscopy [TDS], diffraction analysis, and electron energy loss spectroscopy [EELS] in a transmission electron microscope are a few that come immediately to mind).
- The proposed work on phase stability of the carbide-rich microstructures and the tailoring of the carbide composition are reasonable next steps. However, what is missing is how and why these efforts relate to hydrogen embrittlement mitigation. Perhaps the project aims to determine whether martensite will precipitate under operating temperature or hydrogen-related conditions. If that is the case, it is not clear how such understanding affects the overall scope of the project. An interesting aspect of the project is the identification of hydrogen-trapping sites using atom probe tomography (APT), which is seen as the most important outcome of the project for its scientific value. Unfortunately, no reference to the DFT efforts is given, nor to the pathways that will be undertaken to relate atomistic insights with the APT results.
- No milestone list or project roadmap was presented, so it is not clear how the proposed future work represents a progression toward project goals.

Project strengths:

- This program has a very strong, well-rounded project team. The balance of modeling with experimental demonstration of theoretical results is excellent. The early success demonstrating the ability to formulate the desired compositions bodes well for the ability of this project to conclusively demonstrate the potential efficacy of the approach.
- The strength of the project is its experimental component. The development of carbide microstructures that are well-characterized relative to particle distribution, shape, size, grain boundary size, and structure may lead to potential ferritic or austenitic microstructures that are worth testing at Sandia National Laboratories and worth comparing with other existing microstructures.
- The coupling of modeling and experiments is a promising route toward more effective alloy design.
- This project has an innovative approach, and potentially, good fundamental science could result from this study.

Project weaknesses:

- The trapping of hydrogen at microstructural defects has been thoroughly investigated in the past 50 years, and its importance is recognized in its effect on the spatial and temporal hydrogen distribution in a component. The range of the carbide-trapping binding energies the project reported through DFT calculations is not at all different from those reported in the review article by Hirth (*Metallurgical Transactions A*, 1980, 11A, pp. 861). In addition, for an open system, trapping sites eventually saturate; in fact, they saturate very fast in ferritic systems, and eventually hydrogen becomes available at fracture initiation sites. Hence, the relevance of this project can be sought in the case of closed systems operating under known conditions of temperature and hydrogen content. Under such conditions, the project's outcome may be that it can deliver carbide-strengthened steels in which hydrogen is all trapped at carbides and no hydrogen is available in the rest of the lattice to initiate embrittlement. In fact, even this proposition needs to be carefully ascertained with regard to hydrogen effects in the carbide or the carbide–matrix interface. Definitely, hydrogen dispensing involves an open hydrogen system, and it seems unlikely that the proposed carbide mitigation strategy will not work. As for hydrogen storage, the proposed carbide strategy will depend on the hydrogen pressure and carbide distribution, but these aspects are not addressed as fundamental ingredients of the project. Another important aspect of the project is the nature of the carbide–matrix interface, which seems not to have been taken into account when the project was designed and proposed. If the carbides are incoherent, Tsuzaki (e.g., in "Effects of Hydrogen in Materials," *Proceedings of the 2008 International Hydrogen Conference*, pp. 448-455) has demonstrated in the case of TiC that these carbides do not trap hydrogen at room temperature, which may imply that the value proposition of the project is called into question since hydrogen embrittlement is of concern at room temperature. On the other hand, if the carbides are coherent or semi-coherent and trapping takes place at the interface at room temperature, it does not seem likely that interfacial trapping at room temperature will bring about any new mitigation strategy for hydrogen embrittlement. Furthermore, if the project is aiming at incoherent carbides (Mrovec et al., *International Journal of Hydrogen Energy*, 45, 2020, pp. 2382–2389) and trapping within the carbide vacancies, the project needs to address the activation barriers for vacancy trapping (Di Stefano et al., *Physical Review*, B 93, 184108, 2016) and how these barriers affect the overall scope of the project at room temperature. Lastly, it seems that the PIs have placed the emphasis on the binding energy. It is not clear how they plan to assess hydrogen embrittlement in relation to the density and distribution of the nano-carbides.
- The novelty of the approach to reducing hydrogen embrittlement under investigation leaves many potential unknowns yet to be proven out. Even if the sequestration approach is effective, with thermodynamic equilibrium dominating the hydrogen interactions, the sites able to sequester hydrogen may quickly become occupied and limit the overall impact. In addition, the industrial-scale cost of fabricating steel utilizing the techniques developed so far has not yet been evaluated but is likely to be a significant premium over the current processes.
- This project has the flavor of a solution seeking a problem. Without well-defined barriers related to the cost or performance of incumbent technologies, it is not apparent that there is a tangible problem whose solution resides in the objectives of this project.
- There is no clear path to the applications.

Recommendations for additions/deletions to project scope:

- The premise of this project is that hydrogen embrittlement resistance of steels can be improved through tailoring the trapping characteristics of transition metal carbides. In most cases, this concept applies only to closed systems in which materials subjected to stress contain a fixed hydrogen concentration. For fixed hydrogen concentration, benign traps with high binding energy and high density can deplete hydrogen from metallurgical sites that serve to activate hydrogen embrittlement. However, the materials in hydrogen containment components are effectively open systems, as the materials are subjected to stress and are exposed to an infinite hydrogen source. In this case, the hydrogen concentrations at all trap sites are in equilibrium with the hydrogen gas, so traps with high binding energies are not scavenging hydrogen from sites with low binding energies. For this reason, the target of maintaining 95% of the notched tensile strength after hydrogen charging will be misleading for the performance of the CDS in an open system. One property that may benefit from trap-site engineering in an open system is hydrogen-assisted fatigue crack growth rate, since this may scale with the effective hydrogen diffusion coefficient. It is recommended that the project not focus on notched tensile strength as a performance target but rather pursue the prospect that trap-site engineering can reduce effective hydrogen diffusivity and, therefore, affect hydrogen-assisted fatigue crack growth.

- It will be interesting for the project's APT effort to identify the magnitude of the hydrogen concentration in the lattice next to the carbides and that in the carbide or at the carbide–matrix interface, if there is such interfacial trapping (Takahashi et al., *Scripta Materialia*, 67, 2012, 213–216). Another important issue is the determination of the nature of the carbide–matrix interface because, as is discussed in the section on overall project weaknesses, it governs the trapping capabilities of the carbides. The computational component of the project needs to identify the activation barriers for hydrogen trapping in the carbides specifically at room temperature and by accounting for the nature of the interface. It is important that the results be validated experimentally. Calculated binding energies as shown on slide 7 are conventional and do not hold promise for mitigation, especially for open systems. Within the framework of the project, the density and distribution of the carbides also need to be determined, as they both affect the hydrogen populations and diffusion paths.
- If the approach proves successful in avoiding hydrogen embrittlement, the team should add long-hydrogen-exposure testing to the project to understand whether the effect is permanent or transient—and on what timescale.
- The characterization feels lacking. The project needs someone with strong credentials and access to good and varied capabilities to fully characterize the carbides and interfaces, not just cursory checks.

Project #IN-025: Hydrogen Delivery Technologies Analysis

Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	3.4.0.1
Start and End Dates	10/1/2005
Partners/Collaborators	Energy Technology Analysis, U.S. DRIVE Partnership
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools • Stove-piped/siloed analytical capability for evaluating sustainability

Project Goal and Brief Summary

This project aims to evaluate the economic and environmental costs and benefits of hydrogen fuel and fueling infrastructure. Researchers will analyze various hydrogen technologies throughout their lifecycles and identify the technologies with the highest cost-effectiveness and lowest environmental impact. Argonne National Laboratory's (ANL's) Autonomie Team is collaborating with Energy Technology Analysis, the U.S. DRIVE Partnership, and other industry partners on this project.

Project Scoring

The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach this presenter took focused on how the team evaluated the impacts of various approaches for hydrogen delivery and the selection of hydrogen refueling station (HRS) components using models. The presenter explained the economic assumptions, after identifying the objectives of the project and the critical barriers, such as consistent data, assumptions, guidelines, tools, and capabilities for analyzing sustainability. When this presenter explained the team's evaluations of the overall fuel cell electric vehicle (FCEV) cost and energy storage for the fuel, he described output from the Hydrogen Delivery Scenario Analysis Model (HDSAM) and suite of models. The approach is strong and believable, given that ANL updates and harmonizes these models with other U.S. Department of Energy (DOE) models, i.e., Hydrogen Analysis (H2A) and Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET). To overcome insufficient data (a barrier) and prepare the models for use with emerging applications, such as refueling of medium-duty (MD) and heavy-duty (HD) FCEVs, ANL developed the Heavy-Duty Refueling Station Analysis Model (HDRSAM), which is used worldwide by thousands who seek to evaluate the cost of hydrogen refueling for various fueling station configurations and demand profiles. HDRSAM remains unique and is the only model of its kind that is available in the public domain. This way, DOE and the public have a consistent set of tools that are harmonized in their assumptions and thus overcome the barrier of stove-piped/siloed analytical capability for evaluating the sustainability of hydrogen delivery approaches and hydrogen dispensing based on the selection of components. The approach is valid in that it links technical, economic, and environmental performance to identify opportunities and challenges for different hydrogen supplies and refueling station components and various station costs (i.e., capital, operating, and energy). The project is very well-designed and also practical. The presenter explained that, for delivery options, the HDSAM scenario and delivery cost are evaluated over a wide set of options. Because of the wide set of scenarios, a user of the model can evaluate a variety of delivery options without investing in any one particular option. A user can evaluate regional power options, for example, without making an agreement with the power provider, and the user can examine greenhouse gas (GHG) emissions using HDSAM using different approaches to producing hydrogen, prior to any actual investment in the technologies for low-carbon pathways. The evaluation and assessment approaches, the presenter explained, are already proven, and using the model is feasible for numerous applications. The project approach also integrates a lifecycle analysis of GHG emissions for various transmission and distribution (T&D) options used for hydrogen. Since T&D is very expensive and often represents the bulk of a project's cost, this approach addresses a key part of the hydrogen value proposition.

- The scope of this project is timely and relevant to the deployment of HD vehicles such as Class 8 fuel cell electric trucks (FCETs). Furthermore, DOE's investment in this project highlights the importance of HD transportation in achieving the national goals to reduce emissions and decarbonize the transportation sector.
- The project meets its intended goal of providing technical, economic, and environmental analysis of hydrogen markets.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project contributes to the DOE focus area of cost drivers. The project facilitates the ability of a wide audience of people who use HDSAM and HDRSAM to provide input to DOE so that the agency knows where to focus future DOE projects so that those projects can resolve challenges identified by the user community. For example, the models are "decision-making tools" for the user community to test out advanced low-/no-carbon pathways without investing in plants or informing competitors or suppliers. Additionally, the models cut research and development (R&D) costs for the private sector since those stakeholders can run the models, without investing in technologies and systems, to pre-determine the best opportunities for their firms. Those stakeholders can also minimize the risk of not knowing about the costs of particular hydrogen production and hydrogen refueling investments. The presenter explained that the models provide predictive tools that help the user community gain traction on their advanced applications for hydrogen and fuel cells, another stated goal of DOE. Those who use the models and provide results via an input form to DOE can assist the agency with its plan to focus on areas of research that are needed for the more advanced hydrogen technologies to gain traction. DOE has stated in this Annual Merit Review (AMR), as well as in previous AMRs, that the agency wants help and input on its projects, and HDSAM and HDRSAM provide ways for the user community to learn of the opportunities and pitfalls of hydrogen and fuel cell projects, which they can then report to DOE in a standardized approach. Those who use the models can also provide feedback to DOE on how to make the models better in terms of usability.

- The preliminary findings and costs associated with low-pressure liquid hydrogen (LH2) appear promising. These could drastically reduce the fueling infrastructure capital and operational costs, including those for high-flow fueling, which requires large quantities of precooled hydrogen for back-to-back fueling. However, understanding the state of the art, availability of LH2, and system reliability will be crucial to the feasibility of these approaches.
- The project provides analysis that is useful for companies aiming to understand the hydrogen pathway options, some of which are not intuitive. The barriers are clearly stated, particularly with regard to obtaining accurate data. Despite the attempted validation work with industry, it is still not clear that this information is accurate since companies are likely to hold certain information proprietary. The project would benefit from clear objectives that can flow down from the overall goal. It is not clear what sets the individual tasks in a given year. For such a long-term project, charting out objectives and pathways over multiple years would provide a better roadmap and a way to gauge progress.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- When explaining how the team collaborates and coordinates with other institutions in the area of hydrogen and FCEV technology feasibility, the presenter mentioned that non-disclosure agreements are signed, as needed. This approach builds trust and confidence. When asked about the partners already participating in this project, the speaker mentioned the U.S. DRIVE Hydrogen Interface Taskforce (H2IT) and ANL's Autonomie Team, among others. When asked about hydrogen blending in natural gas pipelines and whether the models will be applied to this area, the speaker mentioned coordination with the related DOE consortia, which are focused on pipelines. The presenter convinced the audience that the team does not work in a vacuum but rather relies on input from others in the public and private sectors. The presenter described the benefits of the collaboration and coordination in highly practical terms: "We do this with others." This message instilled credibility in the 2021 AMR audience.
- A comment was made that there is industry input, but it would be helpful if more information could be shared regarding industry participants to better answer this question. Some of this information is better supplied from individual sources rather than from organizations where it might get watered down and become more general.
- The collaboration relies heavily on literature and published work but could benefit from direct end-user input. Unfortunately, much of the data available for high-capacity onboard storage are for buses with 350 bar systems, which are much less technically challenging and require less precooling than 700 bar, Type 4 tanks. A great portion of this work could inform the anticipated deployment of high-capacity HD HRS. More engagement and collaboration with key stakeholders could help direct this work toward current challenges with HD fueling infrastructure.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project advances DOE goals to provide R&D that supports HD applications for fuel cells. The degree to which this project advances the DOE Hydrogen Program (the Program) is very high. This project provides comparisons of well-to-wheel GHG emissions of different hydrogen production technologies, including varying blends of hydrogen produced via steam methane reformation, and compares these to diesel used in HD fuel cell applications. Industry is currently attempting to conduct the same comparisons for investment decisions. When describing the outcome and evaluations of using the models, the presenter showed side-by-side comparisons that evaluated investments in the technologies for hydrogen production systems. The presenter demonstrated how one can remove the guesswork from investment decisions. As in the private sector—and most likely before the private sector—the DOE commitment to support the related R&D can focus on where the hydrogen technology/systems are predictably most beneficial. Both public- and private-sector focus and investment can result in an informed plan. This project advances DOE's stated Program goal, and those supported by its subprograms, of $1.5/kg of hydrogen in one decade by helping the overall agency decide where to focus its commitment on R&D in hydrogen and fuel cells. These likely represent the goals of industry, also, since DOE and industry use the same models and share their results.

- This project clearly aligns with the goals of the Program. The outcome from this project will directly inform industry on multiple HRS design options and further assess the impact and GHG reduction of various production paths.
- The project is aligned with DOE objectives to demonstrate the effectiveness of hydrogen to lower GHG emissions.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The presenter explained the iterative process, which includes heavy stakeholder participation in determining the selection of future technologies on which to focus. The presenter explained the team's plan for future work in terms of the continual ("organic") process the project uses to address new technologies and to integrate those technologies into models. For example, HDRSAM for MD and HD FCEVs was developed only three to four years ago, and presently, the model is expanded to include new technologies such as LH2 onboard storage, including its impact on fueling costs. The MD and HD FCEVs were only starting to emerge three to four years ago, yet the model included them when they were still emerging. An argument could be made that DOE's future-proofing of this model could have contributed to the emergence of that industry. For a second example, many industry stakeholders are interested in hydrogen storage on board vehicles, and the presenter covered the influence of the hydrogen supply method (gaseous or liquid) on the cost of onboard storage. DOE may also need to expand the model to examine future applications such as rail, aviation, and marine, as was mentioned. Additionally, issues related to large-scale hydrogen export terminals will need to be added to the model, as this is another area of stakeholder interest. The presenter mentioned that the research team is in the process of adding hydrogen pathways in the GREET model for rail applications that use hydrogen fuel cells, with funding from the U.S. Department of Transportation. Additionally, the energy associated with hydrogen delivery and fueling is needed. The presenter mentioned that that can be sourced from expanding HDSAM/HDRSAM to incorporate those data and that information in GREET. The presenter explained that the team members either develop new models or expand existing models as the need arises to address new and emerging technologies and applications that are not in the current models. The previous scope of the models and the need to update for new and emerging issues was presented.
- The future work is appropriate, with the exception of further work on the economics of LH2. The analysis to date is sufficient. It would be good to see a longer-term horizon of future work and what constitutes the remaining 30% of the project. The costs listed on slide 13 are thematically correct, but it is surprising to see that gaseous hydrogen delivery does not get less costly than LH2 out to 500 km. This seems excessive, which makes me question the basis of the cost model.
- The future work could expand on more challenging fueling profiles. The 350 bar and Category D fueling scenarios are relatively limited. A more aggressive look at high-flow-fueling challenges can best inform industry on associated costs of high-flow fueling. In addition, a more detailed assessment of liquefaction costs at scale, impact on the environment, and available capacity and LH2 outlook could be of value, as HD vehicles are starting to roll out and are expected to displace diesel trucks in the next 15 years.

Project strengths:

- The overall project strengths include its contribution to the goals that Ned Stetson presented at the 2021 AMR, when he gave an overview of the cost drivers on which the projects focus, i.e., production, components, storage, and fueling stations. This presenter explained how the models can be used over a wide range of scenarios and that, when the scenarios become refined with experience, they can focus specifically in areas of importance. Evaluations can be run affordably prior to investment and commitment of time and money. This pre-planning through modeling saves resources, which drives down costs. Another strength of the models presented is their usefulness in evaluating the costs of HD FCEV fleets. Much of the cost of such fleets remains important in the investment decisions, such as which station capacity to use, which size of refueling components to use, and what really influences the overall cost of a fleet operation.

The answer to the latter could be the fueling cost, the station capital expenses, operating costs, energy costs, or cash flow.

- This project is working in an area of high importance for the successful rollout of hydrogen. Understanding the economics and demonstrating the best pathways will be helpful to those considering this technology. The future work proposed is all pertinent, especially the fueling protocol work for MD and HD vehicles. The material generated is useful for setting policy and goals elsewhere within DOE and at a high level.
- This project team is well-known in the field. This team has demonstrated knowledge and capabilities for this project to be successful and impactful; the assessment tools developed by ANL, the insight from U.S. Drive, and the direct input from industry are critical to the output of this project.

Project weaknesses:

- It would help if there were a clear pathway for this analysis to potentially affect codes and standards (C&S). It was mentioned that sometimes fueling protocols can be conservative, but the project should evaluate how it might influence the C&S in a more economical direction. The information and details will not likely be useful to industry at a detailed level to make decisions. The market will decide the successful pathways based on real-world economics. The project needs a feedback loop after several years to understand the accuracy of its analysis. It is time to chart a pathway to completion of the project over the next several years and then initiate a new project(s) as needed, with better-defined goals and objectives.
- From a broad perspective, the models appear to take a long time for users to learn how to use them adequately, although it appears possible to use the models without any background or training, and the investment in learning appears to be justified since the investments in hydrogen and fuel cells are typically high. Perhaps this is an overall project weakness. It would probably be useful to add comments to the presentation of the project about the learning curve for effectively running the models, recommended training for running the models, and online training/coursework that is available to start to learn how to use the models. Additionally, the models could possibly be enhanced with artificial intelligence to make them easier to run and even more "automatic." If the models become easier to use, perhaps they could become more influential and drive the cost of hydrogen production and use down because questions about the value chain, GHG reduction, and the breadth of the opportunity to use hydrogen can be addressed.
- This project has strong partners and expertise. The project scope, however, could benefit by expanding into real-time challenges with HD fueling and high-flow infrastructure.

Recommendations for additions/deletions to project scope:

- It is recommended that information be provided on the potential to reduce (1) the cost due to the high level of expertise presumably needed to run the models and (2) the level of expertise required to run the models. In the agency in which this reviewer works, staff read the output from these models and use that output but do not typically invest the time to learn how to use the models, per se. It seems better to be self-reliant and learn how to use the models. Staff have suggested adding these reductions to the project scope. It is also recommended that time be put into the graphics to simplify them and to connect them directly to the areas of focus presented by Ned Stetson at the 2021 AMR. These recommendations do not take away from the excellent and outstanding ratings given here to the presenter and the work of the presenter. This work is invaluable and helps many people.
- The LH2 work is interesting, but it is not clear that there is much benefit to pursuing this further. Companies are building additional LH2 plants, including some with green pathways. This project will not directly influence those plans.
- The project scope could benefit by expanding into real-time challenges with HD fueling and high-flow fueling infrastructure.

Project #IN-026: Tailoring Composition and Deformation Modes at the Microstructural Level for Next-Generation Low-Cost, High-Strength Austenitic Stainless Steels

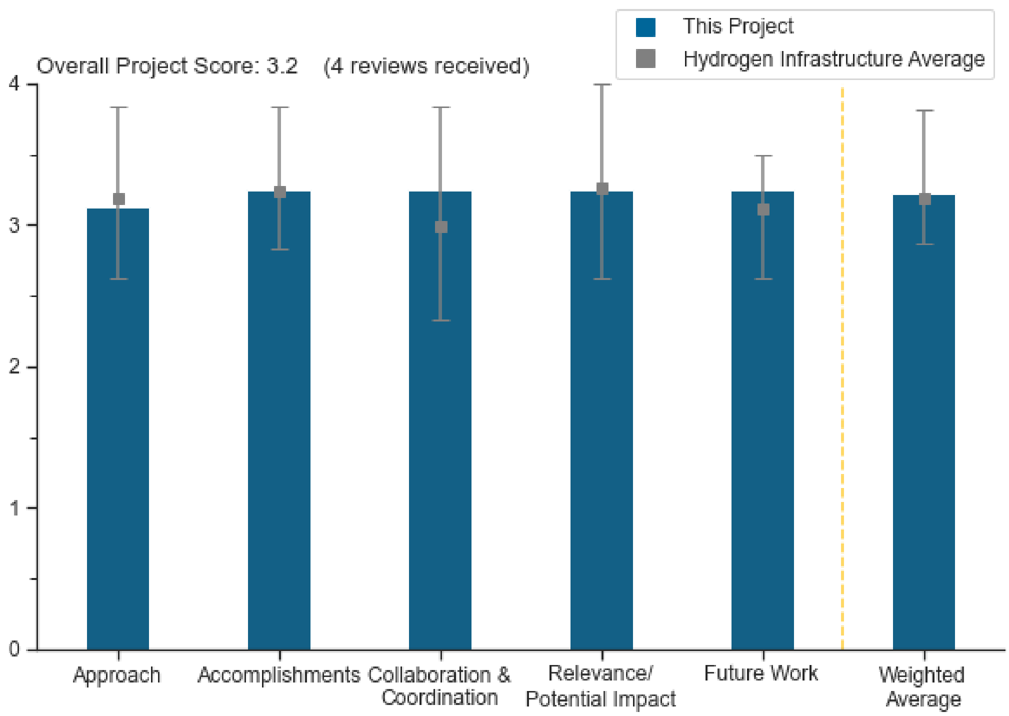
Petros Sofronis, University of Illinois Urbana–Champaign

DOE Contract #	DE-EE0008832
Start and End Dates	10/1/2019
Partners/Collaborators	Swagelok, Linde/Praxair, Arcelor-Mittal, Massachusetts Institute of Technology, Sandia National Laboratories, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, Argonne National Laboratory
Barriers Addressed	• Gaseous hydrogen storage and tube trailer delivery costs

Project Goal and Brief Summary

This project aims to establish detailed relationships between the chemical composition of alloys and localized plasticity caused by exposure to hydrogen. The results could enable the design of new, cost-effective alloys resistant to hydrogen embrittlement (HE). These materials could be used to construct and deploy economical hydrogen fuel infrastructure.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Based upon the oral presentation and the slides, it is fair to say that the primary goal of the project, as worded by the project team, is establishing a mechanistic connection between local chemistry and local deformation behavior, in combination with the appropriate technoeconomic analysis that will enable design of cost-effective hydrogen-resistant alloys or, to put it a different way, to design more cost-effective austenitic alloys by tailoring microstructure at the local level. Neither the oral presentation nor the slides were explicitly clear in stating the project's primary outcomes and impacts. The above will be used as this reviewer's understanding relative to this review. If the understanding of the outcomes and impacts are incorrect, then this commentary may also be off-base. The approach to the work seems sound. The research team is first attempting to understand the local ordering of existing microstructure at a length scale below that which is typically probed. The research team is then performing atomistic and continuum-level models to predict the effects of chemical constituent ordering on dislocation dynamics. The research team then proposes to perform in situ experiments to elucidate these potential interactions. Finally, the research team intends to leverage the overarching team's metallurgical and metal processing expertise to create tailored microstructures that are more hydrogen-damage-resistant. Overall, the approach is sound. Based upon the recent literature, there is uncertainty about any in situ neutron or synchrotron experiments that will provide the measurement data that the team needs in order to be successful.

- The goal of the study is the development of a new HE-resistant material via compositional modifications. The work to date has identified highly novel clustering short-range order (SRO), and modeling suggests that this could affect the deformation in the absence of hydrogen and the segregation behavior of hydrogen. The use of the characterization and modeling approaches to address these concerns is world-class. Investigation of this novel phenomenon is important to understanding the grain-scale plastic deformation behavior, with possible implications on materials design. The only drawback is that the extent to which these SROs will actually affect the fracture and HE behavior remains uncertain. It is possible that they do not. This does not mean that the question should not be asked and investigated. However, the fact that it is possible that there is no clear link between these features and fracture/HE is a risk factor that should be acknowledged.
- The approach uses well-established methods and tools to identify candidate materials and explore chemical homogeneity and deformation modes. The knowledge gained from this approach addresses the cost and reliability of hydrogen transport and storage infrastructure if the work continues to reveal useful scientific understanding of the mechanisms governing hydrogen damage mechanisms. The work is very exploratory and does not appear to have multiple paths to overcoming scientific barriers. The inclusion of technoeconomic analysis is critical to the work's success.
- The cost reduction target was not presented. Perhaps it is based more on lower alloy cost with the addition of Mn, which is not likely to lead to significant gains, or on higher strength and reduced wall thicknesses, which is possibly more likely. The approach to the alloy development matrix is good, but elements/ranges may need to be broadened. The project should not put too much stock in the data comparing the behavior of the commercial-grade materials, Nimonic 40 versus 316, but should focus on modifications to 316 or 304 that may improve strength/increase HE resistance.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The identification of the role of local compositional segregation as a potentially key contributor to the behavior of materials, when exposed to hydrogen, could be a critical advantage in designing lower-cost metal alloys with increased hydrogen damage resistance. The project is making excellent progress.
- The principal investigators (PIs) have made impressive progress, given COVID-19 restrictions. The emphasis on modeling/characterization is well done, as other paths for the project were hindered.
- Assuming the reviewer's understanding of the project goals and the work elucidated in the slides, the project has not been very fruitful, given the 16-month period of performance as of slide creation (February 21, 2021). The reviewer understands the effects of COVID-19, as the reviewer also had three federally funded grants occurring during fiscal year 2019. Even with COVID-19, the characterization of the existing metals' local compositional segregation, the atomistic modeling, and the continuum-level modeling fell short of what would have been possible.
- More progress could have been made on novel alloy development and less on characterizing commercial alloys.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The PIs list an excellent bevy of collaborators. In the talk, the collaboration with Kyushu University was highlighted. While opportunity is there, details of the collaboration with other partners were not provided. This will presumably be invigorated as the pandemic constraints are alleviated.
- The project team should be commended for going out and locating a new, unfunded partner to support project progress.
- Collaborators and their roles are clearly defined, and the project is making positive headway, but the actual role of collaborators was not evident in the review. It seems like the work is performed in-house at the University of Illinois, with limited interaction with collaborators. The transition from modeling and microstructure characterization to Milestones 1.1 and 1.3 would be a natural place for increased collaboration but was only touched on during the review.
- A project like this should have very close connections to a raw material provider and end user. If this is the case, it was not clearly presented during the review.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Establishing a mechanistic connection between local chemistry and local deformation behavior, in combination with the appropriate technoeconomic analysis, will enable the design of cost-effective hydrogen-resistant alloys that will have impacts on both the cost and reliability of hydrogen infrastructure. A key to realizing the potential impact will be how well the knowledge/technology can be transferred to stakeholders. This was not well-described during the review.
- Without any doubt, the successful completion of this project is relevant to progressing hydrogen's use as a clean energy carrier and, therefore, would have very high impact. As mentioned prior, the team's ability to perform measurements that sufficiently support what may come from the combined atomistic/continuum modeling is questionable. The measurement techniques to track dislocation mobility/accumulation in a bulk material, in either a hydrogen or laboratory atmosphere, in situ, are currently lacking.
- The topic area and new findings are certainly high-impact in the field of HE in stainless steel relevant to the hydrogen applications. The foundational knowledge gained will be very important. However, it remains uncertain whether the SRO is relevant to the deformation, fracture, and/or HE properties. As such, there is risk involved as to the direct relevance of detailed interrogation of these features to the design of HE-resistant alloys.
- This reviewer is not familiar with specifics of DOE Hydrogen Program goals, but it is unclear what the cost reduction target is and how much would it save if the "hydrogen economy" were to take off.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The proposed work path is clear, logical, and state of the art to further investigating the impact of SROs on HE behavior. The linkage between the SRO work and the alloy design is not fully clear (as would be expected, owing to the novelty of the SRO observations). Linking the atomistic modeling and characterization to continuum approaches is clearly challenging, and there was not time during the talk for elaboration on how this future effort will be achieved.
- The future work should be focused on novel alloy additions that change the microstructure and lead to better properties or lower costs.
- Continued integration of scientific discovery with technoeconomic analysis will increase the likelihood of far-reaching impacts. The fact that the proposed beam line work is not likely to have the needed resolution may not be the best use of funding.

- The team's ability to perform measurements that sufficiently support what may come from the combined atomistic/continuum modeling is questionable. The measurement techniques to track dislocation mobility/accumulation in a bulk material, in either a hydrogen or laboratory atmosphere, in situ, are currently lacking.

Project strengths:

- The project has world-class characterization and modeling; identification of novel SRO clustering; a logically outlined, state-of-the-art framework to interrogate the impact of SROs on dislocation interaction and hydrogen distribution; clear plans to understand the impact of SRO on HE; and good collaboration with Kyushu University on alloy development.
- The project is making excellent progress in identifying new insights into the mechanisms that control hydrogen damage in materials. The insights may provide a new lever for resining low-cost reliable materials.
- The collection of people in the project is probably the project's primary strength at this point.
- The project topic is interesting and worth pursuing. It needs more industrial collaboration.

Project weaknesses:

- The unclear relationship between SROs and fracture/HE is a risk factor with regard to whether tailoring this microstructure feature will have an impact on the desired property. The in-depth characterization/modeling is current decoupled from the material design. (To be clear, the material design strategy is still solid but is currently proceeding decoupled from and in parallel with the main research effort.)
- The work does not appear to have multiple paths to overcoming scientific barriers. The extent of collaboration needed for success is not demonstrated in the review, and a careful consideration of knowledge/technology mechanisms is not evident.
- There is concern that, if the atomistic and continuum-level models cannot be validated by use of measurements, the work will not have the impact desired.
- The first year focused too much on the limited scope of work and should have focused more on alloy development.

Recommendations for additions/deletions to project scope:

- With the plan the PIs have put forth, increasing the collaborations will occur naturally. Right now, there is a focus on the dislocation interaction with the SRO and the impact on hydrogen segregation. It seems like there remains room to interrogate and link the failure behavior. This is likely outside the scope of the project; however, it would be the next step in the path to understanding the role of these SROs.
- Considerable time and effort should be expended, sooner rather than later, on determining an appropriate measurement technique to validate the modeling results.
- The project should look at the effect of cold work on the alloy and properties with different elemental additions and the effect of nitrogen on alloys and precipitates.

Project #IN-029: Reducing the Cost of Fatigue Crack Growth Testing for Storage Vessel Steels in Hydrogen Gas

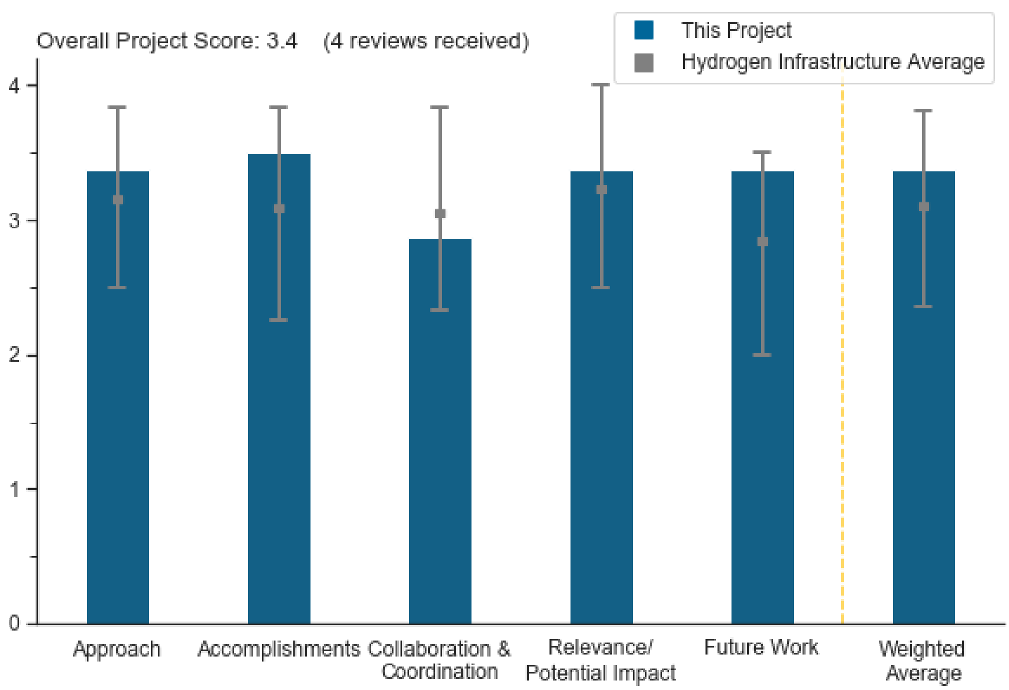
Kevin Nibur, Hy-Performance Materials Testing, LLC

DOE Contract #	DE-EE0008829
Start and End Dates	3/24/2020 to 2/28/2023
Partners/Collaborators	Someday Consulting, LLC, Sandia National Laboratories (via the Hydrogen Materials Consortium (H-Mat)
Barriers Addressed	• Permitting

Project Goal and Brief Summary

Hy-Performance Materials Testing, LLC, Someday Consulting, LLC, and the Hydrogen Materials Consortium (H-Mat) are designing efficient and affordable testing to measure fatigue crack growth rate (FCGR) in hydrogen gas storage vessels. The service life of hydrogen storage vessels at fueling stations is dictated by fatigue crack growth, and current FCGR testing methods are time-consuming and expensive. A more cost-effective approach to FCGR measurement would facilitate market adoption of hydrogen storage vessels at fueling stations.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach to the project is systematic and laid out exceptionally well. This is supported by the results that have been produced to date.
- There is a strong systematic approach to addressing a specific technical problem.

- The approach seems logical, but a better understanding of how the proposed activity could affect the overall component development and acceptance process would be helpful. The approach does not seem to be novel, but tying it to acceptance and implementation is important.
- There does not seem to be as much value in reducing test time as increasing capacity and choosing the right tests to get the best answers to questions.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Project results to date indicate that a considerable reduction in cost to create hydrogen-accelerated fatigue crack growth (HA-FCG) data may be realized as a result of this work. It is very clear that DOE Hydrogen Program objectives are a primary focus of the project team. It is clear that the objectives met to date are far more valuable than the cost of the project to date.
- Progress appears right on schedule, based on the presented plan.
- This project seems to be well on track.
- Good progress has been made. It is not clear if there are any technical hurdles and challenges that will need to be overcome or how this improves the work that has already been done at Sandia National Laboratories.

Question 3: Collaboration and coordination

This project was rated **2.9** for its engagement with and coordination of project partners and interaction with other entities.

- The project team has a long history of working well together and is progressing well as a team.
- The team has good coordination and collaboration.
- It is not clear that collaborations are ongoing. There was a plan to coordinate with Sandia National Laboratories, but everything presented appeared to have been done in-house. However, the project does not appear to need collaborations at this point.
- The National Institute of Standards and Technology (NIST), Oak Ridge National Laboratory, and industry are not involved in the project. It is unclear what tests industry is pushing for where capacity is constrained.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Roughly 20 years ago, the relevant code bodies (American Society of Mechanical Engineers [ASME] B31.12 in particular) endeavored to modify the design codes specific to hydrogen. Specifically, they needed to make the codes more realistic relative to combined hydrogen mechanical loading damage mechanisms. Ultimately, it took Sandia National Laboratories and NIST on the order of 10 years to create a sufficient number of data to support a modification to the B31.12 code to allow for higher-strength materials and more realistic design requirements. The primary barrier to shipping and storing hydrogen in the United States in mass is twofold: reduction in the cost of hydrogen pipeline and storage infrastructure and the private sector’s willingness to invest in the infrastructure relative to a risk posture that is supported by data. This project sets out to define a testing protocol that enables the creation of quality HA-FCG data at far faster rates than what can be performed currently. Given that data collection is the rate-limiting step to overcoming the two barriers mentioned above, this project will have exceptional impact.
- Updating testing standards to allow quicker and cheaper testing would reduce cost burdens to companies that need this type of testing and time burdens on the few facilities that can perform this type of testing.
- If an American Society for Testing and Materials standard is developed and ASME adopts it as well, it could open a possible lower-cost qualification pathway for hydrogen component developers.
- Added testing capacity from a commercial entity is a good step.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- Proposed future work for continuing the primary project looks appropriate and feasible. Proposed interactions with code committees look fine and presumably will be appropriately timed. Proposed future work that includes Sandia National Laboratories is rather vague.
- The proposed future work is aligned well with what the reviewer would expect.
- The project should examine crack closure more closely, especially for alloys such as aluminum that are very sensitive to oxide-induced closure.

Project strengths:

- This is exceptional work to date. The project has already shown results that will be greatly impactful to the hydrogen community at large. Strengths of the project are likely bolstered by the project team assembled.
- Having commercial test facilities for hydrogen materials testing is important for the hydrogen economy to evolve.
- There is a strong, systematic, technical approach to answer technical problems, and it appears to have a strong foundation for project success.

Project weaknesses:

- In terms of reaching overall goals, there is limited benefit to reducing the testing time.
- The project is light on scientific understanding, though that appears to be through design of the project scope.
- There are no noteworthy weaknesses.

Recommendations for additions/deletions to project scope:

- There are no recommendations at this time.

Project #IN-030: Micro-Mechanically Guided High-Throughput Alloy Design Exploration toward Metastability-Induced Hydrogen Embrittlement Resistance

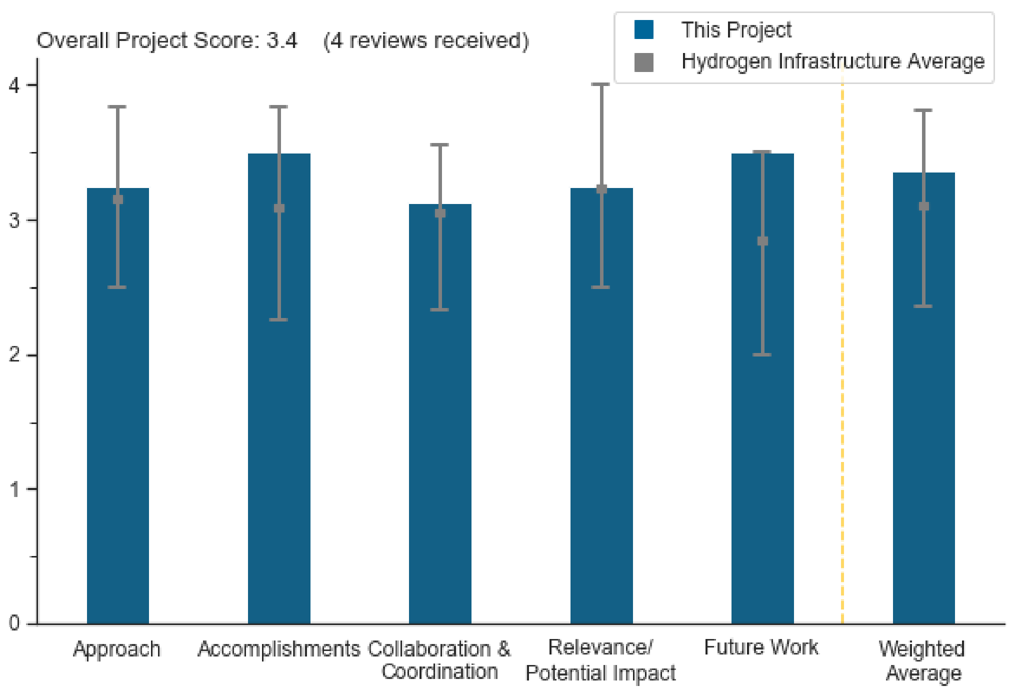
C. Cem Tasan, Massachusetts Institute of Technology

DOE Contract #	DE-EE0008830
Start and End Dates	4/1/2020 to 3/31/2023
Partners/Collaborators	Harvard University, Allegheny Technologies Incorporated
Barriers Addressed	• Gaseous hydrogen storage and tube trailer delivery costs • Materials of construction

Project Goal and Brief Summary

This project aims to develop a novel, high-throughput compositional and microstructural screening approach to developing new alloys with superior hydrogen embrittlement (HE) resistance. The research will focus on using metastability to enhance resistance. If successful, the project will provide novel testing methods that allow researchers to screen the hydrogen-related physical properties of multiple alloys simultaneously, thereby drastically reducing the research and development period for new alloy development.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach leverages advances in high-throughput materials development methods to explore the materials space and identify candidate materials with increased hydrogen-degradation resistance. The team is clear about the advantages and limitations of different aspects of the methods, specifically using small-scale techniques to probe the response of bulk-scale materials. The plan to use small-scale experiments to identify areas to explore with modeling and bulk-scale approaches is likely to provide new insights at a much faster pace than conventional approaches. The approach is sharply focused on enabling safe, lower-cost containment technologies to address hydrogen storage and delivery barriers.

- Alloy development on thin films with gradient chemistries is a novel and interesting concept.
- The link between the identified knowledge gap and goal and the proposed high-entropy alloy (HEA) concept is reasonable. The use of metastable HEAs can be a solution in this space, but the scalability, production, cost, and other important factors are not adequately considered. The lack of investigation of other properties is concerning but will likely occur in future efforts. There are sophisticated methods and data science approaches to address the phase-stability issue, but the authors should comment on the trade-offs of this with other properties. The technical approach is reasonable and state of the art for design, fabrication, and quick screening. However, there are several potential pitfalls in extrapolating beyond the initial screening stage.
- The project objectives are clearly presented. However, the detailed hydrogen technology barriers motivating the objectives are not described. For example, it is unclear whether the technical approach is designed to address the high cost of incumbent structural metals in hydrogen infrastructure, such as 316 stainless steel. One of the stated project goals is to develop new alloys with superior HE resistance, but HE resistance is not a shortcoming of high-nickel 316 stainless steel. Rather, it is the high cost of 316 stainless steel that renders it impractical for widespread deployment in hydrogen infrastructure.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team has surpassed all of the Year 1 project milestones. The calculation of phase-diagram-based high-throughput alloy screening has led to the fabrication and testing of materials for γ phase metastability. The demonstration of combinatorial-style co-sputtering, followed by post-deposition heat treatments, to fabricate materials and control microstructure is impressive within the timeframe (especially considering the pandemic). The design and fabrication of an in situ hydrogen charging setup were completed and are in the process of being validated. Overall, the Year 1 accomplishments are excellent and promise to serve as the basis for future work.
- This project seems to be well on track. Much of the budget appears to have been spent in the early phases, presumably for equipment purchases.
- Solid progress has been made on this project with regard to modeling and design.
- The presentation is well-crafted, so it is evident that the technical accomplishments represent progress toward achieving the stated project goals. However, the project goals are not directly oriented toward resolving critical barriers in the deployment of hydrogen technology, e.g., the high cost of incumbent alloys such as 316 stainless steel.

Question 3: Collaboration and coordination

This project was rated **3.1** for its engagement with and coordination of project partners and interaction with other entities.

- The collaboration and coordination for the project are excellent. The project is engaged with appropriate expertise at various scales and between experimental and computational aspects of the project.
- The relationships with external partners Sandia National Laboratories and Allegheny Technologies Incorporated are described well, and the roles of these partners appear productive for the project. The goals of the project could be honed toward resolving technology barriers by including industry partners that are stakeholders in hydrogen infrastructure deployment.
- This project could consider an industrial partner, but the focus should be on developing the best compositional spaces for detailed commercial exploration. Therefore, it is not necessary to involve industry in this sort of project.

- The academic collaboration is solid; however, the applicability/relevance of the project will suffer without further engagement to understand the cost, scalability, and production considerations. Comments during the talk suggest that this is on the radar of the principal investigator (PI) but has yet to be realized.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is a higher-risk project that could provide a significant new approach to materials design in general and specifically in support of DOE Hydrogen Program objectives. The length of time and cost to develop new alloys for hydrogen have been top barriers to realizing a hydrogen economy for years. This approach, if successful, could significantly advance progress to reach DOE objectives.
- The approach could be very beneficial for the Hydrogen Program, but it also has far-reaching potential in many other industries and applications.
- The foundational work in this study will inform the efficacy of the HEA approach to HE resistance. The atomistic modeling and other outputs will be of great importance to the academic community. However, the potential for this effort to result in actionable progress toward a material that can be applied is very low.
- With its currently stated goals, it is not clear that this project will have an impact on issues that need to be resolved to advance hydrogen technology. The project focuses on enhancing HE resistance of structural alloys, but this material characteristic by itself is not an impediment in the deployment of hydrogen technology. Rather, the HE resistance of cost-effective structural metals is an issue that must be addressed to enable the deployment of hydrogen infrastructure.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The proposed work will achieve the scientific goals of the study with novel and state-of-the-art methods. The rapid screening approach is novel and well-conceived. The PI expressed plans for more detailed testing during the talk.
- The proposed future work represents a progression from the current accomplishments and is targeted toward achieving the stated goals of the project.
- The proposed work, looking at sputter-deposited materials, is appropriate and drives progress toward addressing HE barriers. It is concerning that the proposed work included no mention of how the work will extend to the bulk scale. This is a key component of the project and should be under consideration in the near future.
- The next phase of this project is more focused on alloy development, which should be more exciting than equipment/procedure development.

Project strengths:

- This project combines and leverages recent advances in materials design to address the challenge of hydrogen materials compatibility. The approach has the potential to have an impact on the materials used for hydrogen storage and transportation, but the approach could also extend to any other hydrogen application areas where metallic materials are employed. The team is appropriate, and its roles are clear. Year 1 progress was impressive and has set the stage for the rest of the project. The proposed future work addresses key challenges for the small-scale experimental and computational piece of the project.
- State-of-the-art modeling approaches, novel screening, and materials design and fabrication are high-throughput and unique. The scientific quality is excellent.
- The central concept of this project, i.e., integrated high-throughput alloy design, is sound and could lead to innovations in structural metals designed for hydrogen service.
- This project has a novel idea for alloy development and a good overall approach.

Project weaknesses:

- The primary weakness of this project is its unqualified goal of developing new alloys with superior HE resistance. The project must identify incumbent materials with shortcomings that are hindering the deployment of hydrogen infrastructure. For example, the primary shortcoming of the incumbent 316 stainless steel is its high cost. In this case, design goals for alternative alloys are twofold: (1) replicating the high HE resistance of 316 stainless steel and (2) lowering costs relative to 316 stainless steel.
- This is a multi-property assessment, with linkage to actionable engineering materials. Thus far, there is a need for more consideration of cost, scalability, and production.
- The microstructure effects of the different compositions should be considered. It is microstructure that affects the properties. Composition is used just to change the microstructure. The project should address scale-up in processing from depositing to bulk processing.
- The proposed future work, as stated in the review, does not include a clear pathway to bulk-scale experimental work.

Recommendations for additions/deletions to project scope:

- The project should include details of the next-level characterization of HE behavior and considerations of multi-properties.
- It is recommended that the project include industry stakeholders in hydrogen technology as project partners.

STORAGE

Project #ST-001: System-Level Analysis of Hydrogen Storage Options

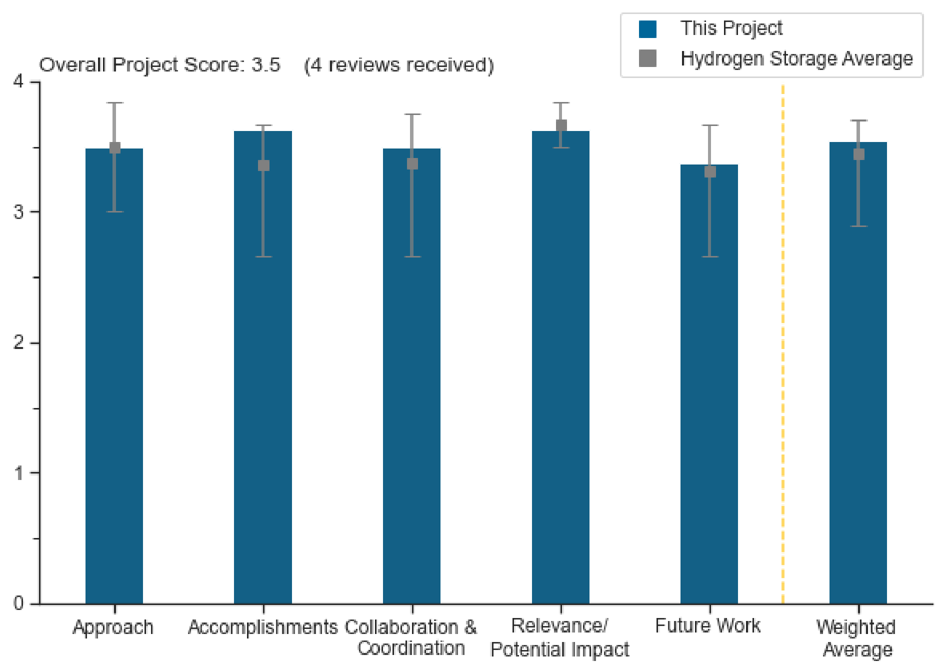
Rajesh Ahluwalia, Argonne National Laboratory

DOE Contract #	4.4.0.2
Start and End Dates	10/1/2009
Partners/Collaborators	Hydrogen Materials Advanced Research Consortium (HyMARC), Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, Hydrogen Interface Taskforce, Argonne National Laboratory – Hydrogen Analysis (H2A) model, Argonne National Laboratory – Hydrogen Delivery Scenario Analysis Model, Hydrogen Materials Consortium, U.S. Army Tank Automotive Research, Development and Engineering Center, Lawrence Livermore National Laboratory, Ford Motor Company, Strategic Analysis, Inc.
Barriers Addressed	• System weight and volume • System cost • Efficiency • Charging/discharging rates • Thermal management • Lifecycle assessments

Project Goal and Brief Summary

The main objective of this project is to develop and use models to analyze the onboard and off-board performance of physical and materials-based automotive hydrogen storage systems. Specific goals include (1) conducting independent systems analysis for the U.S. Department of Energy (DOE) to gauge the performance of hydrogen storage systems, (2) providing results to materials developers for assessment against system performance targets and goals and for guidance in focusing on areas requiring improvements, (3) providing inputs for independent analysis of onboard system costs, (4) identifying interface issues and opportunities and data needs for technology development, and (5) performing reverse engineering to define material properties needed to meet the system-level targets.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is a continuing project, subject to annual direction and guidance from DOE. This important technical effort focuses on systems-level analysis of DOE hydrogen storage needs and options. The 2020–2021 work addresses three technology areas that have significant impact on the successful development of hydrogen-based options for future energy systems: (1) pathway analysis for (hydrogen) liquid carriers, (2) transmission costs for liquid hydrogen (LH2) transport, and (3) hydrogen storage for renewable energy systems. The analysis methodologies employed in all three areas have facilitated meaningful results and conclusions to be obtained on the project. The analyses address critical barriers and provide a compelling and useful way to assess and compare hydrogen transport alternatives, as well as requirements, costs, and scenarios for hydrogen storage in renewable energy applications.
- The principal investigator (PI) uses a thorough and consistent approach using the best available data within the DOE network of programs.
- The presentation was excellent, with plenty of information packed into 20 minutes. The scope of the project is large enough that getting into the details would take significantly more time.
- The project developed systematic approaches for the hydrogen supply chain pathway analysis by hydrogen liquid carriers with different transportation methods. Regarding this pathway analysis, if the liquid carrier is re-used after carrier decomposition, the transportation of the re-used carrier back to Texas should be considered.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project provides a comprehensive analysis of hydrogen transport options, including technoeconomic comparisons of different hydrogen carrier systems for both stationary and transport applications. This work directly complements the ongoing materials work being conducted in the Hydrogen Materials Advanced Research Consortium (HyMARC) and other DOE projects, and it provides useful tools that help guide the materials development efforts. The Argonne National Laboratory (ANL) team has generated an impressive amount of detailed information that allows liquid carrier transport options (e.g., pipelines, rail, tanker ships) to be compared and correlated, and costs to be assessed. Likewise, useful new information is provided that quantifies the impact of different hydrogen storage approaches for off-load storage, backup power, and load leveling in renewable energy power generation applications. The results of the analysis in all of these areas are important for developing optimized storage and transport systems, in addition to providing a better understanding of how hydrogen systems compare with other (incumbent) storage technologies. On a side note, it is unclear why, in the two text boxes on slide 13, capital expenditures and levelized cost of electricity were expressed as $/kW instead of $/kWh.
- This project completed a good evaluation of the hydrogen transmission paths and costs. The scope of evaluation appears to be very thorough. It would be nice to see the cost for hydrogenation and dehydrogenation for each of the carriers in the charts. Also, cost comparison to energy storage methods other than hydrogen would be informative and interesting.
- The PI manages to efficiently communicate a tremendous amount of information in a short presentation. These presentations need to be reviewed afterward to dissect the tremendous amount of data and assumptions made. It is too much to cover in 20 minutes.
- The project demonstrated excellent accomplishments and progress, developed cost correlations for various transportation methods of different hydrogen carriers, and developed cost models for LH2 storage and shipping.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The valuable collaborations with the HyMARC core team and Strategic Analysis, Inc., are evident. The systems analyses being conducted in this project provide a useful complement and adjunct to the foundational studies in HyMARC. Continued close interactions with the HyMARC team will be essential to ensuring that DOE receives a meaningful "end-to-end" examination of hydrogen system status and challenges.
- This PI always pulls in the best available data from the DOE network of projects.
- The collaboration with other institutes looks to be very good. It would be nice if more input from the industry was available in the analyses.
- The project team should consider having more partners from industry to provide validation on the cost assumptions.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Hydrogen-based fuel cells are emerging as important elements in the DOE energy portfolio. The analyses being conducted in this ANL project are vital to understanding how this technology will be implemented on a large scale that is both efficient and economical. This ongoing project is closely aligned with the DOE research, development, and demonstration (RD&D) goals and objectives and continues to have positive impacts on the progress achieved in the DOE Hydrogen Program (the Program).
- Understanding the role of hydrogen and fuel cells in the grid energy system will be crucial for realizing their use and the adoption of renewable energy sources. It is important to conduct this kind of research.
- Understanding hydrogen supply chain and transmission cost is critical for the hydrogen economy as it moves into higher demand. Identifying the costs and opportunities early will help the industry capitalize on the correct technologies.
- The project is very relevant to DOE's current focus, as well as industrial perspectives, and has the potential to advance progress toward DOE RD&D goals and objectives.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The proposed future work follows logically from the technical effort initiated in 2020–2021. The reviewer strongly supports the proposed effort to fully document the results of the hydrogen carriers and bulk storage work.
- The plans are clearly defined and well-planned. The team should consider adding one more study on supply chain development based on utilization of existing hydrogen storage infrastructure, such as hydrogen pipelines and hydrogen storage caverns.
- Heavy-duty fuel cell electric vehicle applications are attracting higher interest from industry. Understanding the cost of storage systems, as well as total cost of ownership (TCO) for vehicles, is important. It is important to consider fuel costs as part of the storage system, as changes in fuel cost become much more significant to TCO for heavy-duty vehicles.
- The next steps are appropriately chosen.

Project strengths:

- The project developed systematic approaches and scenarios for the hydrogen supply chain pathway analysis with various transportation methods. The project demonstrated excellent accomplishments and progress, developed cost correlations for various transportation methods of different hydrogen carriers, and developed cost models for LH2 storage and shipping. The project is very relevant to DOE's current focus and industrial perspectives and has the potential to advance progress toward DOE RD&D goals and objectives.

- This 2020–2021 project represents a new direction for the ANL analysis team. By focusing on hydrogen transport issues and storage for renewable energy applications, the researchers have expanded their impressive capabilities to address important new areas that underlie the successful development and implementation of hydrogen fuel cell technologies. The results provide an important complement to the ongoing materials and systems development work being conducted elsewhere in the Program.
- The project's strength is in its collaborations using the available data. The PI's experience in this area helps him to avoid making mistakes and choosing poor assumptions, parameters, etc.
- This project provides a good summary of various transmission methods and media and breaks the information down into understandable and actionable data.

Project weaknesses:

- This is a strong project with few deficiencies. The ANL team has demonstrated the ability to move quickly to effectively address new important issues that have impacts on the Program.
- The project can be further improved from the following points:
    - For the study on hydrogen storage for renewable wind and solar plants, in the scenario setting, toluene and methylcyclohexane (MCH) are considered as the hydrogen storage methods. Other hydrogen storage options should be considered, and more explanation should be provided on the cost assumptions of various transportation methods, such as pipelines, trains, and ships.
    - For Task 1, pathway analysis with transmission by trains, the project team might consider adding the LH2 as the reference, similar to LH2 ships. For the LH2 export study, the handling of boil-off gas during the trip is not clear; an explanation would be appreciated. Also, the team should consider the scenario using boil-off gas as the propulsion power supply, which may significantly influence the economics. The sensitivity analysis should be added on the hydrogen storage cost analysis for renewable wind and solar plants. For the study on hydrogen storage for renewable wind and solar plants, the study is targeted at 10 MW; a similar study should be carried out at a higher scale to show the effect of scale.
    - The project should include partners from industry to provide validation of the cost assumptions.
- This is not a project weakness, but there is simply too much information presented to be digested in 20 minutes. The PI should strive to provide high-level conclusions and trends up front to allow users to wrap their heads around the context of all that is being presented.
- The scope may be too large to get a good evaluation for each technology and comparison to current incumbent technologies. Significantly more work could be done on hydrogen storage for wind and solar.

Recommendations for additions/deletions to project scope:

- There are two recommendations for addition to the project scope. (1) The PI has stated that new pipelines will be required for hydrogen carrier transport (i.e., retrofitting of existing pipelines is apparently not workable). It will be important to identify infrastructure cost requirements (e.g., scope of the pipeline distribution networks and pipeline production and installation costs) to fully establish the efficacy of implementing the pipeline-based transport approach. (2) It is recommended that the hydrogen storage analysis for renewables include a comparison with existing incumbent storage technologies (grid-scale batteries, solar thermal, pumped hydro, etc.). Such a comparison is needed to fully benchmark the hydrogen storage technology against current storage approaches.
- The project should add sensitivity analysis to scalability of these processes and what the limiting steps are to scale up or down. It would help researchers to determine what storage material characteristics would be useful to allow scaling up or down. This is similar to the intent of the Hydrogen Storage Engineering Center of Excellence.
- Heavy-duty applications are expected to grow significantly over the next few years; identifying barriers to adoption and defining TCO in comparison to diesel will be critical for growth.

Project #ST-100: Hydrogen Storage Cost Analysis

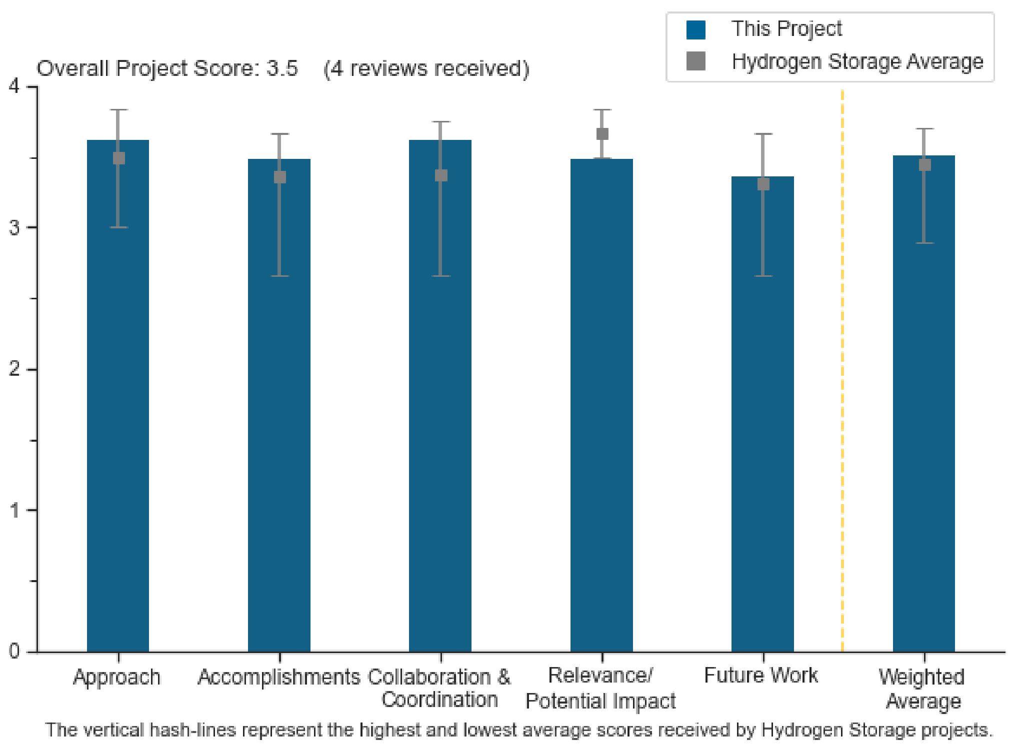
Cassidy Houchins, Strategic Analysis, Inc.

DOE Contract #	DE-EE0007601
Start and End Dates	9/30/2016 to 9/29/2021
Partners/Collaborators	Pacific Northwest National Laboratory, Argonne National Laboratory
Barriers Addressed	• System weight and volume • System cost • System lifecycle assessment

Project Goal and Brief Summary

The goals of this project are (1) to conduct independent Design for Manufacture and Assembly (DFMA) cost analysis for multiple onboard hydrogen storage systems and (2) to assess/evaluate cost-reduction strategies to meet U.S. Department of Energy cost targets for onboard hydrogen storage for different types of fuel cell electric vehicles (FCEVs).

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The DFMA methodology has proven to be a powerful analysis tool for predicting material and process costs and for identifying optimum design and manufacturing pathways. The approach was used effectively in the last year to evaluate and develop hydrogen storage system cost models for Class 8 long-haul systems. In addition, the approach has facilitated a detailed cost analysis for gaseous hydrogen (GH2) and liquid hydrogen (LH2) onsite stationary storage systems and analysis of low-volume 700 bar GH2 storage for light-duty vehicles (LDVs). This work complemented and extended prior work by the Strategic Analysis, Inc. (SA) team on analysis of LDV storage, fuel cell electric buses, and Type 4 natural gas storage systems. The approach adopted in this work also serves as a useful adjunct to the storage and transport system analyses being conducted by Argonne National Laboratory (ANL) and collaborating institutions.

- Compressed and liquid hydrogen are expected to be the primary on-board hydrogen storage systems for FCEV systems for the next several years, so understanding system costs and how these can be reduced is paramount to making FCEVs commercially viable. SA has done a good job of breaking down storage costs and identifying key contributors to costs at high volume.
- This is a very relevant topic and system selection, given the move to heavy-duty FCEVs.
- The project developed a DFMA methodology to track annual cost impact of technology advances. Cost models have been developed for hydrogen storage systems for Class 8 long haul FCEVs, light-duty FCEVs, and hydrogen refueling stations.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Solid progress has been made in four areas. (1) The definition and preliminary analysis of a baseline Class 8 long-haul system based on a 700 bar, Type 4 hydrogen storage approach has been completed. A component-level cost breakdown was generated, and carbon fiber used in tank production was shown to dominate the system cost. (2) Analysis of LH2 storage and delivery for Class 8 long-haul vehicles has been completed. Collaboration with ANL showed that balance-of-plant (BOP) components and insulation dominate the system cost. (3) Companion cost and sensitivity analysis for LDVs provided a basis for estimating storage system costs in out-years (2025, 2030). (4) A bottoms-up cost analysis was performed for onsite compressed gas and LH2 storage systems at refueling stations. Cost breakdowns were provided for bulk liquid storage and industrial tube trailer systems used for compressed gas storage. Overall, these analyses and projections provide a useful foundation for more quantitatively assessing storage system costs and evaluating component and system design requirements.
- This principal investigator consistently delivers good progress every year. Presentations are clearly laid out and described.
- The project demonstrated excellent progress toward project objectives.
- For LDV hydrogen storage systems (HSSs), cost is a significant factor in vehicle adoption. Many of the DOE goals are based on passenger vehicles, and the progress toward these goals is good. However, on heavy-duty vehicles (HDVs), hydrogen storage system cost is much less significant, as fuel costs have become much more significant to total cost of ownership. This is outside of the scope of the project and is being addressed by other institutes, but it should be considered to provide a complete picture for HDVs.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- Collaborations with national laboratories (ANL and Pacific Northwest National Laboratory) effectively support the technical effort in this project. The collaboration with ANL is especially noteworthy because it provides an overall systems analysis context for the cost and design analysis in this project. More extensive collaborations with industry have also been established during this reporting period. This inspires confidence that a "real world" perspective is being incorporated into the project. Closer attention should be paid to evaluating hybrid ideas involving compressed gas storage in tanks comprising hydrogen storage media. This will necessarily involve establishing more robust collaborations with organizations conducting the materials and system development investigations (e.g., the Hydrogen Materials Advanced Research Consortium [HyMARC] and Pacific Northwest National Laboratory).

- SA has a strong history of working with the full range of industry and DOE tools/collaborators to deliver the best available data on which to build modeling.
- It looks like an excellent collaboration with a good mixture of industry and institutes.
- Page 18 shows an excellent consortium for the work. It would be good to have more industrial partners for system validation.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- As in the case of the ANL systems analysis work, the technoeconomic cost projections derived from this project support the DOE objectives, and these projections are useful in providing a more quantitative view of system efficacy and future market penetration. DOE is using this information to inform system and manufacturing development decisions and to project overall costs for stationary and onboard storage systems. Overall, the project is well-aligned with the objectives and goals of the Hydrogen and Fuel Cell Technologies Office.
- Storage systems are a significant cost of the system. A sensitivity analysis as to where costs can be reduced in future systems provides essential guidance to all parties.
- Compressed gaseous and liquid hydrogen storage is going to be the primary method of on-vehicle storage for the next several years, so this work is very important to early adoption of FCEVs.
- The project aligns well with the DOE Hydrogen Program (the Program) and objectives.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- HDVs have become of greater interest, as battery vehicles are becoming the better solution for short distances and light vehicles. Storage costs for HDVs and bulk ground storage need to be understood in conjunction with reducing hydrogen fuel cost to a cost level comparable to petroleum fuels.
- The proposed future work on Class 8 long-haul 700 bar hydrogen and LH2 storage systems and LH2 bulk storage is a logical and reasonable extension and follow-on to the 2020–2021 efforts. The proposed work should result in successful project completion in 2021. It would be helpful to include an analysis of hybrid ideas involving compressed gas storage in tanks comprising hydrogen storage media (e.g., adsorbents, nanoscale hydrides, etc.). Instituting a hybrid approach for tank and storage system design could result in relaxation of the demanding requirements currently imposed for tank design and construction.
- Future topics are on point with the Program and industry shift to heavy-duty applications.
- Though the project is close to the end, the team still provided a good plan for the future work.

Project strengths:

- The project does a good job of taking current dominant technologies and extrapolating to potential high-volume cost and comparing them to other possible storage solutions and cost estimates. Additional examination into bulk storage cost is of interest for understanding initial capital costs.
- An experienced and highly capable analysis team at SA and collaborating organizations is conducting important technoeconomic assessments and developing projections that are directly relevant to DOE hydrogen storage goals and system needs. The project is well-managed and -coordinated, and it is effectively aligned with other DOE storage systems analysis efforts.
- The project provides consistent results and modeling in line with work done at ANL and overall Program objectives. This is great work, as usual.
- The project demonstrated an effective approach by DFMA analysis to predict costs and provided insight into which components are critical to reducing the costs of onboard hydrogen storage and meeting DOE cost targets.

Project weaknesses:

- No notable weaknesses are apparent. The project is concluding in the third quarter of 2021. Detailed documentation and reporting on project results and recommendations are essential.
- This is not SA's fault, but the proprietary nature of data from industry limits the ability to further tune or improve the fidelity of the model. In general, SA does a good job of filling in the blanks and soliciting the maximum amount of information possible.
- As we move to larger systems that are expected to have lower fuel economy and higher mileage/usage, storage costs become less important in total cost of ownership unless fuel costs are equivalent. BOP costs are a small percentage of overall HSS costs, which currently has not been observed. This may be true as volumes increase but should be examined more closely to ensure assumptions for regulators and valves are valid for high-pressure hydrogen.
- (1) For the Class 8 long-haul system on page 7, it will be interesting to show which property has the potential for reducing system cost. (2) On page 8, how the safety factor is defined and how the relaxed safety factor at 2.0 will affect the safety should be explained. Also, the assumption for the DOE target of carbon fiber price reduction of 40% should be provided. (3) On page 9, the schematic of the LH2 system design for Class 8 long-haul (similar to page 7) should be shown, and comparisons with 700 bar GH2 systems should be made. (4) On page 10, for the figure on the left, the difference between PAN-MA and T700S should be explained. In addition, using the unit of $/kg hydrogen for the system cost would be consistent with previous system costs. The 2030 target and ultimate target should be added into the figure. (5) On page 17, whether the cost in the figure includes the compression cost should be explained, as compression is one major part of cost and one system has a pressure of 500 bar—much higher than the other two systems. (6) More industrial partners should be added for system validation.

Recommendations for additions/deletions to project scope:

- It will be useful to evaluate cost and performance trade-offs for hybrid system designs employing compressed gas in a tank containing a solid-state hydrogen storage medium. (Of course, this requires close collaboration and consultation with investigators conducting materials development for hybrid systems.) Since lower tank pressures would likely be required in the hybrid system, this could result in reduced cost and complexity of tank manufacturing and assembly.

Project #ST-127: Hydrogen Materials–Advanced Research Consortium (HyMARC) Overview

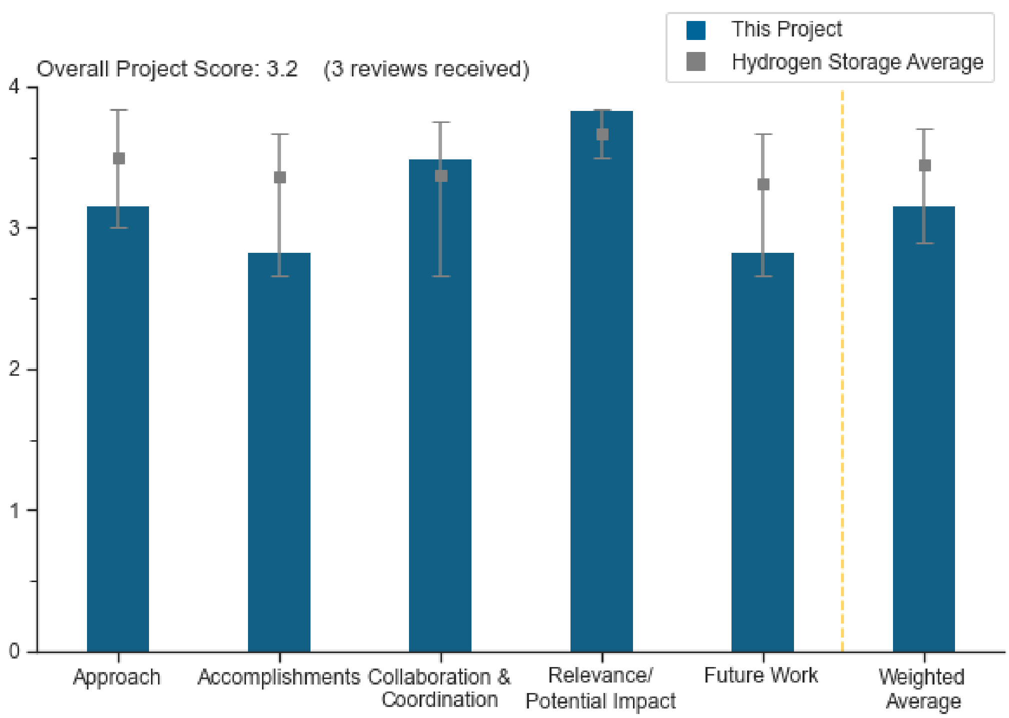
Mark Allendorf, Sandia National Laboratories

DOE Contract #	4.1.0.805 (SNL); 4.1.0.501 (NREL)
Start and End Dates	10/1/2015
Partners/Collaborators	National Institute of Standards and Technology, University of Nottingham, University of Uppsala, U.S. DRIVE Hydrogen Storage Tech Team, Colorado School of Mines, University of Hawaii, Université de Genève
Barriers Addressed	• Cost • Weight and volume • Efficiency • Hydrogen capacity and reversibility • Understanding of hydrogen physi-and chemisorption • Test protocols and evaluation facilities

Project Goal and Brief Summary

Critical scientific roadblocks must be overcome to accelerate materials discovery for vehicular hydrogen storage. The project objective is to accelerate discovery of breakthrough storage materials by providing capabilities and foundational understanding. Capabilities include computational models and databases, new characterization tools and methods, and customizable synthetic platforms. Foundational understanding is needed for phenomena governing the thermodynamics and kinetics-limiting development of solid-state hydrogen storage materials.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The "co-design" approach adopted by the Hydrogen Materials Advanced Research Consortium (HyMARC) team is a rational and powerful way to address hydrogen storage material challenges. The incorporation of push projects serves to complement the core HyMARC effort and provides a means to readily expand the technical scope and depth of the consortium. The HyMARC team clearly understands the obstacles that must be overcome to implement improved hydrogen storage capabilities in both onboard and stationary systems. That said, it is not clear whether the goals of achieving "foundational understanding" are being effectively met by the consortium. At present, there are multiple, disparate efforts that address specific materials systems and approaches, but detailed information concerning reaction mechanisms, kinetic roadblocks, and reversibility issues seems to be limited.
- The approach is largely sound and clever. The consortium uses a multipronged approach that provides several paths to success. Theory and experiment are used to develop materials faster, with theory, at least in concept, providing an accelerated screening and experiment giving feedback to theory. The use of seedling projects with lower funding for high-risk areas, plus the use of push projects for high-possibility areas, is a very good way to spread funding. It is less clear if there is much pruning of dead ends. If this major allocation of funds is to be maximally successful and lead to jobs in a hydrogen economy, the leadership needs to make a call on projects that are not looking promising. This is not the National Science Foundation or even the Basic Energy Sciences office, and therefore, the allocation should flex to give maximal chance to the most successful avenues of inquiry—but not simply abandon whole areas of inquiry (e.g., do not defund all metal hydride work just because metal–organic framework [MOF] storage looks more promising, or vice versa, but definitely also do not award equal funding to all projects, regardless of progress).
- The objectives and barriers are clearly defined. The metrics for what success would look like are defined less well for the various pieces of the overall approach. The consortium has focused on push projects, which have brought some coherence to the consortium, and there is evidence that the seedlings are rather well-integrated into the overall consortium. The feasibility of the individual project areas was not well-defined. It is not clear how some of these very-low-capacity, somewhat reversible systems will find use.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Solid progress is being achieved on the core activities and push projects devoted to developing adsorbents containing multiple hydrogen adsorption sites. Likewise, as in past HyMARC work, the results from the theory and modeling efforts are providing useful guidance and support for the experimental efforts. The publication record in the last 12 months (more than 40 publications) is impressive. In addition to creating scientific impact, the publications serve as a useful way to document the consortium's progress. In the metal hydride arena, serious challenges concerning reversibility/cycling and sorption kinetics remain. For example, although nanostructured materials show great promise for improved hydrogen desorption rates, it is unclear whether the adsorption rates and reversibility/cycling can be improved to levels commensurate with practical systems applications; understanding those barriers is essential. High-capacity liquid-phase hydrides (borohydrides) are also intriguing, but again, finding a catalyst that can improve sorption kinetics seems to be elusive. Overall, development of an improved understanding of how additives and catalysts alter sorption reaction kinetics in complex hydride systems remains a serious challenge. The work on reversible storage in nanoconfined alane is new topic area; however, many questions remain, and it could be argued that the alane work is an unnecessary diversion that is tending to defocus the HyMARC effort. Even if confinement enables reversibility, it is not clear whether the gravimetric penalty imposed by the bipyridine-CTF (covalent triazine framework) host has significant impacts on the capacity. Likewise, it is unclear whether rehydrogenation can occur at useful temperatures and rates. The HyMARC team (mainly the Pacific Northwest National Laboratory group) is making good progress on hydrogen carriers, especially on understanding and improving catalyst deactivation in inorganic formates and developing a better understanding of kinetic bottlenecks and the full-cycle release of hydrogen in ethanol carriers. Questions remain about the extent to which the Advanced Light Source (ALS) diagnostics effort is providing meaningful impact. The new high-pressure x-ray absorption spectroscopy (XAS) system could yield important new insight, but progress to date has been slow.

- There has been good progress, given the conditions of the year. The consortium achieved adsorption of over two molecules H_2 per open K atom, a long-sought goal. The team increased both thermal conductivity and capacity of the bulk Li amide by using the surface energy of a nanoconfinement carbon structure. This system also achieved 50 cycles with no capacity loss. The team got 1.64 wt.% at 100 bar by first defining the correct energy range for 300 K operation, designing materials to get there, and then making the MOF, which is very encouraging. Also, there has been significant progress on Type 5 absorption curves. In a new area, the consortium performed an extensive theoretical search for destabilized metal hydride alloys and made a few, which perform as predicted. Verification of life and kinetics of these alloys would be a good addition.
- A roadmap and set of down-select criteria for each project area that define what must happen to enable "twice the energy density of compressed systems for hydrogen storage" were not described, and those down-selects are coming up at the end of fiscal year (FY) 2021. There were many unanswered but critical parameters that were not at least outlined, such as the minimum amount of scaffold that can still be used to obtain the energy density, the minimum amount of solvent, and the minimum amount of CTF to avoid the significant weight and volume penalties associated with these strategies. Also, it is unclear what use cases are being targeted for each of these projects and whether these weight and volume issues are obviated or exacerbated for these cases. There are a few areas that appear rather "sandbox-y"; the control of kinetics using coated MOFs is one of these areas. It was a nice trick, but with such a low capacity, it is unclear where this is heading. The carrier portion of the consortium's work seems solid; the team is addressing key problem areas effectively and using analysis of potential use cases to direct down-selects and focus areas for improvement. Some of that is apparent in the metal amide work, where the Tankinator model has been automated to help define where success lies. More of that sort of analysis-based approach should be applied more uniformly to each project area. The integration of theory and computation into the consortium has been, and continues to be, excellent. The machine learning exercise to find new metal hydrides is interesting but lacks a discussion of how this capability will be directed at other materials cases in the future.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The successful merger of the legacy HyMARC and Hydrogen Storage Characterization Optimization Research Effort (HySCORE) activities has created a more streamlined and manageable framework for consortium operations. The overall effort seems to be well-coordinated and -managed. Extensive industrial and international collaborations strongly support and complement the core HyMARC effort. Likewise, the push projects are a welcome addition, and they are serving to expand the scope and reach of the consortium into important new areas.
- This is an inherently massive collaborative; however, some projects (in their own reviews) seem to be more cooperative, while others are more lone experimenters. To get the most benefit of this large consortium, everyone needs to be researching as one team. This is hard to accomplish, but it would be a way to improve.
- There was good evidence supporting a high level of collaboration and coordination within HyMARC and with the seedlings. One problem area was illuminated in one of the seedling presentations: when one of the key high-pressure hydrogen sorption capabilities was taken offline because of an incident, the consortium did not quickly figure out how to cover that temporary loss of capability. It is unclear where the communication may have failed here, but perhaps it is an area on which to work. Overall, the seedling projects are well-coordinated and appear to be outproducing many of the core HyMARC projects.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- HyMARC is a critical element of the DOE Hydrogen Program (the Program). DOE derives important benefits from the focus on developing an improved foundational understanding of processes and mechanisms operative during hydrogen storage reactions in solid-state and liquid materials. The project is well-aligned with Program research, development, and demonstration (RD&D) objectives.
- This consortium that is making materials and developing systems that enable hydrogen storage is perfectly aligned with the Program goals. The expansion of the goals to include stationary uses opens up many materials methods that were eliminated for vehicles. The consortium also helps other projects make progress toward their goals.
- The goals of HyMARC and the associated projects clearly support Program goals and objectives and are thus highly relevant to the potential advancement of the Program.

Question 5: Proposed future work

This project was rated **2.8** for effective and logical planning.

- Continuing the focused work on the push projects is essential, and the end-of-year go/no-go decisions should be made rationally, with close attention to progress on objective milestones. The consortium must adhere to its stated objective of providing foundational understanding and avoid the risk of investigating multiple unrelated systems that may show promise arising from speculative criteria. For example, careful consideration should be paid to continued work on diversions such as hydrogen sorption reactions in nanoconfined alane and photo-assisted hydrogen adsorption/desorption. Without a candid assessment of those and related ancillary activities, there is a serious risk of defocusing and fragmenting the core efforts. In addition, near-term decisions about the ALS diagnostics work must be made. ALS progress to date has been slow. A solid plan for accelerating the diagnostics work should be implemented.
- The future work is appropriate. Given the wider usage parameters in the new focus, all areas have potential to contribute. That said, focusing on those getting the most hydrogen out of the finished tank and materials systems and modest cost still makes sense, but more (not all) resources should be focused in the most promising areas.
- The proposed future work was not well-prioritized, as the top item listed was “international collaborations.” With the push project down-select coming up in FY 2021, this would appear to be an all-hands-on-deck exercise to approach the down-select with an abundance of data. With the down-select rapidly approaching, a good discussion of the down-select criteria toward which the project teams are working is expected, along with discussion of the status in regard to reaching or not reaching a “go” decision.

Project strengths:

- The carrier projects do a nice job of integrating analysis, computation, experimental kinetics, and catalysis into their approach, which is very nice. Also, they have worked well with one of the key seedlings at the University of Southern California. The Lawrence Livermore National Laboratory theory and modeling capability continues to show high value to the projects, including the seedlings. The Lawrence Berkeley National Laboratory work on new materials for sorbents continues to do a beautiful job of pushing the envelope and helping to define what is truly possible in altering capacities, but also the heat of adsorption, via the really tough chemistry of designing and synthesizing open metal sites. The use of the automated Tankinator model to define the boundaries of practicality in the metal amide area is an important contribution. Defining barriers between success and failure is an approach that should be applied more generally to the other materials classes as well.
- HyMARC is a critical element of the DOE RD&D portfolio. Providing a foundational understanding of the thermodynamics and kinetics of hydrogen storage reactions and processes is vital to the development of storage materials that meet or exceed DOE goals. A strong and capable HyMARC core team has been assembled to conduct the work on this project. The addition of push projects is infusing new ideas and expertise into the consortium.

- The team is the project's greatest strength; it has excellent principal investigators. The addition of push and seedling projects to the main effort makes the consortium's structure a major strength. The breadth of approaches is a strength, as is the pairing of theory and experiment in a feedback loop.

Project weaknesses:

- The consortium must remain keenly focused on its stated objective to provide foundational understanding of hydrogen storage processes and mechanisms. The inclusion of projects and materials systems that are likely to be "non-starters" with little impact on overcoming obstacles is tending to defocus and fragment the overall effort. At this point in the life of the consortium, a thoughtful and detailed assessment of future directions must be made. In addition, even though the ALS diagnostics activity has significant potential, progress has been excruciatingly slow; a candid assessment should be made concerning the future of that effort.
- Size might be the consortium's biggest weakness, though of course, it comes with the breadth of effort requested of the consortium, which is a positive thing. It is very hard to properly manage so many projects and to move funds around in ways that might make the most progress. Also, it is hard to get communication across so many participants without wasting time in endless meetings.
- There continues to be a lack of a roadmap to success for many materials types. It is not clear what it will take, or what use cases are applicable, to get a low-capacity material across the finish line. This should be outlined for each materials project with the current status, the path forward, and the probability of achievable improvements.

Recommendations for additions/deletions to project scope:

- Four areas should be emphasized: (1) provide a greater focus on overcoming kinetics obstacles, especially in the amide and borohydride push projects; (2) conduct a careful evaluation of activities that have little or no bearing on foundational understanding and limited potential for meeting DOE goals; (3) conduct a candid evaluation of ALS diagnostics progress, and take remediation action as appropriate; and (4) provide a thoughtful and detailed view of where the consortium stands, what foundational information is missing, and what mid-course corrections should be made to address those issues. This information should be made available to Program management and the Hydrogen Storage Tech Team. On another note, for the benefit of the reviewers, it would be helpful if the team could provide what it considers to be the most noteworthy examples of foundational understanding that have emerged thus far from the HyMARC work.
- The work on MOFs and on carriers, especially formate, seems to be making the most aggressive progress, so the consortium should increase the resources (not necessarily monetary resources) provided to those projects to help them continue that progress.
- Any materials research and development that cannot be adequately defended as to what use case it will address, and how it will achieve success with respect to current status, should be considered for deletion from the work scope. From the few details given, it would appear that the MOF/PDMS (polydimethylsiloxane) and the alane/CTF projects are in this category.

Project #ST-209: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Theory-Guided Design and Discovery of Materials for Reversible Methane and Hydrogen Storage

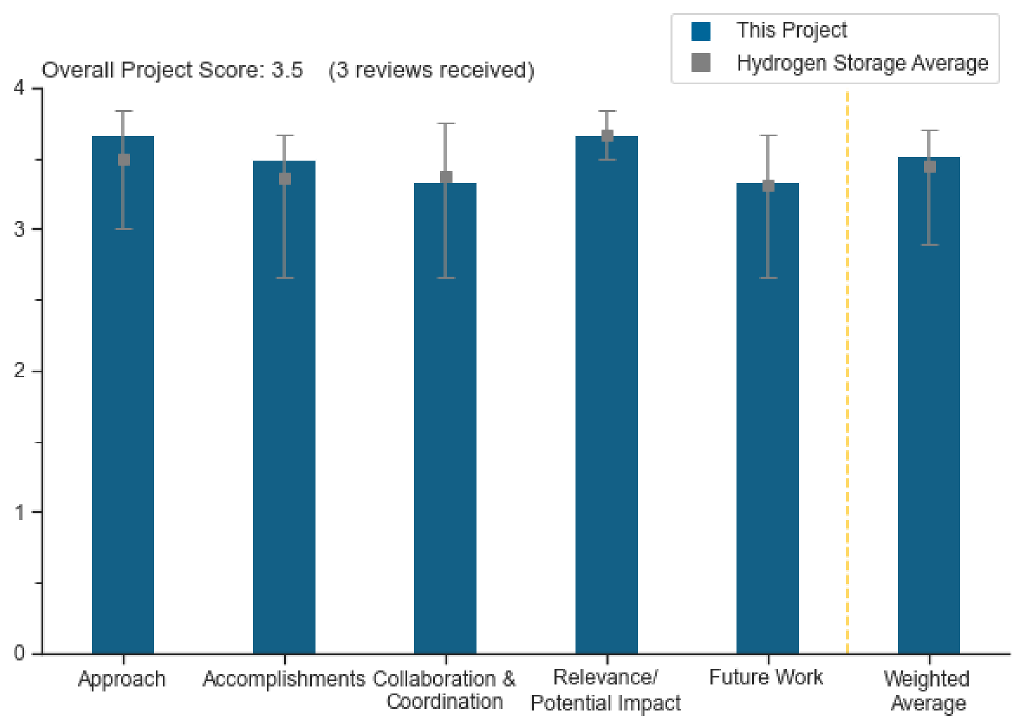
Omar Farha, Northwestern University

DOE Contract #	DE-EE0008816
Start and End Dates	1/1/2020 to 1/31/2023
Partners/Collaborators	National Institute of Standards and Technology, National Renewable Energy Laboratory
Barriers Addressed	• System weight and volume • System cost • Efficiency • Durability/operability • Materials of construction

Project Goal and Brief Summary

This project aims to exploit high-performance metal–organic framework (MOF) sorbents by combining synthesis with machine learning to find stable and scalable materials for hydrogen storage while maintaining a reasonable cost of production. The project researchers will use a machine learning algorithm to screen a database of materials for hydrogen uptake. Having identified the top candidate MOFs, researchers will synthesize and characterize them and study their behavior under pressure- and temperature-swing (PT swing) operation. The project team will also look at removing solvent molecules from MOFs to yield open metal sites for storing molecular hydrogen at near-room temperature. If successful, this project will advance economical hydrogen storage technology.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project focuses on the use of computational screening and material synthesis to identify and demonstrate improved MOF adsorbents for high-capacity hydrogen storage. High-throughput computational discovery, coupled with machine learning, is used to identify materials with different structural topologies, allowing the team to predict which MOFs will have the highest capacities at practical operating temperatures and pressures. Subsequent synthesis and characterization are used for experimental validation. The approach is powerful and allows for rapid investigation of a broad parameter space. The project parallels very similar work on MOF identification and screening by Siegel, et al., at the University of Michigan, Savannah River National Laboratory, and Ford Motor Company. However, the principal difference is that this project focuses on exploring a broad range of different MOF topologies, leading to identification of promising candidates that are down-selected for subsequent synthesis and characterization. Overall, the approach is innovative and addresses critical obstacles to hydrogen storage in adsorbent systems in a novel way.
- Use of theory, experiment, and spectroscopy is a good plan for this MOF work. Machine learning to accelerate the search seems to be the method these days and makes sense as a means of isolating some good candidates. While setting up the algorithm used to generate MOFs to simulate, the project team used considerations of how easy or hard it would be to synthesize certain linker and corner groups; this is a good step.
- The modeling, simulation, and machine learning high-throughput approach, which is then validated through synthesis and characterization of promising structure types, may yield adsorbents with enhanced properties. This approach addresses critical barriers in developing improved sorbents for hydrogen storage.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- An extensive parameter space has been explored, and several promising storage candidates have been identified. An energy histogram (volume fraction vs. energy) is used as a useful descriptor and discriminator. Initial experimental work has been performed to synthesize and characterize top candidates identified in the computation screening studies. Impressive performance, comparable to or exceeding the storage characteristics of the best incumbent adsorbents, has been demonstrated from several of the recently synthesized materials (e.g., MFU-4l, PCN-61). Although solid progress has been achieved, it is not clear whether a dominant chemical and/or structural property/topology has been identified as being most critical for enhanced storage. It will be important to focus on this issue to effectively guide future work. There is one minor point: creation of open metal sites requires removal of solvent molecules from the structure. Since incomplete solvent removal limits sorbent performance, it is worthwhile to consider whether removal of solvent molecules depends on the structure/topology.
- The project has demonstrated over 45 g/L and 13% specific capacity on a material basis from 100 bar using 83 K of temperature swing. Theoretical values were used to train the algorithm to seek the best MOFs. The researchers then made one of the best ones and again got over 45 g/L using PT swing. The researchers tuned it further and got 9.5% and over 50 g/L in PT swing. This material also could be reactivated after air exposure with little loss; that is an important point. Theory suggested that PCN-61 might be good, too. Results were a little shy of prediction, but 8% and 48 g/L were still delivered in PT swing.
- The researchers have rapidly approached the go/no-go milestone that they have set for themselves. They have made solid, steady progress in spite of COVID.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- Useful collaborations have been established with National Institute of Standards and Technology (NIST) (primarily isotherm testing) and the National Renewable Energy Laboratory (NREL) (sorbent performance and experimental validation). The interactions among collaborating organizations appear to be well-coordinated and -managed. No other collaborations with the HyMARC core team are apparent. Also, it is surprising that, given the large overlap in project direction and scope, more active interactions with the University of Michigan group have not been established.
- There is very good coordination with the NIST in obtaining high-pressure sorption data, which have subsequently been validated by work at NREL.
- There is good cooperation within the team. There is value in getting structure and data from NIST and, of course, in NREL validation.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Providing experimentally verified rapid-throughput screening of a very large database of sorbent structure types can support the fundamental understanding of what barriers exist in breaking through the roughly 50 g/L hydrogen capacity “ceiling,” which in principle could lead to materials that enable lower-pressure, lower-cost storage systems. This potential result is highly relevant and impactful to DOE’s Hydrogen Program.
- This is a potentially impactful project that is well-aligned with DOE research, development, and demonstration objectives and goals for improved hydrogen storage in adsorbent systems. Although similar to the University of Michigan screening work, this project extends the computational parameter space to include a large number of different structural topologies. The project provides DOE with a new look at promising candidates for improved hydrogen adsorption, and the project has significant potential to advance progress in this important technology area.
- The project is well-aligned—it seeks to improve capacity and thus reduce mass and volume and cost of storage material through higher capacity and milder conditions.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The future work is a direct and logical extension of the earlier technical effort. In addition, the investigation of MOFs functionalized with metal catecholates has been initiated, and experimental validation of simulation results is under way. This is an interesting new direction that has intriguing potential. Project milestones are unambiguous, and a quantitative go/no-go objective for Year 1 is in place. There is a minor point: there is no mention of future efforts to increase packing density, although it seems possible that limited packing density is an issue. If so, a description of a plan to increase the density would be helpful.
- This is a good team that combines theory and simulation with synthesis and characterization. The future plans take full advantage of these capabilities, and it is expected that the current level of productivity will continue.
- Extending the methods to 300 K (just pressure swing) materials that are predicted to exceed 2.8% and 18 g/L makes sense. One suggestion is that working to clean up the MOFs and/or look for damage while in transit to the test site would be good and a fast way to potentially improve the material results.

Project strengths:

- The project has an excellent team, combining strengths in characterization and synthesis with computation and simulation. The machine learning aspects and the development of a descriptor that contains the energy landscape of hydrogen molecules on or at the surfaces of sorbents seem to comprise a powerful approach. Apparently, hybrid descriptors are also in the plan and are expected to further advance the machine learning aspects of this project.

- This seedling project has potential to generate new, improved adsorbent materials for hydrogen storage. The research and development team and collaborators are highly capable and have expertise in all relevant areas. This is facilitating rapid and efficient progress.
- There is very active cooperation between the theory and experiment teams. Limiting the MOF theoretic analysis to those MOFs likely to be possible to make improves efficiency.

Project weaknesses:

- At this stage, no major weaknesses or deficiencies have been identified. To avoid duplication of effort, communication and collaboration with the University of Michigan high-throughput screening group might be helpful.
- The best results are based on a PT swing, but the researchers do not appear to have studied the impact on use.

Recommendations for additions/deletions to project scope:

- There are no suggestions for major revisions. There is one minor point: as was pointed out in the future work section, increasing the MOF packing density is an issue that could be explored further. Collaboration with the University of Michigan group would ensure that computation and screening efforts are not duplicated.
- Perhaps having some communication between this project and Jeff Long's project vis-à-vis the catecholate approach could add value to both projects.
- All results are based on a significant temperature swing. In a real tank, this will have significant cost when it is time to refill, as the material and tank will need to be cooled. The project team should look at the overall scenario. Also, the MOFs should be checked for damage after testing to see if the validation values might be low because of changes that might have occurred in transport.

Project #ST-211: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Optimal Adsorbents for Low-Cost Storage of Natural Gas and Hydrogen: Computational Identification, Experimental Demonstration, and System-Level Projection

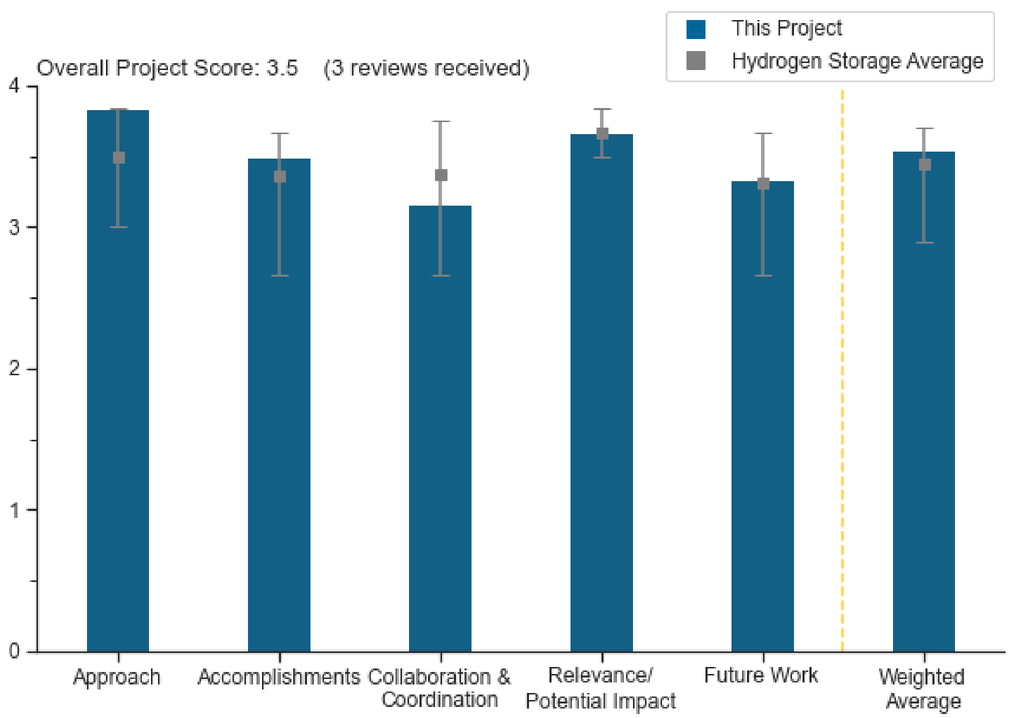
Don Siegel, University of Michigan

DOE Contract #	DE-EE0008814
Start and End Dates	1/1/2020 to 12/31/2022
Partners/Collaborators	Ford Motor Company, Hydrogen Storage Engineering Center of Excellence, Savannah River National Laboratory
Barriers Addressed	• Volumetric density • Gravimetric density

Project Goal and Brief Summary

This project aims to demonstrate adsorbents that, when incorporated into an adsorbed natural gas system, have the potential to surpass the capacity of compressed natural gas systems. If successful, this project will allow for smaller and lighter natural gas storage systems that operate at lower pressures, overcoming a significant barrier to the deployment of natural gas vehicles with long driving ranges. The project will use computational screening and machine learning techniques to identify target adsorbents with high capacities for synthetic exploration.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project provides for the application of a significant amount of knowledge of hydrogen sorption and transfers it to an examination of materials for natural gas sorption. The focus is on searching for and experimentally validating the gravimetric and volumetric capacities of candidate materials that have been identified by modeling and simulation combined with machine learning algorithms. This approach appears to be very much state of the art and is directly addressing key barriers that are common in hydrogen and natural gas sorption for applications important to the U.S. Department of Energy, such as for onboard storage of natural gas or hydrogen for medium- and heavy-duty trucks.
- The project builds upon extensive prior work devoted to identifying optimum metal–organic framework (MOF) adsorbents for hydrogen storage. The high-throughput approach combines crystal structure analysis, grand canonical Monte Carlo simulation (GCMC), and machine learning to systematically identify MOFs for high-capacity methane storage. The approach is novel and powerful, allowing for the identification and evaluation of a huge number (>500,000) of real and hypothetical MOFs having high usable volumetric and gravimetric capacity for natural gas (NG). Usable capacities for candidates identified from application of the computational screening are compared with benchmark materials, and results from those characterizations provide the foundation for further materials synthesis and testing. The project is well-focused on overcoming limitations of conventional NG storage approaches (e.g., compressed natural gas [CNG] systems).
- The exhaustive computational process offers an excellent chance for progress, and the underlying theoretical fundamentals have been tested extensively, so this is a sound approach. Screening is based on machine learning, not direct calculation, for speed. The regression to complete simulation is quite good in general. Using a well-understood benchmark material and one that has excellent performance itself is a challenging but excellent strategy. The system-level component (while on pause at present) puts this effort above other similar projects that look only at materials.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Solid progress was achieved on extending the prior work on hydrogen adsorbents to MOF adsorbents for NG storage. A high-throughput methodology similar to that used for the hydrogen work is employed, with an emphasis on evaluating different interatomic potentials suitable for open metal and non-metal adsorption sites. The comprehensive screening approach was successful in identifying several MOFs that potentially surpass the performance of HKUST-1, a leading incumbent. The computational results offer a straightforward pathway to subsequent synthesis and testing of MOFs optimized for NG storage capacity. Raman spectroscopy was demonstrated to be a useful method for near-real-time measurement of MOF sorption kinetics. The authors have used Raman spectroscopy to monitor the C-H stretch for bound methane at 2910 cm^{-1} in order to infer methane sorption kinetics. It could be possible to use the same method to monitor hydrogen adsorption in MOFs using the H-H stretch at ~4160 cm^{-1}.
- The researchers have made good progress, especially in this bizarre year. They passed their go/no-go milestone. The potentials they developed have been demonstrated as giving good agreement with data. Error is only a few percent of the value with a single set of generalized potentials. With experiments, the researchers showed that equilibration is on the order of seconds, which is important for control in fueling and use. The team has identified hundreds of materials that might give as much as 10% more volumetric capacity and double or triple the gravimetric capacity of useable CNG. This was determined using the longer GCMC modeling. The researchers proved out the machine learning model so that, in the future, they can test an order of magnitude more MOFs in a very short time. The project then made USTA-76, and it did outperform the benchmark in a pressure swing trial.
- The well-thought-out modeling and simulation approach coupled to a machine learning approach has led to a number of potential high-capacity candidates. Many of these have been experimentally validated through synthesis and characterization. The modeling work has been very successful in predicting the sorption

properties of MOFs. There is excellent progress toward the milestones. The unexpected departure of a team member that was providing storage system-level modeling has hampered that portion of the project; the remaining team members are actively working to mitigate this unforeseeable gap in the project.

Question 3: Collaboration and coordination

This project was rated **3.2** for its engagement with and coordination of project partners and interaction with other entities.

- Close and effective interactions among investigators at the University of Michigan (chemical and mechanical engineering departments), Savannah River National Laboratory, Ford Motor Company, and the Hydrogen Storage Engineering Center of Excellence have accelerated progress. The project is well-managed, and collaborations are well-coordinated. Future work may involve a more extensive collaboration with an industrial partner (e.g., Ford Motor Company) to facilitate potential product development. As pointed out by the principal investigator (PI), the departure of the co-PI, D. Tamburello, from the project has limited the system modeling work. Efforts are under way to find a person to lead this important aspect of the project.
- Up to the unexpected departure of the systems modeling expert on the project, the project exhibited good collaboration.
- There is not much collaboration outside the project, but there is good coordination inside it between three partners.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This novel and impactful project is well-aligned with DOE research, development, and demonstration objectives and goals for improved storage of natural gas. The project provides DOE with a comprehensive offering of potential candidates for improved CH_4 adsorption, and the project has significant potential to advance progress in an important technology area within the DOE energy portfolio.
- The project is addressing key issues and barriers for natural gas storage that have been leveraged by previous work on hydrogen sorption. These two areas are objectives of both the DOE Hydrogen Program and the Vehicle Technologies Office (VTO).
- While CNG might not seem relevant, the Hydrogen Program expanded and partnered with VTO, and this does fall squarely in the desired goal of increasing storage density of NG for use in transport. Additionally, there is some chance, if small, that this will help in our understanding of how to store hydrogen if there are fundamental and applicable rules of storage discovered.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Future work follows logically and reasonably from the current technical effort. The future focus will undoubtedly be on synthesis and testing of MOFs identified in the computational screening work. An important issue that should be addressed is potential identification and mitigation of adsorption site poisoning by (non-methane) contaminants that may be present in the natural gas source. In addition, a detailed plan is needed to address the daunting challenge of efficiently down-selecting the most appropriate candidates for subsequent synthesis and characterization.
- Future work is on-task and seems sound.
- The team has future plans that will maintain the project’s focus on high-capacity sorbents and will seek out a path to mitigate the departure of the systems modeling collaborator.

Project strengths:

- This is a first-rate project that addresses an important DOE technology need. A highly capable team with expertise in all relevant areas is conducting the technical effort. The project is well-managed and -coordinated. (The PI continues to provide clearly stated, candid, and succinct presentation and review materials, which is appreciated.)

- There is a great team for theory and lab development of MOFs. The team seems to have the best monolayer system for rapidly and accurately screening MOFs. The project uses theory at material and system levels to work toward a viable product.
- There is a very cohesive, well-experienced team in the modeling and the experimental areas and excellent integration among the team members.

Project weaknesses:

- Only two (minor) weaknesses are evident:
  - The vast number of materials identified by computation cannot all be synthesized. Implementation of efficient method(s) for down-selection of materials for synthesis remains problematic.
  - As pointed out in the future work section, contaminants in the NG gas stream could create major problems. That issue should be addressed explicitly.
- The project lost the system partner and needs one to finish the plan.
- No weaknesses were detected.

Recommendations for additions/deletions to project scope:

- Apart from addressing the contaminant issue and identifying a partner to conduct system-level modeling (as discussed in the presentation), no additional revisions to project scope are recommended.
- It is suggested that the team also look at poisoning by S, P, and Si compounds found in landfill gas. Pacific Northwest National Laboratory or Argonne National Laboratory could be potentially good system partners, though someone in the gas industry would be even better.
- Depending on whether the team can identify a storage systems modeler, the project may or may not have to alter the project scope.

Project #ST-212: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Methane and Hydrogen Storage with Porous Cage-Based Composite Materials

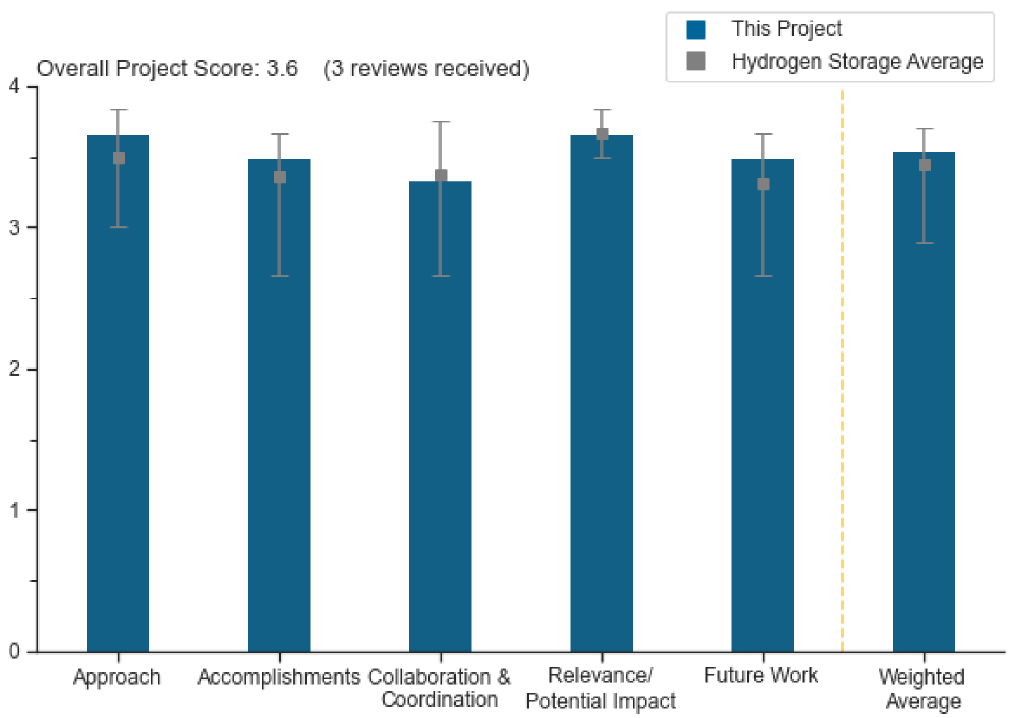
Eric Bloch, University of Delaware

DOE Contract #	DE-EE0008813
Start and End Dates	11/15/2019 to 11/30/2022
Partners/Collaborators	National Institute of Standards and Technology, National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, University of California, Berkeley
Barriers Addressed	• System weight and volume • System cost • Efficiency • Lack of understanding of physisorption and chemisorption

Project Goal and Brief Summary

Metal–organic frameworks (MOFs) have low bulk densities that present challenges to their use as methane and hydrogen storage materials. This project will attempt to address those shortcomings by preparing high-capacity soluble absorbents that can be placed in the space between MOF crystals, resulting in a porous cage–MOF composite with increased density and volumetric storage capacity.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The idea—to fill in between MOFs with “cages” that also hold hydrogen—is clever, and it seems to be playing out. Low-pressure screening is innovative.
- The approach is focused on maximizing the storage density of sorbent materials, which can have an impact on the barriers related to storage capacity, cost, and efficiency.
- Increasing volumetric performance of MOF powders or compacts (a primary goal of this project) is an important objective. It is unclear from the presentation how the densities of MOF powders are being measured (shaking for a given number of iterations, pressing, etc.) or whether these measurements are being conducted in a repeatable fashion.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The approach of filling the voids between particles of a sorption material with a molecular sorbent is simple but elegant and appears to be novel. If successful, the team anticipates an improvement of 25% in the sorption capacity of these materials for hydrogen and methane/natural gas. This, in turn, has impacts on the goals of both the DOE Hydrogen Program and the Vehicle Technologies Office.
- The researchers made reasonable progress; they selected and made MOFs and cages and created a composite. The project met the go/no-go with 37% improvement over MOF alone. While results were based on total capacity, it appears that the usable capacity has also improved by enough to meet project goals. The researchers found that there is no real preferred cage for any particular MOF, so they can go for ones that are easy to make and to add to the MOFs—and, of course, favor ones that are cheap.
- Accounting for a slowdown due to Covid-19, this project has made excellent progress in its first year.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- Given the circumstances of the last year, the project is doing well in collaborating with the National Institute of Standards and Technology and the National Renewable Energy Laboratory on materials characterization and validation and is having discussions with one of the key sorption experts within HyMARC: Jeff Long of Lawrence Berkeley National Laboratory and the University of California, Berkeley.
- There is good interaction for a smaller project, and the interactions have been useful to the team.
- The project team is collaborating adequately with others as needed.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project addresses packaging problems with MOFs by placing a material between crystals, so it does address a relevant problem.
- Improving the volumetric and gravimetric capacities of MOF-type sorbents for hydrogen or methane supports the goals and objectives of the DOE Hydrogen Program, as well as those of the Vehicle Technologies Office.
- A successful outcome would have a positive impact on the practical energy densities of MOFs for storage of hydrogen or natural gas.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- Future work is directed at developing the necessary understanding of the interplay among the MOFs and the interstitial molecular adsorbent cages, including durability of these composite materials. The future work is well-focused on achieving enhanced capacities for gas storage, an important barrier to application.
- The team plans to look at compression and cycling durability and attempt to tune results to better capacity. These are all good ideas.
- The future plans are adequate.

Project strengths:

- This is a novel idea for easily improving capacity. It seems that there is no interaction between cage and MOF, so there will be no need to tune the cage to each MOF, so the team can look for an inexpensive and high-capacity material.
- This is a novel approach that is well-thought-out, well-explained, and well-executed.
- Many MOFs have been evaluated.

Project weaknesses:

- The methodology for densification needs to be standardized (or at least better explained) so that repeatability can be ensured.
- There are no serious ones. The team ought to focus on useable gas rather than total capacity.
- No weaknesses were detected.

Recommendations for additions/deletions to project scope:

- The researchers really need to show the usable capacity and would be better off doing their analysis and their predictions that way because that is what will matter to users. The project should look at the impacts of higher hydrocarbons and normal poisons in landfill gas (gases containing P, S, Si) on cage performance. It would be good to test kinetics relative to the same MOF with no cages.
- This project may benefit from collaboration with the team at the University of Michigan, which is performing similar experiments.
- The principal investigator seems to have the project well in hand.

Project #ST-214: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Heteroatom-Modified and Compacted Zeolite-Templated Carbons for Gas Storage

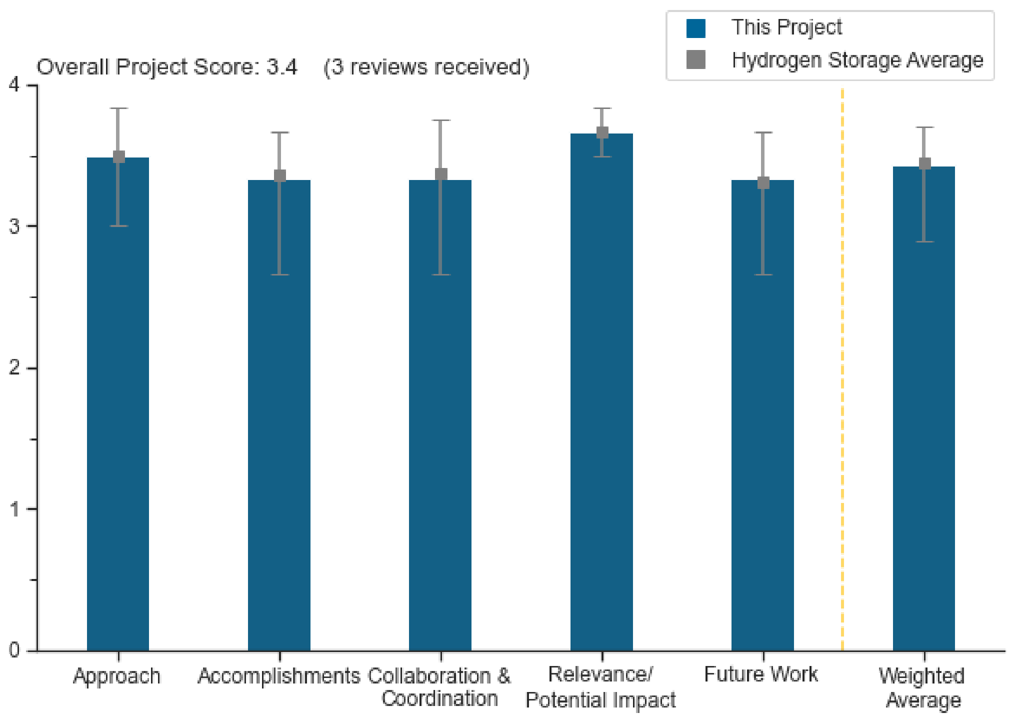
Nicholas Stadie, Montana State University

DOE Contract #	DE-EE0008815
Start and End Dates	10/1/2019 to 12/31/2022
Partners/Collaborators	California Institute of Technology, HyMARC, Tohoku University
Barriers Addressed	• Lack of understanding of (methane) physisorption • System weight and volume • System cost

Project Goal and Brief Summary

This project seeks to increase the volumetric energy density of zeolite-templated carbon (ZTC) as a methane storage medium, while reducing its cost. This research team will first determine the ultimate volumetric methane delivery limits in porous carbon framework materials, focusing on ZTCs as model absorbents. The team will quantify the effect of boron–nitrogen heteroatom dopants on methane adsorption thermodynamics and storage/delivery at near-room temperature. Researchers will then optimize conditions for the densification of graphene-like fragments in ordered pore networks suitable for methane adsorptive storage and delivery.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The use of doped ZTCs for methane storage is novel and innovative. The homogeneous, metal-free binding sites and controlled pore size in ZTCs provide a unique adsorption environment that can potentially overcome problems inherent in other (primarily heterogeneous) adsorbent systems. This approach is a departure from more conventional adsorption methods, and it provides an intriguing opportunity to facilitate high-capacity methane storage and improved delivery. B and N doping of the porous ZTCs may be useful for tailoring the CH_4 binding energy. Theoretical studies of dopant interactions are providing useful guidance for the experimental work. In addition, compaction of the adsorbent by densification into robust pellets is enabling achievement of higher volumetric densities.
- This is a good approach: using a metal-free framework to try to get a large amount of surface in the "perfect" binding energy region and then tuning that energy with heteroatom substitution. ZTCs are a scalable technology; they could be made at a potentially modest price in enormous amounts, if the approach is successful.
- Well-defined project objectives address barriers to enhanced methane/natural gas adsorption on porous carbons. The experimental and theoretical approach is well-thought-out and logical. As this is a "seedling" project, collaborations with the HyMARC team have been identified mainly in the area of spectroscopic characterization but also in an international collaboration on the compaction of high-density nitrogen-doped carbons.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Solid progress has been made on this project in 2020–2021. Increase in volumetric density has been achieved by hot-pressing the ZTC with a reduced graphene oxide (rGO) binder to form robust pellets. This densification approach provides a straightforward pathway to meeting DOE goals for CH_4 capacity. The initial studies of heteroatom doping are interesting and provocative. First principles quantum mechanical calculations suggest that nitrogen doping of the ZTC framework should yield enhanced methane binding, whereas boron doping actually suppresses binding. This difference is surprising and requires more detailed validation. The perceived disparity between dopants notwithstanding, the theoretical results clearly suggest that heteroatom dopants/additives can be effective in controlling the binding energy. However, retention of homogeneity with increased dopant/additive incorporation could be problematic. Overall, the dopant work is clearly important for further development of ZTC-based systems for methane storage, and it remains a critical topic for future work. Reversibility and efficient sorption cycling in the densified pellets are also important issues. Although the ZTC system apparently shows reasonable reversibility, swelling and breakage of the pellets occur upon cycling. The impact of pellet degradation during cycling on the incorporation of the densified ZTC material in a practical system remains an outstanding issue.
- The project has been productive so far, with modeling and simulations coupled with experiment well under way. Key measurements are being obtained, and early milestones are being achieved or approached. Higher binding enthalpies of methane have been observed at low to medium methane loading, which is a significant observation. One main goal is to synthesize homogeneously substituted nitrogen-doped carbon derived from the zeolite template approach. Computational simulations of a highly idealized model of nitrogen sites in a graphene-like environment have predicted enhanced binding of methane on such a site. So far, experimental verification of the homogeneity of sites, as indicated by a constant heat of adsorption versus loading, has been elusive. This may be related to the lack of site homogeneity in the realistic material as synthesized, where there are likely a variety of carbon chemical environments and, hence, a variety of different types of nitrogen-containing doped sites (pyrrolic, pyridinic, etc.) that likely have a variety of binding enthalpies with methane. The plan allows for more characterization using HyMARC capabilities to explore the local electronic and chemical structure at the nitrogen and carbon sites that may shed additional light on this matter. Approaches to densification of the zeolite-templated, nitrogen-doped carbons have been quite successful so far. However, the principal investigator (PI) indicates that, with

several adsorption–desorption cycles, the mechanical durability may be compromised. More work is planned.

- There is good progress on pellet formation with minimal function loss. The project is close to crystalline values of surface area versus density, especially in a specific surface area basis—basically, 200 v/V delivery at room temperature and max 100 bar pressure. The researchers used theory to suggest a poor chance of progress using boron, so they were able to focus on a nitrogen heteroatom addition. They were able to add nitrogen to the matrix and found increased binding but a high slope of the binding energy curve.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- Effective collaborations with the California Institute of Technology (Caltech), Tohuku University, and HyMARC have been established, and these interactions are enhancing progress on the project. The research and development (R&D) team is highly capable and has expertise in all relevant project areas. The project is well-managed, and all external collaborations are well-coordinated. A more active collaboration with the nuclear magnetic resonance (NMR) group at Pacific Northwest National Laboratory (PNNL) is recommended.
- There is good collaboration with colleagues at Caltech and at Tohoku University, with good plans for expanded collaborations with HyMARC capability leaders in the future.
- The collaboration is about right for a project of this size. There is cooperation between partners but also use of DOE resources to get high-end work done.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This innovative project is a welcome addition to the DOE R&D portfolio. The project is a useful and potentially impactful complement to other gaseous adsorption projects. DOE has identified methane storage as an important emerging technology area, and this project has potential to overcome many of the critical obstacles to achieving high-capacity storage and delivery. The work is well-aligned with DOE research, development, and demonstration objectives and goals.
- Methane adsorption is now part of the DOE Hydrogen Program goal structure and also supports DOE's Vehicle Technologies Office. Plus, the general learnings may be clues to how to do the same thing with hydrogen. The project is working on reducing the system's cost, volume, and mass, all of which are spot on for relevance.
- Striving to enhance adsorption of methane on high-surface-area adsorbents via novel approaches may advance the state of the art and is relevant to the goals of both the DOE Hydrogen Program and the Vehicle Technologies Office.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Future work focuses on improving N doping and densification while maintaining structural homogeneity. These are challenging tasks, but a reasonable approach for meeting the goals is in place. Cycling and reversibility issues are not inconsequential, and greater emphasis on finding ways to maintain homogeneity and capacity during sorption cycling is recommended. Likewise, questions remain about the accuracy of the first principles calculations with regard to heteroatom doping type and efficiency. Based on the calculations, nitrogen has been down-selected. However, if time and resources permit, synthesis and densification of a boron-doped sample would be useful in order to validate the theoretical predictions and to probe a different doping environment. Although PNNL is a collaborating institution, future work on solid-state NMR at PNNL is not mentioned. That powerful diagnostic capability could be employed effectively to probe structural details and provide important mechanistic understanding; the project team is urged to utilize that capability more extensively in future work.

- The researchers are focused on regaining homogeneity through densification and heteroatom addition, which is exactly what they need to do. N-bearing precursors have to be smaller than benzene to make ZTC; multiple precursors might be needed. The researchers should try getting as much N in as possible. They may look at properly packed powders to get dense powders.
- The project team is very good, highly capable, and will likely overcome many of the experimental hurdles and move the project forward. Whether the project's ultimate goal of achieving homogeneously doped carbons to enable high heats of adsorption independent of loading can be achieved is still to be determined.

Project strengths:

- This is a unique and potentially impactful project being conducted by a highly capable R&D team. The approach is innovative, and it serves as a new and important complement to related methods for methane storage and delivery in adsorbent systems.
- This is a fairly flexible method. The project uses the center resources effectively. The PI is open to suggestions for improvement, more so than most PIs.
- There is a strong team combining simulation and modeling with experiment.

Project weaknesses:

- Homogeneity of the material is lost in both densification and heteroatom addition. This may be overcome yet, so it is not an inherent weakness.
- This is a minor weakness: the project may want to avoid getting too closely wed to the highly idealized homogeneous model of nitrogen-/boron-doped sites.
- Maintaining structural homogeneity at high dopant/additive concentrations and pellet densification remains a serious challenge to efficient reversibility and cycling. Although overcoming this obstacle is being addressed, the effectiveness of the proposed approaches remains an open question.

Recommendations for additions/deletions to project scope:

- As pointed out in the future work section, three topics for additional work are recommended (as time and funding permit): (1) synthesis and characterization of a boron-doped ZTC sample and subsequent comparison with a nitrogen-doped sample to validate the first principles predictions, (2) a more detailed characterization of sample integrity and reversible capacity upon sorption cycling, and (3) use of solid-state NMR (PNNL) to probe chemical environments and sorption mechanisms in the doped ZTC system.
- The project should use polydisperse crystals to get higher packing with no need to compress the sample. Maybe the team could make melamine inside the zeolite, if the precursor used is small enough. The project might benefit from a look at precursor methods to make melamine that would be compatible with zeolites.

Project #ST-215: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Developing A New Natural Gas Super-Absorbent Polymer

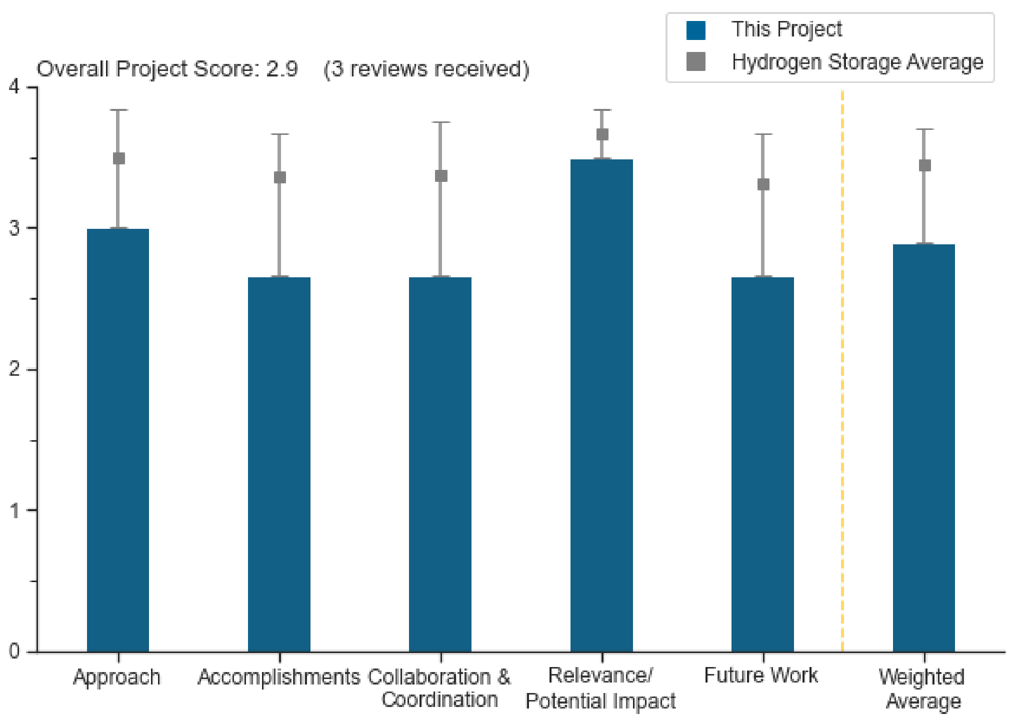
Mike Chung, The Pennsylvania State University

DOE Contract #	DE-EE0008811
Start and End Dates	10/1/2019 to 1/31/2023
Partners/Collaborators	HyMARC, National Renewable Energy Laboratory
Barriers Addressed	• Natural gas storage density, temperature, pressure • Polymer absorbent synthesis • High polymer surface area • Suitable natural gas binding energy • Charging/discharging rates

Project Goal and Brief Summary

Reduced-pressure natural gas storage in a materials-based system provides significant cost advantages over conventional liquefied or compressed natural gas storage. Such materials-based systems have the potential to reduce, or possibly eliminate, the need for expensive carbon fiber in natural gas fueling infrastructure. This project aims to synthesize new hydrocarbon polymers for use in materials-based storage systems for natural gas.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project uses inexpensive materials with known affinity for higher hydrocarbons. The researchers adjust backbone and substituent and cross-link content to achieve the best uptake. They are considering the cost of materials as an important factor, so they have a good chance of making a commercial product if they get good performance. The project is attempting to make the expansion internal, which should help with functionality in real systems.
- The use of polycyclic hydrocarbon polymers is a novel approach for uptake and delivery of methane. Synthesis of both doped and undoped hydrocarbon polymers, characterization of methane binding energies, and sorption capacity are the primary elements of the project. The project provides a pathway to overcoming at least some of the barriers (especially limits to volumetric capacity). However, thus far, insufficient focus is placed on the important issues of methane sorption kinetics and reversibility/cycling in the polymer materials.
- The project goals are adequately defined, and important barriers are recognized. The experimental design appears to be somewhat chaotic; design rules for development of polymers that might lead to enhanced methane adsorption have not yet been communicated.

Question 2: Accomplishments and progress

This project was rated **2.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Solid progress has been made in the synthesis and characterization of polycyclic aromatic networks having a variety of pore sizes and volumes and methane binding energies. A promising polycyclic boron-doped aromatic network candidate system (PAH – "B-pitch") has emerged from the initial studies. The methane binding energy (~18 kJ/mol) and volumetric energy density (~264 cm^3/cm^3) at 100 bar and room temperature are commensurate with a practical polymer-based methane storage system. However, there are many important issues concerning the suitability of the material for storage and delivery applications that must be addressed. These include, for example, what happens to the petrogel structure when the methane is liberated—i.e., whether the swelling is reversed. It is also unclear whether data are available concerning the sorption kinetics and cycling efficiency (i.e., although it is suggested that mesoporous channels in the petrogel matrix can facilitate fast kinetics and good cycling efficiency, no supporting data are provided). Also, since the polycyclic hydrocarbon swells dramatically during methane adsorption, packing density could be a serious issue. Thus far, the dominant emphasis has been on synthesis of hydrocarbon polymers. Future work must focus keenly on kinetics, reversibility, and the impacts of structural changes and packing loss issues on methane sorption efficiency.
- The researchers are focusing on making the swelling internal so that they get excellent kinetics and packaging. They are choosing side groups and cross-linking to accomplish this. The team will work with Pacific Northwest National Laboratory and do high-pressure methane nuclear magnetic resonance experiments to evaluate swelling. The project is getting 19–20 kJ/mol binding energy, which is a good range for 300 K operation, with 700 m^2/g area. Pitch was used for lower cost and better area up to 1800 m^2/g. The project does get 264 v/v at 295 K, but only about half is useable at the material level. The researchers still get roughly twice the capacity of pressure alone. It is somewhat hard to evaluate progress numerically based on the data presented. It is unclear whether they know how well (or not well) they are doing toward reaching goals.
- The progress has been satisfactory. It is unclear at this point that a logical progression in polymer structure and properties is being developed that can lead to logical design of polymers with improved methane sorption at high loading.

Question 3: Collaboration and coordination

This project was rated **2.7** for its engagement with and coordination of project partners and interaction with other entities.

- Useful collaborations with other investigators at The Pennsylvania State University and National Renewable Energy Laboratory (NREL) on design, synthesis, and characterization of new hydrocarbon materials are enhancing progress on the project. The principal investigator (PI) and his team are experts in hydrocarbon synthesis and characterization. The core HyMARC team could provide additional support and expertise for the essential work on kinetics and reversibility. The project seems to be well-managed and -coordinated, and detailed milestones and go/no-go decision points have been formulated.
- The collaboration is adequate for this work; it is mostly internal, with verification at NREL.
- While it is early days in this project, little detail was given as to what the plan is for collaborating with NREL to validate methane adsorption in polymeric systems, particularly where there may be issues of swelling.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- High-capacity storage and efficient delivery of methane at suitable temperatures and pressures are important DOE research, development, and demonstration objectives. Although this innovative project provides a path to achieving the goals, many questions remain, and they must be addressed in future work. Overall, the project has potential to advance progress on methane storage and to successfully address limitations of incumbent approaches.
- Natural gas storage at lower pressure is part of this Hydrogen and Fuel Cell Technologies Office/Vehicle Technologies Office area. The project is aligned.
- The goals of the project are well-aligned with DOE Hydrogen Program and Vehicle Technologies Office goals.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- The future work is a reasonable extension of the prior studies. However, the future work statement lacks sufficient detail to assess what will actually be done to achieve the stated objectives given in the summary. The most critical concern is the limited information regarding plans for evaluating and improving kinetics, reversibility, and cycling and packing density. These are vital project needs that require a thoughtful and detailed research plan. Also, a critical evaluation of major technical risks and mitigation strategies is needed.
- Listed areas are all valuable but seem to be sort of a scatter, with no real plan.
- A list of areas to investigate was presented without sufficient rationale or prioritization. It is difficult to tell what the specifics of the future experimental plan are going to be.

Project strengths:

- The PI and his team have considerable expertise and background in synthesis and testing of the novel methane sorption materials being developed in the project. The approach is innovative and has the potential to meet many of the DOE objectives for methane storage.
- The approach in using organic polymers for methane sorption is leveraged off of prior work in hydrocarbon sorption. The approach complements other Hydrogen Program projects that are focused on metal–organic frameworks and other porous materials approaches.
- This is based on previously proven technology and uses low-cost materials.

Project weaknesses:

- The project focus thus far has been almost entirely on materials synthesis and characterization. As stated above, the critical issues of sorption kinetics, reversibility, cycling efficiency, and impact of large structural changes on packing density and capacity have not been adequately addressed. Moreover, detailed plans to address these issues have not been provided.
- It is hard to numerically evaluate progress. Results are mostly qualitative with regard to gas uptake and release. The plan underlying the work is either loose or not well-communicated.
- The experimental design is not well-described and appeared rather chaotic.

Recommendations for additions/deletions to project scope:

- The project might be able to use neutron scattering to evaluate change in shape. The project needs to understand cycling durability and the impact of higher hydrocarbons and S and P and Si impurities, and the team needs to increase bulk density of the material and increase, or at least not lose, capacity in crystallites.
- As pointed out in earlier sections of this review, a keener focus on methane sorption kinetics, cycling efficiency, and the impact of large structural changes during sorption is strongly recommended.
- The project needs to accelerate the validation of sorption versus loading at NREL.

Project #ST-216: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: Hydrogen Release from Concentrated Media with Reusable Catalysts

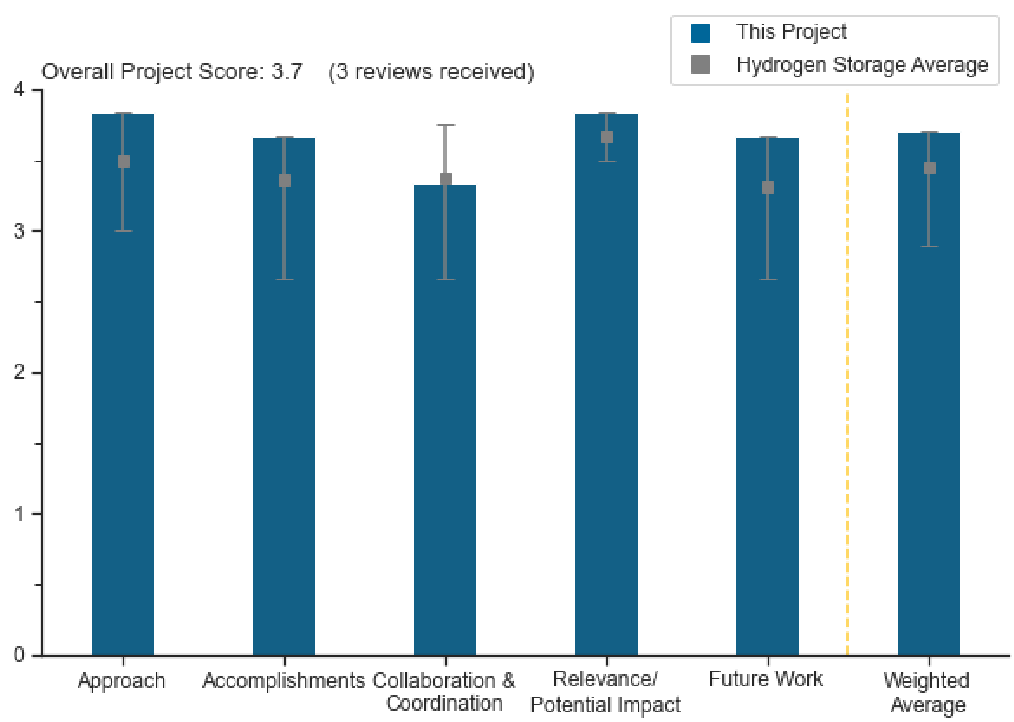
Travis Williams, University of Southern California

DOE Contract #	DE-EE0008825
Start and End Dates	10/1/2019 to 3/31/2023
Partners/Collaborators	Los Alamos National Laboratory
Barriers Addressed	• Generate hydrogen from formic acid: increase reaction scale, demonstrate hydrogen throughput, and remove CO_2 from output stream • Apply technology to blended fuels • Understand the molecular mechanism

Project Goal and Brief Summary

Hydrogen carriers such as formic acid have the potential to improve hydrogen delivery and storage pathways over existing compressed or liquid methods. This project aims to demonstrate on-demand hydrogen evolution from formic acid and formic acid fuel blends using a demonstration-scale flow reactor. Researchers will conduct molecular mechanistic studies to optimize the catalyst and fuel blend. A successful project outcome will further the ability to make hydrogen fuel available in distributed locations, which is vital for transportation applications.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is a good approach; using a catalyst is logical, and if it is regenerable, the use of Ir is only an upfront cost. Developing operating conditions is critical and is a good plan. The project is also looking for better catalysts and is building a pilot reactor to look for scale-up issues.
- The principal investigator has a very thorough understanding of what the barriers are and how to approach the landscape of experiments to make solid progress. The project is well-designed, well-thought-out, and well-executed.
- The project addresses relevant barriers and objectives.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Substantial progress on the very basic science aspects of the combined theory and mechanistic work has led to significant progress on the experimental front. The project is rapidly moving from small-scale batch reactors to moderate-scale continuous flow reactors to enable the exploration of the more applied aspects of catalyst durability, recovery, and hydrogen stream purification, among others. The high-level mechanistic work has led to the realization that the initial catalyst was modified at higher-temperature operation conditions and accessed a wholly new reaction manifold that could dehydrogenate mixed methanol/formic acid to generate hydrogen. The recent progress with regard to the project milestones not only has been met but also has far exceeded the researchers' expectations. Certain aspects of this progress have been validated at Pacific Northwest National Laboratory (PNNL). Good progress is being made in constructing a flow reactor to explore this chemistry at higher throughputs in a continuous mode more closely allied with future applications. This is daunting, as the safety requirements are strict for this sort of activity and the levels of hydrogen production anticipated. The project leadership is also highly cognizant and capable of forming the technology transfer opportunities this project presents.
- The project achieved over 3.9 L/hour at low conversion, which was well over the go/no-go criterion. PNNL demonstrated a rate of over 100 L/hour at pressure. Los Alamos National Laboratory (LANL) almost has the continuous reactor ready; this will be a key test. There is progress toward methanol tolerance. No data are presented, but the project may be able to use a carbene version of the catalyst at pressure (but not at low pressure). This ought to lower synthesis cost.
- No plots of hydrogen release versus temperature (T) and versus pressure (P) were presented. It is unclear whether these have been conducted. The presentation also did not include measurements or estimates of the efficiency for regeneration of the liquid carriers.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The collaboration with computational chemists at LANL has nicely augmented the University of Southern California mechanistic work, which has helped to move the project rapidly forward. The collaboration with the chemical engineering capability at LANL to assist in the design of the continuous flow reactor has also accelerated progress. This collaboration may also enhance the CO_2 separation tasks that lie ahead. Collaboration with scientists at PNNL to validate and confirm the reactivity and throughput at a somewhat higher scale also helped to advance the project in its early stages.
- There is good coordination with LANL. The project is also tied into PNNL for testing.
- LANL is a formal partner. PNNL is a collaborator.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Formic acid is a compelling hydrogen carrier by mass and has excellent thermodynamics from an energy consumption point of view, and the cost is modest. It could be implemented in bulk fairly readily if the release portion of the cycle could be figured out; thus, this is clearly aligned.
- The project is closely aligned with the objectives of the DOE Hydrogen Program and supports the work in developing hydrogen carriers for a variety of use cases. This work can lead to reductions in costs of delivered hydrogen by enabling the transport and eventual conversion to hydrogen at higher pressure, avoiding some compression costs for certain use cases.
- A viable liquid carrier for hydrogen would be a major breakthrough.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- This plan is sound; developing the flow reactor is critical and a high priority in the researchers' minds. It is important to show durability at peak rate concentration in a pressurized flow reactor. If they can run continuously at a high degree of conversion (and so high catalyst density), they will greatly increase their rate. The second critical issue is CO_2 separation from hydrogen. This is also a good issue to start solving.
- The future work flows logically from the progress to date and addresses key issues such as the development of a continuous process for the generation of hydrogen at pressure, the use of mixed methanol/formic acid fuels, catalyst durability under continuous processes, and hydrogen purification from CO_2 in a continuous process.
- No mention of regeneration efficiency is mentioned.

Project strengths:

- The catalyst has high rate at moderate temperature and generates high-pressure hydrogen. The catalyst seems to have good durability. The researchers are working with a commercial product in mind, so they are taking on the right issues. They are making a pilot-scale reactor to look at something closer to the intended system in commercial use.
- The project has a highly motivated and capable team and collaborators.
- This is a relevant project focused on an important goal.

Project weaknesses:

- Co-generation of CO_2 and hydrogen requires separation, which may be expensive.
- The apparent lack of data on hydrogen release versus T and P is a weakness; regeneration efficiency is unclear, and plans to measure efficiency are not communicated.

Recommendations for additions/deletions to project scope:

- The project should measure hydrogen release versus T and P and regeneration efficiency.

Project #ST-217: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: A Reversible Liquid Hydrogen Carrier System Based on Ammonium Formate and Captured Carbon Dioxide

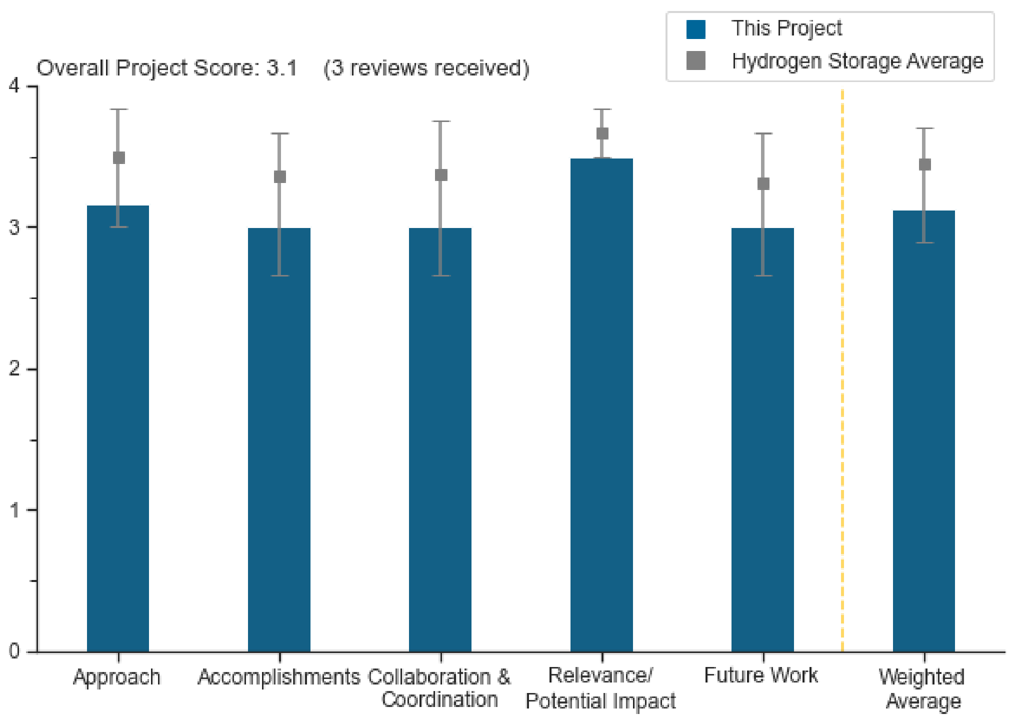
Hongfei Lin, Washington State University

DOE Contract #	DE-EE0008826
Start and End Dates	10/1/2019 to 1/31/2023
Partners/Collaborators	8 Rivers
Barriers Addressed	• Catalyst cost • Energy efficiency • Durability

Project Goal and Brief Summary

This project aims to build a prototype ammonium formate-based hydrogen uptake and release system and evaluate its technoeconomic potential for commercialization. If successful, this project will develop and demonstrate a new generation of hydrogenation/dehydrogenation catalysts superior to commercially available catalysts. Washington State University is collaborating with 8 Rivers and members of the Hydrogen Materials Advanced Research Consortium (HyMARC) on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project's approach includes a technoeconomic analysis (TEA) of hydrogen production from a liquid carrier, ammonium formate, and will assess a baseline cost for the hydrogen generated. As such, this project supports the objectives of the U.S. Department of Energy Hydrogen Program to drive toward reducing the cost of hydrogen and providing for a pathway for transportation of hydrogen in the form of a hydrogen carrier.
- This project has a good approach using parallel development of the catalyst system, creating both the support and the active metal/alloy.
- The project addresses important barriers.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project's progress is good. The project developed a support that uses half the active material but evolves more hydrogen, developed other supports and dispersions and selected one with 88% yield and stability over at least five runs, and developed a bimetal catalyst using metal that is 100 times cheaper than palladium with good stability in six runs and good hydrogen yield. The researchers think they are near that best alloy now. Their studies suggest deactivation could be due to leaching, but they see no clear evidence.
- The TEA has been delayed by COVID-19; the focus of the project to date has been on catalyst optimization. Without the guidance of a baseline TEA, it would appear to be difficult to know where the research and development (R&D) emphasis needs to be focused. It could be that catalyst development, optimization, and characterization is premature.
- The data presented did not appear to include measures of hydrogen release versus temperature and pressure. Measurements or estimations of reversibility and the efficiency of regeneration also appeared to be absent from the presentation. It is difficult to assess the promise of this approach without these data.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- There is decent cooperation inside the team, and it is getting help from Pacific Northwest National Laboratory (PNNL).
- Monthly conference calls with PNNL/HyMARC are occurring; it is unclear what the impact of these meetings have been from the materials presented.
- Some collaborations with Lawrence Livermore National Laboratory were noted. It is unclear what 8 Rivers is contributing to the project; no TEA was presented.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The potential impact of the proposed R&D could be high if successfully and logically executed. Developing cost-effective hydrogen carriers for certain use cases is relevant to the Hydrogen Program's objectives. In practice, the impact of this project will depend upon how well the TEA is performed, what the baseline cost for delivered hydrogen via this carrier system is determined to be, and to what extent additional identified R&D can impact that cost.

- Formate carriers could help deliver hydrogen over long distances. This aligns well.
- A viable liquid hydrogen carrier would be an impactful development.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The plan hits the main needs: try to lower or remove palladium by better understanding the mechanism and using that understanding to seek alternate pathways; optimize ammonium formate concentration to get the best performance; TEA to look at where cost needs to come out; determine rate-limiting step and what the catalyst needs to do to help that. Looking at the flow reactor data will help the researchers understand the true nature of reaction and durability.
- The incorporation of the reactor work should provide data that supports the TEA in providing kinetics data, information on the concentration of impurities and carbon dioxide separation, and information on catalyst deactivation/regeneration, all of which can affect overall costs but also focus future work.
- The project needs measurements of hydrogen release versus temperature and pressure, regeneration efficiency measurements, and TEAs.

Project strengths:

- Lowering platinum group metal content and simultaneously developing support and active material to get a well-tailored catalytic system are strengths. The team is well situated to do its respective tasks, catalyst development, and TEA.
- This is an interesting system to explore as a hydrogen carrier that is potentially of high capacity and can deliver hydrogen at high rates at some pressure that is to be determined.
- The project is focusing on a promising material.

Project weaknesses:

- The focus on catalyst refinements appears premature in the absence of guidance from a baseline TEA.
- Many key measurements and analyses have not yet been performed. There is no mention of these in the future work statements.
- There is no ability to look at technical scale-up issues. There is no meaningful data on the durability of the catalyst, which may lead the team down an avenue with modest up-front cost but no chance of good durability, resulting in a system that is thus economically untenable overall.

Recommendations for additions/deletions to project scope:

- Start generating data on conversion and kinetics (rate) versus cycles or hydrogen produced since the start of the test. That data can tell the project if the catalyst under test has suitable durability. A high-level TEA should be able to give a target that the project must beat.
- The project should accelerate the baseline TEA and identify the major cost drivers based on the currently available catalyst and product stream characteristics/impurities. The project should pay attention to impurities other than CO_2 in the evolved gas stream. Separations costs can be a major contributor to the overall cost of a process, and any issues surrounding this can have a significant impact on cost if no mitigation strategies are put in place.

Project #ST-218: Hydrogen Materials–Advanced Research Consortium (HyMARC) Seedling: High-Capacity, Step-Shaped Hydrogen Adsorption in Robust, Pore-Gating Zeolitic Imidazolate Frameworks

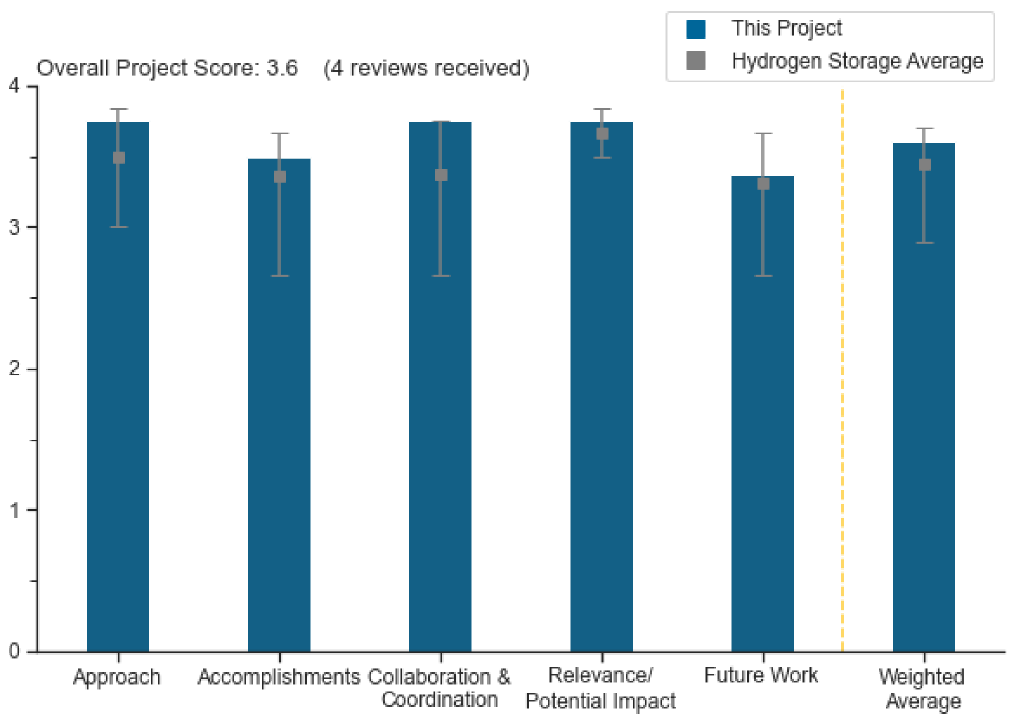
Michael McGuirk, Colorado School of Mines

DOE Contract #	DE-EE0008823
Start and End Dates	2/27/2020 to 2/28/2023
Partners/Collaborators	National Renewable Energy Laboratory, Lawrence Livermore National Laboratory, National Institute of Standards and Technology, SLAC National Accelerator Laboratory
Barriers Addressed	• The cost of producing and delivering hydrogen from zero- or near-zero-carbon sources must be reduced • Compact, lightweight, and low-cost hydrogen storage systems must be developed

Project Goal and Brief Summary

Current approaches to hydrogen transport and delivery entail extreme pressures or cryogenic liquefaction—both energy-intensive processes that increase costs. An alternative is using porous adsorbents that can densify hydrogen under milder conditions by providing enhanced surface area for hydrogen molecular adsorption. However, most porous adsorbents adsorb hydrogen most strongly at low pressures and temperatures. This project is exploring stimulus-responsive porous adsorbents that, through step-shaped adsorption–desorption profiles, can deliver their entire adsorbed capacity with minimal energetic input. These materials could store large quantities of hydrogen under mild conditions, as well as transport and deliver hydrogen with only small swings in pressure and temperature.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach adopted for the development and implementation of "stimulus-responsive porous adsorbent" materials for high-capacity hydrogen transport and delivery is novel and innovative. This project exploits the unique characteristics of selected zeolitic imidazolate frameworks (ZIFs) that undergo reversible porous/non-porous structural transitions to generate step-shaped sorption profiles. The work in progress includes sorption measurements in baseline systems and modification of organic linkers to facilitate step-shaped sorption in a model system (CdIF-13 [cadmium imidazolate framework 13]). This work should provide a foundation for future efforts devoted to optimizing adsorption and desorption properties in relevant pressure regimes. Overall, this is an exciting approach that can potentially overcome many of the barriers faced by other (rigid) porous-adsorbent approaches for high-capacity hydrogen storage and delivery.
- This project has an excellent approach. The use of flexible metal–organic frameworks (MOFs) offers a possibly unique opportunity to greatly increase usable capacity (by all but eliminating the five bar capacity, so total capacity and usable capacity almost match). There is a suitable plan to work from known flexible MOFs toward ones with higher capacity. Also, it is a good plan to tune opening pressure and capacity via new linkers and adjusting the shape of the adsorption curve with metal center substitution. The use of a family of Cd-based ZIFs to learn more about how metal impacts these materials' functional properties is probably a good plan; certainly there is every reason to think that valuable knowledge will come from this approach. The key is to gain sufficient knowledge that can be used (with a high probability of success) to design a high-functioning material with low safety risk.
- This is a high-risk, high-reward opportunity that leverages what has been learned from methane adsorption in pore-gating MOFs and attempts to port that to the adsorption of hydrogen. The project is focused on the critical barriers of employing pore-gating MOFs to enhancing hydrogen sorption above and beyond conventional MOFs, potentially reducing the cost of storing and delivering hydrogen.
- The objectives and critical barriers are clearly defined and are being addressed.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Significant progress has been made in 2020 and 2021. Notably, the first direct proof of step-shaped hydrogen adsorption validated the principal rationale/hypothesis for the project and provided a solid basis for future work. Neutron and x-ray diffraction diagnostics provided insight into the structural changes that accompany step-shaped hydrogen sorption processes. In situ, variable temperature neutron diffraction proved to be a powerful tool to identify primary adsorption sites. In addition, computational modeling was used effectively to identify possible intermediate structures present during the phase change in CdIF-13 and ZIF-7 model systems. The progress to date is impressive, and it inspires confidence that this approach will ultimately result in superior material systems for hydrogen storage and delivery. On another note, packing density is often an issue for adsorbent systems capable of meeting goals for hydrogen capacity. It would help to know whether the ZIF systems studied in this work require increased packing density to achieve acceptable storage and delivery capacity and performance.
- This project has made nice progress. It showed that it could get a stepped adsorption curve with ZIF-7. The best performance occurred at 100 K and 110 K. The project made 13 members of the CdIF-13 ZIF family ahead of schedule. It is anticipated that these members will have a flatter pre-step adsorption (relative to ZIF-7) based on a structure that more tightly closes the "door" of the ZIF in the non-activated state. The researchers were able to show with propane that they could tune the threshold pressure by changing the ratio of linkers. They were also able to show that the ratio of fluorinated linkers can greatly shift the pressure of the step. The team hopes that the Jeff Long laboratory can validate the results. Using x-ray and neutron diffraction, the team also measured the exact structure in open and closed formations in situ. It identified adsorption sites before and after opening the structure. It showed that the material functions as hypothesized, and it validated the concept that the electron-rich substituents on linkers increase the heat of

adsorption. The project modeled the energy of intermediate states, which cannot be captured experimentally.

- This project has moved forward in a logical, well-thought-out manner. Delays due to COVID-19 have largely been mitigated, which is a remarkable accomplishment on its own. The effort in the syntheses of key materials has been very productive, and the project has demonstrated step-like adsorption of hydrogen—a major milestone. There are some issues regarding access to the Hydrogen Materials–Advanced Research Consortium (HyMARC) high-pressure hydrogen adsorption capabilities that are temporarily offline; the principal investigator (PI) is actively looking at workarounds. The team has solved single crystal x-ray and powder neutron diffraction analyses of key materials, including some in various states of adsorption, in collaboration with the National Institute of Standards and Technology (NIST). These measurements provide some valuable details as to the structural/energetic landscape along the trajectories of hydrogen adsorption in these materials that provide guidance to future experimentation. The collaboration with the HyMARC simulation and modeling capability at Lawrence Livermore National Laboratory (LLNL) has provided insight into the energetics of adsorption at various gas loadings that will also help direct materials modification efforts.
- This project was significantly slowed down by COVID-19. Some good progress on synthesis has been made. The delays in staffing the project and in measurements of hydrogen uptake were noted. The first go/no-go milestone has not yet been assessed due to these delays. The team should not be penalized for these delays, as the delays are beyond the team's control.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- Extensive and valuable collaborations with HyMARC investigators at the National Renewable Energy Laboratory (NREL), NIST, LLNL, and Stanford Linear Accelerator Center (SLAC) are evident. The numerous contributions from those collaborating institutions are significantly enhancing progress on both the experimental and computational modeling aspects of the project. The collaborations are well coordinated, and the overall project is well managed. The core research and development team and collaborating researchers are highly capable, having expertise in all relevant areas of this seedling project. Collaboration with Pacific Northwest National Laboratory (PNNL) on the characterization of transition intermediates using in situ nuclear magnetic resonance (NMR) is recommended. A HyMARC project on MOFs with step-shaped adsorption isotherms has been initiated (see slide 12 in Annual Merit Review 2021 presentation ST-127). Discussions with the HyMARC investigators on how that project might relate to the present work could be useful.
- This project has collaboration in the best sense with some of the best in the business, such as Brandon Wood for theoretical guidance and Craig Brown for powder neutron diffraction of structure.
- This is a well-integrated team of collaborators utilizing key HyMARC capabilities to accelerate the progress of this seedling project.
- Many collaborations exist in this project and it is on the right track.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is highly aligned; it is developing an innovative way to get a lot more hydrogen in a MOF at a higher temperature, which would be a direct enabler for solid material hydrogen storage to compete with compressed gas on a mass cost and volume basis.
- This is an exciting seedling project that has direct relevance to DOE research, development, and demonstration objectives, and it could significantly advance progress toward meeting DOE hydrogen storage and delivery goals. The project complements other hydrogen adsorbent work supported by DOE; however, the novel approach adopted here could offer significant advantages over approaches implemented in related efforts.

- If step-like adsorption of hydrogen in these pore-gated materials can be realized at significant capacities, this will provide a pathway for greater overall useable hydrogen capacity. This can impact the cost of stored and delivered hydrogen, which are factors that are key objectives to the DOE Hydrogen Program (the Program).
- This is a relevant project with good potential for impact.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The proposed experimental and computational efforts are a logical and well-formulated extension of the current work. The future work on tuning the step-shaped behavior is especially important because it provides a solid basis for understanding the hydrogen-induced stimulus response and tailoring the systems having improved performance. The project milestones and an appropriate go/no-go decision point are clearly stated. The project has the potential to overcome many of the notable barriers facing high-capacity storage and delivery in adsorbent systems. A recommendation for future work is to include experiments designed to probe the reaction and structural intermediates during the step-shaped transition in the future work plan. That work could provide valuable insight concerning the transition mechanism. The additional experiments might include, for example, in situ solid-state NMR (maybe in collaboration with PNNL) or some other structural or optical diagnostic capable of providing either time-resolved or “stopped-flow” information during the transition.
- This project has good plans for future work. The key plan is making new MOFs guided by the theory that they should operate at higher temperature and with a better useful capacity and lower pressure peak capacity. The work at SLAC will help the team understand the opening and closing of the new materials. The team feels that if it can get the computations going based on the data in hand, it can accelerate the progress. Also, the project needs the NREL facility to reopen or to get another source of high-pressure hydrogen testing.
- The work on understanding the phase-change transitions is anticipated to help guide the synthesis effort to explore opportunities to increase hydrogen sorption capacities to an even greater extent. The combination of theory-guided experiment involving an LLNL/HyMARC collaboration and in situ diffraction at SLAC is a well-thought-out plan. Replacing Cd with a more benign cation is perhaps desirable, but perhaps lesser priority. It is also a higher-risk activity in that it is unknown at this point whether these same structure types are accessible via other, more electropositive cations as proposed.
- The project needs some extra time to catch up after the COVID-19 slow-down.

Project strengths:

- This is a first-rate project that is innovative and well formulated. The PI and his team have expertise in all relevant project areas, and solid progress is being made on demonstrating and optimizing the novel step-transition behavior in ZIFs for improved hydrogen storage and delivery.
- The project’s strength is the use of these rare but special structures to eliminate residual hydrogen in the ‘empty’ state. It has a really superior supporting team in theory and spectroscopy.
- This is a very well-thought-out, planned, and executed project that is highly relevant to the Program objectives. It has very effective use of HyMARC and external collaborations at LLNL and NIST, and in the future at SLAC.
- The project has good collaborations and a sound scientific approach.

Project weaknesses:

- In this reviewer’s opinion, there are no notable weaknesses or deficiencies.
- The project is focused on a group of materials that will teach the team about what makes a better material, but those materials under test are clearly not the ones the team seeks. Thus, the team is taking the bet that it will learn enough so that at the end it can pull a high-quality material out of the hat; that may not be the case, though.

Recommendations for additions/deletions to project scope:

- Two questions/issues could form the basis for additions to the project scope: (1) if increased packing density is required in order to achieve adequate hydrogen capacity, an experimental plan should be developed and described; (2) the ability to probe intermediate states during the step transition could provide powerful and useful information concerning the step-transition mechanism. A possible collaboration with PNNL (in situ NMR) or another organization capable of performing time-resolved or "stop-flow" diagnostics might be considered.
- The work needs to focus on getting the data the theory team needs to validate models and generate high-probability guidance toward high-capacity metals and linkers.
- A minor recommendation is to think about the priority of the cation-replacement tasks; it could be that the effort is better expended on the framework/ligand modification tasks and characterization.

Project #ST-223: Cost Assessment and Evaluation of Liquid Hydrogen Storage for Medium- and Heavy-Duty Transportation Applications

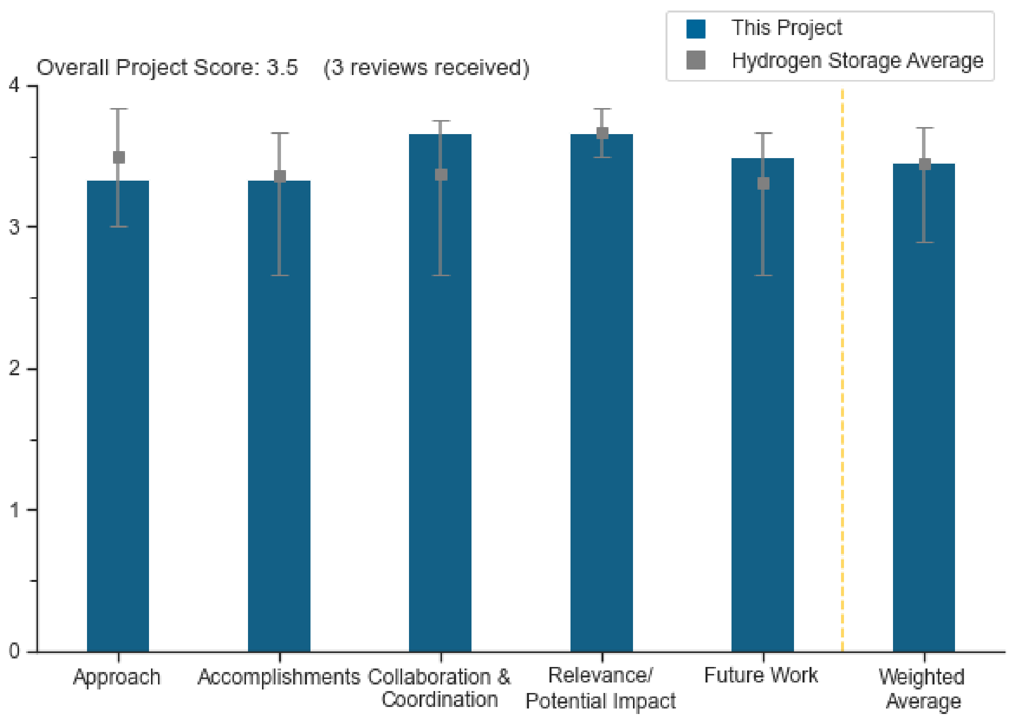
Rajesh Ahluwalia, Argonne National Laboratory

DOE Contract #	4.4.0.2
Start and End Dates	10/1/2020
Partners/Collaborators	Lawrence Livermore National Laboratory, Sandia National Laboratories, Strategic Analysis
Barriers Addressed	• System weight and volume • System cost • Efficiency • Charging/discharging rates • Thermal management • Lifecycle assessments

Project Goal and Brief Summary

This project will analyze the cost and performance of onboard liquid hydrogen (LH2) storage concepts for heavy-duty trucks. The analyses will look at capacity, insulation and dormancy, refueling rate, and hydrogen venting loss. The project will explore the design parameters best suited to at least three different heavy-duty truck vocations to inform the design of LH2 storage systems optimized for the needs of medium- and heavy-duty trucks. Argonne National Laboratory is collaborating with Lawrence Livermore National Laboratory, Sandia National Laboratories, Strategic Analysis, Inc., Air Liquide, Cummins, General Electric, and Navistar on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Fuel cell electric vehicle (FCEV) use is moving toward heavy-duty (HD) applications; understanding the capability and limits of various storage methods is essential to enabling this sector. Evaluation of LH2 in this area is of practical interest.
- As fuel cells become of more interest to heavy-duty vehicles (HDVs), larger storage capacity is also becoming increasingly critical. LH2 is a clear possible solution to meet HDV range requirements. Understanding the cost of large on-vehicle LH2 storage is needed to help determine the correct selection of vehicle storage system.
- The project developed a systematic approach for system analysis of Type 1 vacuum-insulated cryogenic vessels for LH2 storage systems for medium-duty and HD trucks. The project also developed an ABAQUS finite-element analysis of liner and shell failure modes, liner/tank materials of construction, sloshing behavior, and tank weight. The project should provide necessary explanations of basic assumptions and some terms ($\delta_{\text{Liner mass}}$, $\sigma_{\text{allowable}}$, etc.) used for the analysis in the appendix for the reviewers.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- As usual, Rajesh never disappoints in delivering consistent and strong results; there is often too much data to absorb in 15 minutes.
- The project demonstrated excellent progress toward the objectives with several achievements.
- The project only started in October 2020, so the results of the work that could be used by industry for selection of systems were not available for the DOE Hydrogen Program Annual Merit Review. However, evaluation of various system design requirements such as with or without a pump, vessel design, balance of plant, etc., should be on the path to finish work within the remaining time in the project.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- There is a good selection of industry and institute collaboration to identify critical considerations in design. There is good coordination in and between laboratories to divide tasks and provide feedback to the group.
- Rajesh always does a great job of coordinating and aggregating data from all the available data inputs from DOE and industry.
- The team showed strong collaboration with a well-organized task assignment as shown on page 18.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Gaseous hydrogen (GH2) and LH2 are still the predominant onboard storage solutions for vehicles in the near term. Understanding LH2 cost benefits and challenges is critical for development of HDVs in the fuel cell applications.
- The project aligns very well with the DOE objectives. One suggestion is to show the number or percentages of different types of medium-duty vehicles (MDVs) and HDVs in the current market to ensure the analysis is focusing on the major types.
- Focus on HD applications is where the FCEV market is heading. This project work is timely.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- Understanding boil-off given the different usage scenarios is the next practical step. DOE has significant history in evaluating these criteria. Rajesh will use the best available data to deliver on his next presentation.
- The scope of future work is appropriate and important for the HD truck industry to make decisions for hydrogen storage systems until better technology than GH2 or LH2 is developed.
- It is suggested to include a hazard identification analysis for the safety assessment.

Project strengths:

- Doing ground-up analysis for systems larger than those that have been used for passenger vehicles is very beneficial to the HDV industry as they move into fuel cells. The project does a good job at considering various requirements and challenges of LH2 in the HD environment.
- The project developed a systematic approach and advanced analysis methodologies, showed strong teamwork, and achieved several significant accomplishments.
- There is strong modeling by a very competent and experienced team to deliver useful models in a relevant subject.

Project weaknesses:

- As a summary of the previous comments, the project can be further improved from the following points. (1) It is suggested to provide necessary explanations of basic assumptions and some terms ($\delta_{\text{Liner mass}}$, $\sigma_{\text{allowable}}$, etc.) used for the analysis in the appendix for the reviewers. (2) For the stress analysis and effects of sloshing studies, as the speed of vehicles may significantly increase the stress and sloshing effects, it is suggested to carry out the analysis and studies under different vehicle speeds. (3) On page 6, different LH2 storage systems (size, mounting methods) are provided. It is suggested to carry out the stress analysis and effects of sloshing studies under different mounting methods and tank volumes. (4) It is suggested to use a table to compare the features and parameters of the two systems with and without pump on pages 7 and 8. (5) The percentage of LH2 in the tank during the dormancy for the analysis should be explained on page 9. (6) On page 5, the engine-off period in the third bullet point for semi-trailer truck is different from the number in the red summary box; this should be corrected. (7) On page 10, the definition of usable hydrogen in this study should be provided. (8) It is suggested to provide the number or percentages of different types of MDV and HDV in the current market to ensure the analysis is focusing on the major types. (9) It is suggested to include a hazard identification analysis for the safety assessment.
- Only looking at the storage system and not considering refueling station issues/cost and fuel cost is a weakness. This might give a skewed picture of total cost of ownership for HDVs.
- There is too much information to be presented in 15 minutes. Rajesh needs to focus a bit more at the beginning and end doing the boil-down of the results and provide context to the results in terms of how they relate to the targets and what industry needs to do to get to targets based on his model outcomes.

Recommendations for additions/deletions to project scope:

- The two tanks shown in the analysis don’t seem to be the maximum amount of fuel that can be stored on the vehicle. It would be interesting to establish the bookmark of what the maximum fuel storage amount could be, what range that gets, and if that’s useful to the industry given the lack of infrastructure availability, or if it would be excessive given the cost or length of routes run. Surely the deciding factors for the sizing have already been discussed at length and were perhaps presented in other projects, but it would be nice to provide some quick context up front as to why that particular sizing was selected.
- It would be beneficial to see a comparison to GH2 systems with total cost of ownership as a reference.

Project #ST-227: Integrated Onsite Waste-Heat-Driven Hydrogen Carrier System for Steel and Renewables

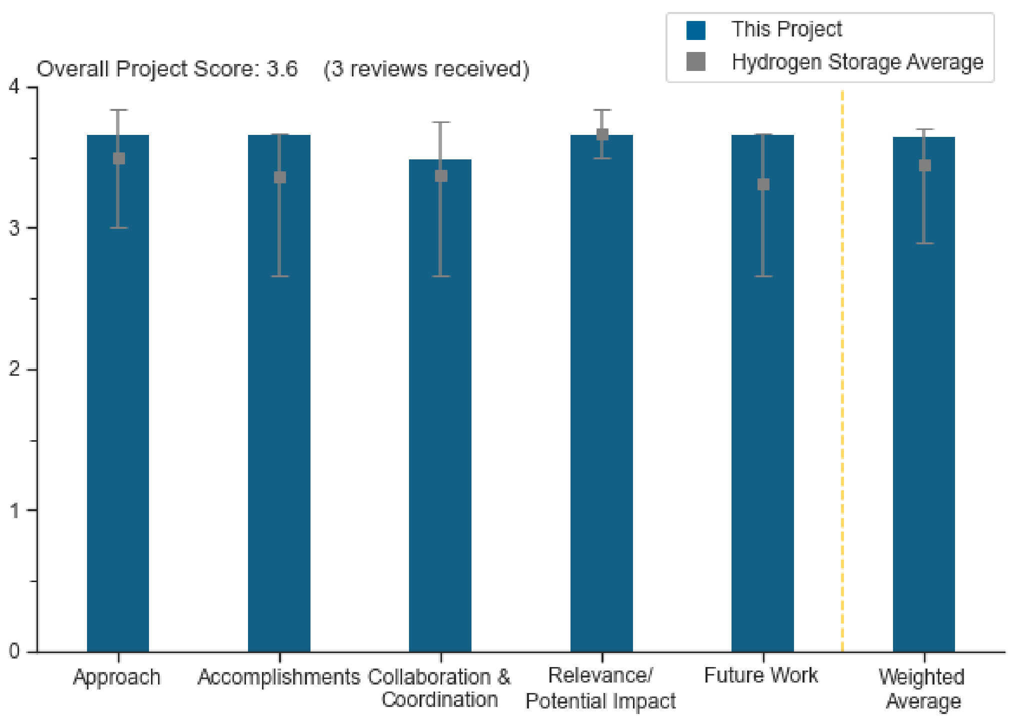
Hanna Breunig, Lawrence Berkeley National Laboratory

DOE Contract #	4.4.0.204
Start and End Dates	10/1/2020
Partners/Collaborators	Lawrence Berkeley National Laboratory, Argonne National Laboratory, Pacific Northwest National Laboratory
Barriers Addressed	• System cost • Efficiency • Codes and standards • Thermal management • System lifecycle assessments

Project Goal and Brief Summary

Traditional iron ore reduction creates significant amounts of carbon dioxide. When hydrogen replaces carbon monoxide in iron ore reduction, the only byproduct is water vapor. However, iron reduction with hydrogen has been demonstrated only at pilot scale. This project aims to develop and use models to analyze the performance and cost of a methylcyclohexane (MCH)-based hydrogen storage system for delivering hydrogen to iron and steel processes. If successful, this project will verify the feasibility of renewable hydrogen in iron and steel processes, enabling a more resilient, efficient, and low-carbon industry. Lawrence Berkeley National Laboratory (LBNL) is collaborating with Argonne National Laboratory (ANL) and Pacific Northwest National Laboratory (PNNL) on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Systems analysis is important to evaluate hydrogen carriers for specific applications, as seen here for steel. The study comprises market analysis and industrial outreach, as well as comprehensive scenarios of the usage of MCH-based hydrogen storage and delivery systems for the specific application of the iron and steel processes. A transparent system design and process model is developed, systems analysis conducted to gauge the performance of the hydrogen carrier system, results provided to materials developers, and industrial outreach conducted. The results are to be compared to the use of compressed hydrogen gas (CHG) and liquid hydrogen (LH2) storage and delivery in the frame of the targeted application. This approach is very persuasive and it is difficult to improve.
- This project is well poised to take a critical look at a baseline techno-economic analysis (TEA) of hydrogen and hydrogen carrier-driven steel manufactured from renewable energy sources to assess where the current technology lands in terms of costs and particularly delivered hydrogen costs. These costs are critical barriers in meeting the objectives of the U.S. Department of Energy's (DOE's) H2@Scale activities. The project has well-defined, rational milestones. The output of this project will provide guidance to future research and development (R&D) endeavors.
- The project developed a process model for the use of hydrogen carrier storage systems integrated with green hydrogen production and application to iron and steel processes. One comment on the approach is that for Task 1 on page 8, the analysis set 200 metric tons per day (MTPD) H_2 production as the fixed target to develop the scenarios and do the analysis. It is suggested to extend the approach to study the impact of hydrogen production capacity.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- A very transparent system design and process model has been developed. The required hydrogen quantities and purities have been determined. ProSim process simulation was performed to design and model different scenarios for hydrogen use in direct iron reduction units. Material and energy balances from process simulations determined and provided for exergy and efficiency analysis. The design for a dual-reactor system, including system size, capital and operating cost, and efficiency, has been finished. Geographics of mills were compared considering the renewable energy profiles. Electrolyzer and storage operation has been modeled, as well as the co-located toluene hydrogenation and dehydrogenation process.
- The project is well posed, logical, and is being executed by a talented team of researchers and collaborators. A logical spectrum of renewable energy scenarios is being analyzed against conventional technology and reasonable hybrid cases. The project takes advantage of the leverage provided by prior work on the MCH carrier at ANL and the analysis of geographic profiles of renewables potential in Texas and Illinois performed by PNNL. Process models of the MCH hydrogenation/dehydrogenation, coupled with the geographic renewables profile, have allowed for preliminary estimates of renewables inputs to costs, and thus, the project is making excellent progress toward meeting the objectives of the project's overall TEA, which will be very relevant to the DOE Hydrogen Program's (the Program's) interests.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- It is readily observed that there is excellent communication, collaboration, and coordination among the national laboratories engaged in this project. LBNL has led the stakeholder engagement activity with a key industry participant.
- This is a very well-balanced and interconnected project of the core partners: LBNL, ANL, and PNNL. Monthly project meetings were held. The team has reached out to key stakeholders (iron and steelmakers in

North America). It is not clear, however, how much this work has been performed in collaboration and coordination with external groups and especially international groups.

- The project demonstrated close collaboration and excellent coordination among national laboratories.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project, regardless of the outcome, is highly relevant to the objectives of the Program, as the output of the TEA, as a function of several renewables scenarios, will help to focus future R&D in carrier development and demonstration and establish benchmark costs for hydrogen generation from renewables, all the way through to transport/storage by carriers, and on to dispensing to a major industrial activity.
- In this project, the performance and cost of MCH-based hydrogen storage is analyzed for the specific application of iron and steel processes. Such a carefully performed analysis is required not only for iron and steelmaking applications, but others as well. It is really needed to generate the required knowledge to design our future clean energy-based society and to identify the best solutions for places, technologies, and energy transport.
- The project provided a good example of integrating green hydrogen production with industrial application. However, as green hydrogen production will be significantly impacted by geographic location, which may not be well connected for the iron and steel application, it would be interesting to show actual geographic connections in the United States and demonstrate the potential impact of the study in real situations.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- The evaluation of safety, codes and standards (SCS) and siting is an important part that is required to know which hurdles have still to be taken and what has to be done to prepare for the future use of these technologies. While many technologies are already quite mature, there will definitely be research gaps, which have not yet been dealt with. Finishing the TEA and benchmarking the performance of the system with at least two incumbent technologies is very important, as well as the case studies with different H_3 production and demand scenarios for a range of deployment scales. Also, the look at other new carriers or carriers in the development is extremely important. Furthermore, it should be analyzed if and which of the results could be transferred to other refining industries.
- With this being a very short-duration project, the team must remain very focused, and its future plans need to take this into account. The proposed future work focuses on the key remaining questions. Particularly important are the issues surrounding siting of these large-scale hydrogen activities with large-scale industrial processes regarding SCS.

Project strengths:

- The project provided an interesting opportunity to apply green hydrogen production with an iron and steel manufacturing application. This project provides a comprehensive analysis of the potential need and advantage of having hydrogen storage as a component of this low-carbon transition.
- This project has an experienced team with a good plan and excellent execution. The project has a high value and is impactful to the Program’s goals and objectives relating to their H2@Scale activities.
- A very good consortium is doing a very profound and comprehensive analysis of the use of liquid organic hydrogen carriers for hydrogen transport and storage in steel and iron industries.

Project weaknesses:

- The only weakness this reviewer can assess is that it is not clear how and if the results of other international research groups are taken into account. International collaboration is not mentioned.

Recommendations for additions/deletions to project scope:

- The project can be improved from the following points. (1) For Task 1 on page 8, the analysis set 200 MTPD H_2 production as the fixed target to develop the scenarios and do the analysis. It is suggested to extend the approach to study the impact of hydrogen production capacity. (2) On page 8, in cases 1b and 1c, the balance hydrogen came from MCH dehydrogenation. Please explain the source of hydrogen used for toluene hydrogenation to MCH. In addition, it is suggested to add another scenario to produce additional hydrogen from electrolysis using grid power to meet the target of 200 MTPD. (3) It is suggested to consider other storage options such as CHG and LH2 for this study. (4) On page 12, please provide an explanation of why wind requires larger toluene and MCH storage capacity. Similarly, please explain why solar requires a larger hydrogenation plant versus wind. (5) In the green NH_3 production process, the hydrogen storage cost could be reduced by increasing the flexibility of the Haber-Bosch process for NH_3 synthesis. Similarly, it is suggested to study the flexibility of the iron reduction process with reduced hydrogen input for reducing the hydrogen storage cost. (6) The title of waste-heat-driven hydrogen carrier system seems not much reflected in the studies. There is not much analysis in the slide showing the waste-heat recovery and energy balance. (7) As green hydrogen production will be significantly impacted by geographic location, which may not be well connected for the iron and steel application, it would be interesting to show actual geographic connections in the United States and demonstrate the potential impact of the study in real situations.
- Case studies for different hydrogen production and demand scenarios and different scales might change the results. Furthermore, this work should be extended to the use of other carriers as well.
- This project is well conceived, so there are no changes recommended.

Project #ST-228: Determining the Value Proposition of Materials-Based Hydrogen Storage for Stationary Bulk Storage of Hydrogen

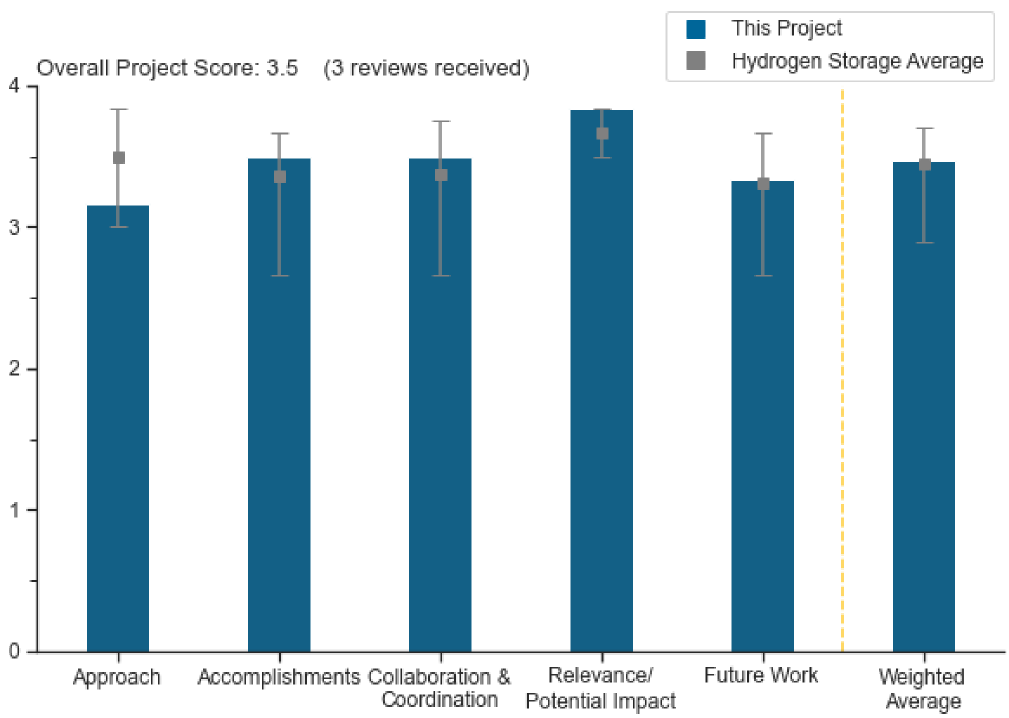
Bruce Hardy, Savannah River National Laboratory

DOE Contract #	WBS 4.4.0.905
Start and End Dates	10/1/2020
Partners/Collaborators	National Renewable Energy Laboratory, Savannah River National Laboratory
Barriers Addressed	• Technoeconomic analysis for cost challenges • Heat source availability and system size • Ability of system to supply H_2 flowrate to power a 20 MW data center for 72 hours at the required fuel cell pressure • Identify transient heat required rate for hydrogen discharge

Project Goal and Brief Summary

This project aims to evaluate the capability and design of materials-based stationary bulk hydrogen storage for backup power applications, starting with fuel-cell-powered data centers. The research team will leverage technoeconomic models developed by the National Renewable Energy Laboratory (NREL) to understand the value proposition of hydrogen and fuel cells for data centers. Researchers will determine a priority list of reversible materials, develop a detailed model to validate the suitability of a metal hydride-based storage system, and identify parameters and designs that yield the most significant performance improvements.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Storage projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project is primarily an economic assessment effort to assess current baseline technology and the ability to achieve system-level performance for backup power for a data center. As such, the project will develop relative costs versus other competing incumbent technologies. This approach is feasible and supports U.S. Department of Energy objectives in the H2@Scale activity.
- The project has developed a systematic approach for the analysis, including technoeconomic analysis (TEA), performance/integration, and space considerations. The project is suggested to use a figure to clearly illustrate the relationships among “information technology (IT) load,” “data center total load,” and “fuel cell (FC) system/data center thermal output” on page 6.
- The approach to evaluate the usage of fuel cells and metal-hydride-based hydrogen stores as backup systems for data centers is wisely chosen. Also, to perform the TEA, the performance/integration analysis as well as space considerations and comparisons of the different storage options (gaseous, liquid and metal hydride [MH]) are very important tasks. However, since there is quite a huge number of possible hydrides to be used for such an application, either a variety of different hydrides has to be taken into account or the specific hydride has to be chosen very wisely to allow for a fair comparison with the different storage options. The chosen hydride is by far not the most suitable. For such an application where several thousand tons of hydride are required, the chosen hydride, $(Ti_{0.97}Zr_{0.03})_{1.1}Cr_{1.6}Mn_{0.4}$, is much too expensive. There are much cheaper room-temperature interstitial metal hydride options available. Only 6 bar hydrogen pressure is required by the fuel cell. An equilibrium pressure of 73 bar, therefore, is not required. Also, for such an application, the $NaAlH_4$ is a poor choice since it requires high operation temperatures. The consortium should have taken more care for selecting the more appropriate low-cost room-temperature hydrides.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made excellent progress in analysis of a baseline case for an MH-based storage system to provide hydrogen to fuel cells to provide extended backup power to a data center. The MH case has been baselined against potential competitive technologies. Preliminary results and accomplishments indicate key advantages and disadvantages of this MH–fuel cell approach and so can drive future research and development (R&D) to mitigate the disadvantages and maximize any advantages of this approach. In this regard, the project supports the objectives of the DOE Hydrogen Program.
- Given the poor choice of the project team’s initial selection of hydride candidates, the consortium did a very good job characterizing and assessing the different systems.
- The project can be further improved from the following points. (1) A 5 megawatt (MW) data center is selected, as explained on page 5. However, as on pages 3 and 20, a 20 MW data center is the initial target, so the project is suggested to carry out a similar study for the 20 MW data center as well and show the effect of the scale on the TEA analysis for different scenarios. (2) On page 7, the project is suggested to add another scenario into consideration: hydrogen delivery in metal hydride plus metal-hydride-based hydrogen (MH2) stationary. (3) It would be interesting to show how the reduced footprint could influence the capital expenditures (CAPEX), etc. (4) It is unclear what the volume of storage tank is for gaseous hydrogen (GH2), liquid hydrogen (LH2), and MH2 in the TEA analysis on page 9. (5) As two different types of metal hydride were used for pressure swing and temperature swing models, it is suggested to provide detailed comparisons between these two models, including tank volume, CAPEX, operating expense (OPEX), etc.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- There is good coordination and collaboration among the principals. A logical division of tasks has been developed, which is being executed.
- The partners seem to collaborate very well with each other. Considering the huge know-how of U.S. and international institutions and researchers in the field of different hydrides, however, it would have been important to collaborate much more with such materials researchers to make the most suitable preselection of hydrides.
- The project demonstrated good collaborations between partners. It is suggested to add more industrial partners to validate some assumptions for the analysis.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This type of project is highly relevant to the DOE H2@Scale activity. By performing TEA of incumbent and emerging technologies, this project can uncover advantages and disadvantages of various approaches, which will help to focus future R&D to remove the barriers identified.
- Energy security is of major importance, not only in the frame of the rise of renewable energy usage. Backup power, therefore, is utterly needed. Also, the importance of the digitalization is rising exponentially. Therefore, to analyze the usage of hydrogen and fuel cells as backup power for data centers is extremely wise and important.
- The project aligns well with the Hydrogen Program and DOE objectives.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The proposed future work is excellent. Nevertheless, to be able to compare the costs of those different technologies, of course the prize of the metal hydrides chosen is of utter importance. Therefore, cheaper room-temperature hydrides should be assessed.
- As LH2 storage shows significant cost advantage, the project is suggested to do more studies on LH2 storage options. Based on the project goals, it seems that a list of reversible metal hydride materials will be evaluated for this application; however, only two hydride materials are considered in the analysis. The reason should be explained.
- The current preliminary costs for the MH system chosen are high; much of the cost appears to be associated with the MH costs. Future work is appropriately directed at exploring the influence of a variety of MH materials with a variety of properties and material costs.

Project strengths:

- The project demonstrated an interesting study to evaluate the capability and design of materials-based bulk storage system options for data center application and developed a detailed model to identify and validate the suitability of a metal-hydride-based storage system and identify parameters and designs that yield the most significant improvements in performance.
- This project aims at backup power solutions for data centers. This topic is of utter importance and should be given a larger budget to investigate and assess the cheapest choices of hydrides to be used in such an application.
- There is a good team and a well-posed approach to the problem. The project is identifying key parameters for the MH system to integrate with the fuel cell backup power system.

Project weaknesses:

- There is a minor weakness. It would be nice, but probably beyond the scope of the project, to automate the MH search space to accelerate the search for an optimum MH, if there is one.
- As a summary, the project can be improved from the following points. (1) The project is suggested to use a figure to clearly illustrate the relationships among "IT load," "data center total load," and "FC system/data center thermal output" on page 6. (2) A 5 MW data center is selected, as explained on page 5. However, as on pages 3 and 20, a 20 MW data center is the initial target. The project is suggested to carry out a similar study for the 20 MW data center as well and show the effect of the scale on the TEA analysis for different scenarios. (3) On page 7, the project is suggested to add another scenario into consideration: hydrogen delivery in metal hydride plus MH2 stationary. (4) It would be interesting to show how the reduced footprint could influence the CAPEX, etc. (5) It is unclear what the volume of storage tank is for GH2, LH2, and MH2 in the TEA analysis on page 9. (6) As two different types of metal hydride were used for pressure swing and temperature swing models, the project is suggested to provide detailed comparisons between these two models, including tank volume, CAPEX, OPEX, etc. (7) The project is suggested to add more industrial partners to validate some assumptions for the analysis.
- Unfortunately, only two hydrides are considered in this study. One of those hydrides is much too expensive. The other one requires high temperatures for operation.

Recommendations for additions/deletions to project scope:

- This is a well-conceived project and it is being well executed. No changes are suggested.
- As LH2 storage shows significant cost advantages, the project is suggested to do more studies on LH2 storage options. Based on the project goals, it seems that a list of reversible metal hydride materials will be evaluated for this application; however, only two hydride materials are considered in the analysis. The reason should be explained.
- The focus of the analysis must lay on cheap room-temperature hydrides. A much cheaper alternative would be, for example, FeTi-based alloys.

Fuel Cell Technologies – 2021

Subprogram Overview

INTRODUCTION

Fuel cells convert the chemical energy of hydrogen or other fuels into electricity and are a key element of a broad portfolio for building an affordable, resilient, and clean energy economy. The Fuel Cell Technologies (FCT) subprogram applies innovative research, development, and demonstration (RD&D), with the main goal of developing a diverse portfolio of low-cost, durable, and efficient fuel cells that are competitive with incumbent and emerging technologies across applications. The subprogram seeks a balanced, comprehensive approach to fuel cells for the near, mid, and long term.

The subprogram's RD&D strategy is target-driven, with technical targets developed for different fuel cell technologies, specifically considering end-use requirements. In this holistic approach, the subprogram develops targets based on the ultimate lifecycle cost of using fuel cell systems in diverse applications. While the subprogram has previously developed comprehensive technical targets in areas such as light-duty vehicles (LDVs), it continues to develop and refine additional targets for emerging and high-impact applications. These include heavy- and medium-duty vehicles (HDVs and MDVs), maritime applications, stationary power generation (primary and back-up), and reversible fuel cells for energy storage. The specific focus on HDVs—which have more stringent durability requirements than LDVs—will also offer transferrable benefits for light-duty, medium-duty, and stationary power fuel cell applications.

The subprogram strategically addresses crosscutting challenges for fuel cell development through focus on materials and components (especially low-platinum-group-metal [low-PGM] and PGM-free catalysts and electrodes); systems and manufacturing (design, standardization, improved supply chains); and analysis and modeling.

GOALS

The FCT subprogram's goal is to develop fuel cell technologies that are competitive with incumbent and emerging technologies across diverse applications.

Specific objectives of the subprogram include:

- Developing fuel cell systems with an emphasis on systems that are highly durable, efficient, and low-cost, while meeting the needs and constraints of varied heavy-duty transportation applications for the near to mid-term.
- Developing new materials and components for next-generation fuel cell technologies for transportation, distributed power, and long-duration grid-scale energy storage, emphasizing innovative mid- to long-term approaches.

KEY MILESTONES

By 2030:

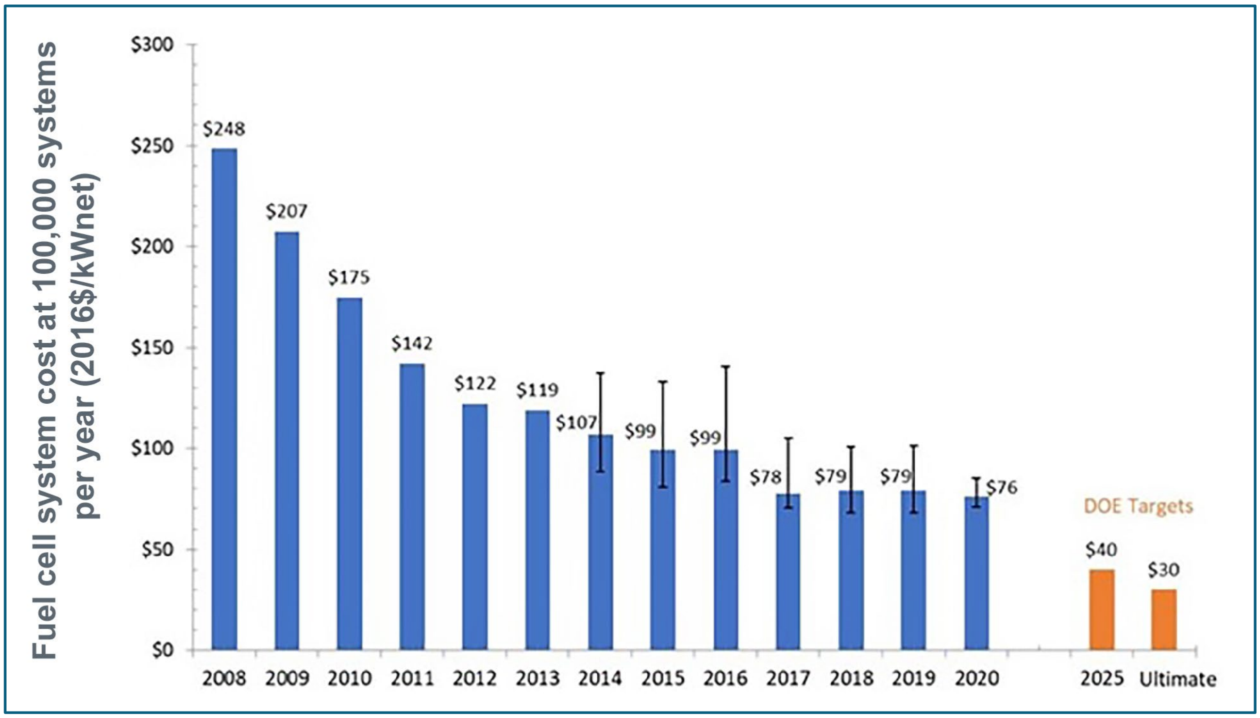
- Develop a 68% (ultimately 72%) peak-efficient, direct hydrogen fuel cell power system for heavy-duty trucks that can achieve durability of 25,000 hours (ultimately 30,000 hours) and be mass-produced at a cost of $80/kW (ultimately $60/kW).
- Develop medium-scale distributed generation fuel cell power systems (100 kW–3 MW) that achieve 65% electrical efficiency and 80,000-hour durability at a cost of $1,000/kW.
- Develop reversible fuel cells for energy storage applications that can achieve 40,000-hour durability at a cost of $1,800/kW ($0.20/kWh levelized cost of storage).

Fiscal Year 2021 Technology Status and Accomplishments

One of the most important metrics used to guide the FCT subprogram's RD&D efforts is the projected high-volume manufacturing cost for automotive fuel cells, which is tracked on an annual basis (see the chart below). The subprogram is targeting a cost reduction to $40/kW by 2025. Long-term competitiveness with alternative powertrains is expected to require further cost reduction to $30/kW, which represents the subprogram's ultimate cost target.

The 2020 estimated cost of an 80 kW_{net} automotive polymer electrolyte membrane fuel cell (PEMFC) system (based on next-generation laboratory technology and operating on direct hydrogen) is projected to be $76/$kW_{net}$ when manufactured at 100,000 units/year and adjusted to meet 8,000 hours of durability.[1] These cost reductions were achieved through factors such as reduced Pt catalyst loading (30% since 2008); increased cell power density (>70% since 2008), which allows for smaller stacks; optimized balance of plant (BOP) components and system design; and innovative manufacturing processes for BOP and stack components.

70% Cost Reduction from 2008 to 2020



Cost status (2008–2020) for 80 kW_{net} automotive PEMFC system (at 100,000 units/year) vs. targets (2025 and ultimate)

Fuel cell electric buses (FCEBs) continue to demonstrate high levels of durability. Fuel cell bus durability was determined to be 17,000 hours with less than 20% degradation (8,500 hours with less than 10% degradation), approaching the U.S. Department of Energy (DOE)/U.S. Department of Transportation interim fuel cell bus target of 18,000 hours (with less than 20% degradation). This status is based on real-world fuel cell bus data collected between 2011 and 2017, and newer FCEB power plants currently undergoing evaluation are expected to be more durable. In fiscal year (FY) 2021, 12 FCEBs surpassed the ultimate target of 25,000 hours, with one FCEB reaching over 32,000 hours. Four of these fuel cell power plants have been retired from service because they no longer

[1] On-road technology is not warrantied for the ultimate lifetime target of 150,000 miles (8,000 hours), suggesting a shortcoming in stack durability that would likely be addressed by replacing the stack. To account for this in the cost of a fuel cell system, a single stack replacement is included in the durability-adjusted cost.

provided the power necessary to meet service requirements, including for the vehicle that operated for over 32,000 hours. The remaining fuel cell power plants have continued service.[2]

In FY 2021, the subprogram also continued its efforts on cost analyses of direct hydrogen fuel cell systems suitable for MDVs and HDVs, aiming toward achieving the 2030 target of $80/kWnet and the ultimate target of $60/kWnet. Recent analysis estimates the 2021 cost status for medium-duty systems at $170/kW and heavy-duty fuel cell systems at $185/kW at volumes of 100,000 units/year.[3]

SUBPROGRAM-LEVEL ACCOMPLISHMENTS

Reversible Fuel Cells for Energy Storage

Performance, cost, and durability targets were developed and published—based on extensive stakeholder engagement and industry input—for unitized reversible fuel cells for electric energy storage applications. These include targets for both low- and high-temperature technologies at both the cell/stack and system levels with the same stack operating in both fuel cell and electrolyzer modes.[4]

Key 2030 system-level reversible fuel cell targets established include the following:

- Uninstalled capital cost of $1,800/kW (on a power basis) and $250 kWh (on an energy capacity basis)
- Roundtrip efficiency of 60% (high temperature) and 40% (low temperature)
- 40,000-hour durability with <10% degradation at end of life
- Levelized cost of storage of $0.20/kWh

Ultimately, innovative RD&D will be needed to improve roundtrip efficiency and durability, decrease levelized cost of electricity/storage to <$0.10/kWh, and meet long-term system capital cost targets by power and energy capacity of less than $1,300/kW and $150/kWh, respectively.

L'Innovator Cooperative Research and Development Agreement (CRADA)

The L'Innovator CRADA was fully executed between industry partner company Advent Technologies, Inc., and three national laboratories: the National Renewable Energy Laboratory, Los Alamos National Laboratory, and Brookhaven National Laboratory. This effort aims to move fuel cell technologies closer to commercialization by bundling state-of-the-art lab intellectual property, lab manufacturing expertise, and the industrial partner's market experience.

PROJECT-LEVEL ACCOMPLISHMENTS

Million Mile Fuel Cell Truck Consortium (M2FCT)

The mission of the M2FCT consortium is to advance PEMFC efficiency and durability and to lower PEMFC cost, thereby enabling PEMFC commercialization for heavy-duty vehicle applications. A "team-of-teams" approach is being used, featuring teams in analysis, durability, integration, and materials development. The objective for fuel cell development efforts under this consortium combines efficiency, durability, power density, and (implicitly) cost in a single metric: 2.5 kW/g_{PGM} power (1.07 A/cm^2 current density at 0.7 V) after 25,000 hour-equivalent accelerated stress tests (ASTs).

An Accelerated Stress Test Working Group (ASTWG) was formed to recommend test protocols and performance targets for fuel cells in HDV applications. M2FCT has developed a membrane electrode assembly (MEA) durability

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[2] DOE, "On-Road Transit Bus Fuel Cell Stack Durability," DOE Hydrogen and Fuel Cell Technologies Program Record #20008, September 15, 2020, https://www.hydrogen.energy.gov/pdfs/20008-fuel-cell-bus-durability.pdf.

[3] Brian James, "2021 DOE Hydrogen and Fuel Cells Program Review Presentation: Fuel Cell Systems Analysis," prepared for DOE by Strategic Analysis, Inc., June 9, 2021, https://www.hydrogen.energy.gov/pdfs/review21/fc163_james_2021_o.pdf.

[4] DOE, "Reversible Fuel Cell Targets," DOE Hydrogen and Fuel Cells Program Record #20001, April 16, 2020, https://www.hydrogen.energy.gov/pdfs/20001-reversible-fuel-cell-targets.pdf.

AST, incorporating relevant degradation mechanisms for catalyst, support, electrodes, and membrane in a single AST. The AST is currently being validated in coordination with the ASTWG.

ElectroCat 2.0

The mission of the ElectroCat (Electrocatalysis) consortium is to develop durable PGM-free catalysts for PEMFCs and for low-temperature electrolyzers as low-cost alternatives to PGM catalysts, addressing critical mineral supply challenges. In FY 2021, the activity of PGM-free catalysts was improved more than twofold compared to the 2016 baseline (16 mA/cm^2). Performance of 38 mA/cm^2 exceeded the FY 2021 catalyst activity target (35 mA/cm^2). These improvements were achieved with a NH_4Cl-treated "single-zone" Fe-C-N catalyst. A total of 193 unique catalysts were synthesized, with 30% enhancement in oxygen reduction reaction (ORR) activity performance improvement over the highest ORR activity reported in FY 2020.

NEW PROJECT SELECTIONS

Fuel Cell Systems for HDVs

- Cummins Inc. – Polymer Electrolyte Membrane Fuel Cell System for Heavy-Duty Applications
- Plug Power Inc. – Domestically Manufactured Fuel Cells for Heavy-Duty Applications

Membrane Development for HDVs

- Nikola Motor Company – Advanced Membranes for Heavy-Duty Fuel Cell Trucks
- 3M Company – Extending Perfluorosulfonic Acid Membrane Durability through Enhanced Ionomer Backbone Stability
- The Lubrizol Corporation – Additive Functionalized Polymers for Extended Heavy-Duty Polymer Electrolyte Membrane Lifetimes
- University of Tennessee, Knoxville – A Systematic Approach to Developing Durable Conductive Membranes for Operation at 120°C

Anion Exchange Membrane (AEM) Fuel Cell Development

- Los Alamos National Laboratory – Advanced Anion Exchange Membrane Fuel Cells through Material Innovation
- National Renewable Energy Laboratory – Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells

Consortia

- ElectroCat 2.0 – A relaunch of the ElectroCat consortium, co-led by Argonne National Laboratory and Los Alamos National Laboratory, to develop durable PGM-free catalysts for PEMFCs as low-cost alternatives to PGM catalysts, addressing critical mineral supply challenges. ElectroCat2.0 expands the scope to include PGM-free catalysts for low-temperature electrolyzers.
- M2FCT – The mission of the M2FCT consortium is to advance PEMFC efficiency and durability and to lower PEMFC cost, thereby enabling PEMFC commercialization for HDV applications.

FY 2021 FUNDING OPPORTUNITY ANNOUNCEMENT SELECTIONS

Fuel Cell RD&D for Heavy-Duty Applications – Low-Cost, Durable Bipolar Plates

- Plug Power, Inc. – Fully Unitized Fuel Cell Manufactured by a Continuous Process
- Neograf Solutions, LLC – Development of Low-Cost, Thin Flexible Graphite Bipolar Plates for Heavy-Duty Fuel Cell Applications
- General Motors, LLC – Fuel Cell Bipolar Plate Technology Development for Heavy-Duty Applications

- TreadStone Technologies, Inc. – Development and Manufacturing of Precious-Metal-Free Metal Bipolar Plate Coatings for Polymer Electrolyte Membrane Fuel Cells
- Raytheon Technologies Research Center – Low-Cost, Corrosion-Resistant Coated Aluminum Bipolar Plates by Elevated Temperature Formation and Diffusion Bonding

Fuel Cell RD&D for Heavy-Duty Applications – Innovative, Low-Cost Air Management Components

- Caterpillar, Inc. – Leveraging Internal Combustion Engine Air System Technology for Fuel Cell System Cost Reduction
- Eaton Corporation – High-Efficiency and Transient Air Systems for Affordable Load-Following Heavy-Duty Truck Fuel Cell
- R&D Dynamics Corporation – Foil-Bearing-Supported Compressor–Expander
- Mahle Powertrain, LLC – Durable and Efficient Centrifugal-Based Filtered Air Management System and Optimized Balance of Plant

Fuel Cell Cost and Performance Analysis

- Strategic Analysis, Inc. – A system-level cost analysis annually updated for technological advancements in fuel cells provides insight into the most impactful research directions to help lower fuel cell manufacturing cost. This project supports cost projections for fuel cell auto, trucks, marine, and rail that will have positive impacts on the industry by quantifying the impact of promising fuel cell manufacturing techniques and designs, charting annual progress, and identifying areas with RD&D/manufacturing deficiencies.

Small Business Innovation Research/Small Business Technology Transfer Research (SBIR/STTR)

FY 2020 SBIR Phase II

- pH Matter, LLC – Multi-Functional Catalyst Supports (IIA)
- Tetramer Technologies, LLC – Improved Ionomers and Membranes for Fuel Cells

FY 2021 SBIR Phase I

- Giner, Inc. – Durable High-Efficiency Membrane and Electrode Assemblies for Heavy-Duty Fuel Cell Vehicles
- Pajarito Powder, LLC – Fine Gradient Electrode and Microporous Layer Structures for Improved Heavy-Duty Fuel Cells
- Celadyne Technologies, Inc. – Nanocoating for Increased Nafion Membrane Durability and Efficiency

FY 2021 STTR Phase I

- Ionomer Solutions, LLC, with The Pennsylvania State University – Optimizing Liquid Free Ionomer Binders for High-Temperature Polymer Electrolyte Membrane Fuel Cells for Heavy-Duty Vehicles
- Energy 18H, LLC, with University of Delaware – Development of a Direct Fuel Cell for the Perhydrodibenzyltoluene/Dibenzyltoluene Fuel Pair

BUDGET

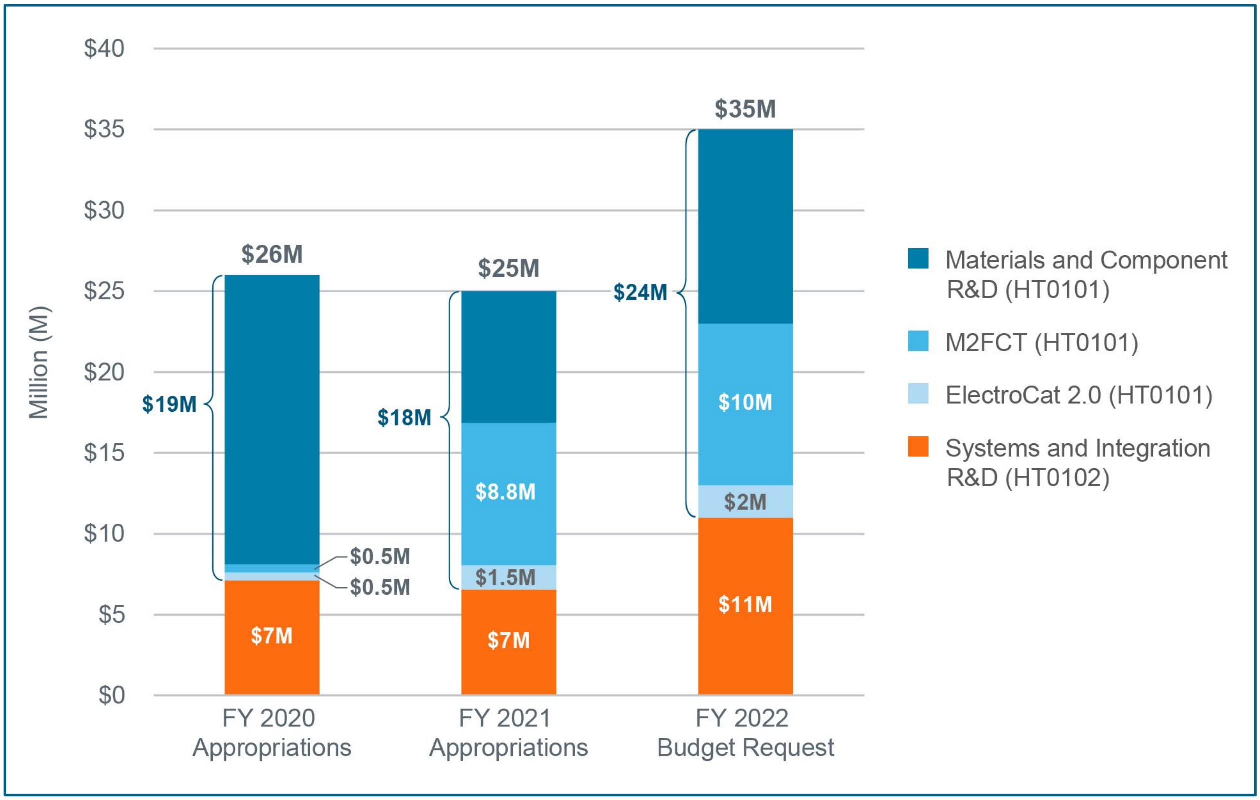
The FY 2021 appropriation was $25 million for the FCT subprogram. In FY 2021, the subprogram funded RD&D efforts in two key areas: materials/components and systems integration. Funding was dedicated to the two national laboratory consortia, M2FCT and ElectroCat 2.0, with M2FCT receiving a majority of the consortia funding (see the chart below).

Funding for research into fuel cell materials and components focused on areas such as low-PGM MEAs and MEA components with enhanced durability, PGM-free catalysts/electrodes, bipolar plates, and advanced manufacturing.

Funding for research into fuel cell systems integration focused on stacks, BOP components (for air management), systems analysis, and advanced manufacturing.

The FY 2022 budget request for the FCT subprogram is $35 million. Activities planned for FY 2022 include continuing RD&D of low-PGM and PGM-free catalysts and membrane durability, initiating development of gas diffusion layers and power electronics, continuing activities of the M2FCT consortium, and meeting durability-adjusted HDV fuel cell cost targets.

Fuel Cell Technologies Subprogram Budget Breakdown



Annual Merit Review of the Fuel Cell Technologies Subprogram

SUMMARY OF FUEL CELL TECHNOLOGIES SUBPROGRAM REVIEWER COMMENTS

Reviewers said that the focus on HDVs—with so many high-impact commercial applications—was appropriate and a great opportunity to decarbonize using hydrogen and fuel cells. However, some reviewers felt that it was somewhat premature to reduce focus on fuel cells for LDVs as a consequence of the increased focus on MDVs and HDVs. It was also suggested that the subprogram prioritize end-use demonstrations and do more to enable deployment in general.

Review panels commended the RD&D leading to PEMFC stack costs decreasing to less than $80/kW, as well as RD&D investigating fuel cell durability through both materials and system design lenses. These achievements were seen as significant milestones on the path to reaching the goals of the H2@Scale effort. The design for manufacturing and assembly approach used yearly to forecast the cost of transportation fuel cell systems—including the recent focus on MDVs and HDVs—was lauded for continuing to refine and expand as needed. Moreover, this approach was seen as key to helping DOE determine relevant goals and progress toward these goals. Reviewers encouraged closer collaboration with M2FCT to integrate the consortium's findings into the cost analyses.

Both ElectroCat and M2FCT were regarded as well-developed consortia and strongly supported by experienced researchers and companies.

ElectroCat was viewed as a well-coordinated and strong consortium, consisting of top-notch researchers and institutions who are collaborating to advance state-of-the-art PGM-free catalysts. The consortium's progress—especially milestones being exceeded—was specifically praised. More involvement of non-national laboratory teams, and especially collaboration with original equipment manufacturers (i.e., end users) was suggested. Increased industry involvement (with more dynamic dialogue between competitors) and linking consortia with state and regional stakeholders were seen as efforts with potential to increase value.

The M2FCT consortium was seen as an effective platform and complementary to other existing consortia. The "team-of-teams" approach used by the M2FCT consortium was commended for having recognized experts and being the most effective way to collaborate on key challenges. However, some reviewers also cautioned that the consortium may be too large for effective management, also noting that it may be better to separate out some of the work for separate reviews. Reviewers also commented that improvements seemed incremental, and thus suggested that the subprogram have stricter requirements for projects funded under this consortium (perhaps even including an advisory board review). It was further advised that the subprogram consider opening up M2FCT to international organizations. Reviewers also commented that the consortium has an opportunity to contribute to standardizing the process of testing and integrating new materials for PEMFCs.

The emerging areas of AEM fuel cells and the use of fuel cells for aviation were suggested for further attention. Reviewers regarded AEM fuel cells as having potential for significant cost reduction in catalysts and membranes and therefore encouraged increasing overall research scope and elevating this research area's priority. A note of caution was that use of catalysts with high PGM loadings would provide substantially different characteristics that are not representative of the desired end product (where PGM-free catalysts are used). Thus, reviewers suggested that more focus should be placed on using PGM-free catalysts.

Regarding the second emerging area, fuel cells and hydrogen are of interest for decarbonizing aviation. Requirements for electric power systems in conventional and emerging markets in aviation, such as drones and urban air mobility, are different from for those in LDV and HDV applications, with weight and specific power density being prime concerns.

Some reviewers regarded projects examining MEAs as high-risk and warranting closer tracking of progress before decisions are made regarding continued funding. Reviewers thought that scalability should also be considered and that there should be more collaboration with industrial partners for membrane performance validation.

The development of durable PGM-free catalysts and research progress on the subject was praised and seen as a key area contributing to reaching DOE goals. Reviewers noted that non-PGM catalyst activity and performance had improved. However, they saw the stringent durability requirements of HDVs as likely to make it extremely challenging to reach levels needed for commercial application.

Developing efficient, stable reversible fuel cells was seen as an enabling technology for energy storage. Reviewers encouraged more focus on catalysts and diffusion media, rather than on membranes. In addition, longer durability testing in electrolysis mode and more cycling between electrolyzer and fuel cell mode were recommended.

Thirty-eight FCT projects were reviewed, receiving scores ranging from 2.2 to 3.6, with an average score of 3.2. Project reviewers were impressed with specific project-level highlights and accomplishments. Following this subprogram introduction are individual project reports for each of the projects reviewed. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Project Reviews

Project #FC-117: Fiscal Year 2018 Small Business Innovation Research Phase IIB: Ionomer Dispersion Impact on Advanced Fuel Cell Performance and Durability

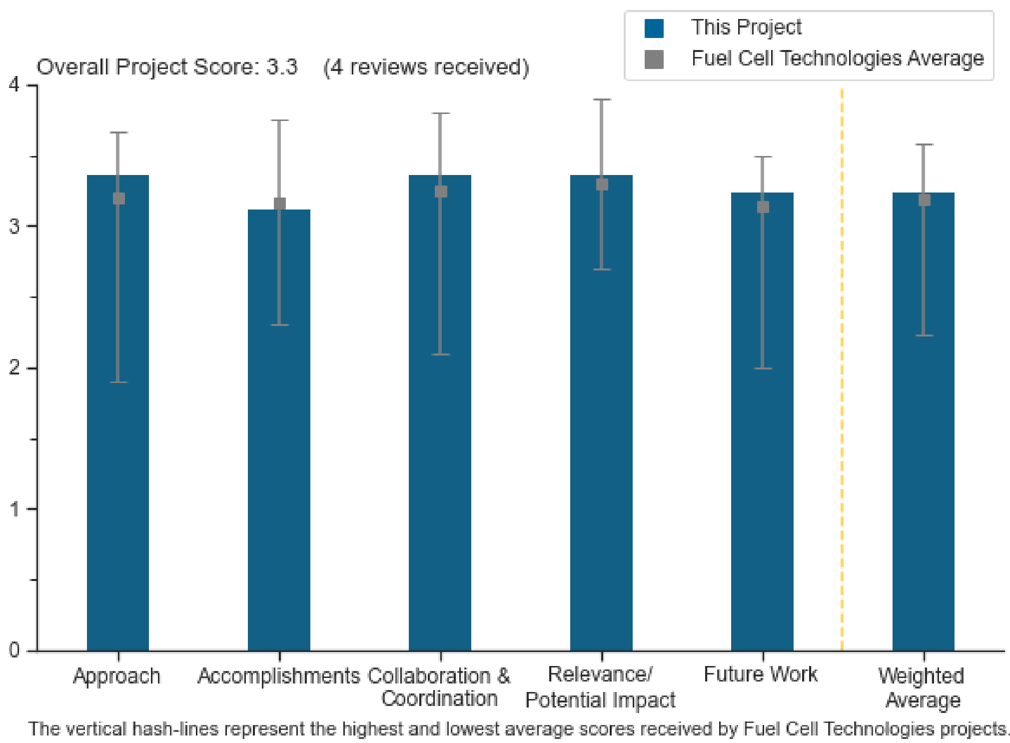
Hui Xu, Giner, Inc.

DOE Contract #	DE-SC0012049
Start and End Dates	8/27/2018 to 8/26/2021
Partners/Collaborators	Los Alamos National Laboratory, National Renewable Energy Laboratory, University of Connecticut
Barriers Addressed	• Polymer electrolyte membrane fuel cell and electrolyzer performance and durability

Project Goal and Brief Summary

This project aims to elucidate solvents' impacts on ionomer dispersion morphology and the associated changes to electrode structures and performance. The research team will design light- and heavy-duty fuel cell membrane electrode assemblies (MEAs) that are mechanically and chemically durable, and researchers will establish a correlation between catalyst ink properties, electrode structures, and MEA performance. Findings from this project could help develop processable and scalable MEA fabrication platforms and identify pathways to commercializing MEAs with enhanced durability via roll-to-roll (R2R) production.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The technical approach is reasonable and well-considered, with focus on correlating catalyst ink properties with electrode structure and fuel cell performance, which can lead to improvements in R2R manufacturing. Starting from investigation on different solvents, the combination of rheology/particle size analysis with microstructure characterization and MEA performance and durability evaluation creates a straightforward path to project implementation.
- The structural changes when casting Nafion using a high boiling solvent such as ethylene glycol during solution casting of membrane layers have been known since the early work of Charles Martin in the 1980s and workers from Virginia Tech in the late 1990s. There is a phase change at 140°C that leads to this morphology transition to microbiphasic, like that structure found in the heat melt of fluorides. It is important to follow up on this in R2R MEA making.
- The approach is good, and solvent variations would likely be a big factor in catalyst layer performance. It is unclear what the mechanism is for improved durability, which was one of the principal goals of the solvent modifications; it could be some more post-mortem analysis to decipher the mechanism of durability improvement. Many other unnecessary variables were introduced into the study, such as different gas diffusion layers (GDLs) and gas diffusion electrodes (GDEs) versus a catalyst-coated membrane (CCM) construction approach, making it difficult to follow the effects of the variations. As a Small Business Technology Transfer project, this should have a good commercial outcome/target, but it looks like technology development just goes full circle; it starts at Los Alamos National Laboratory (LANL), then there is some work at Giner, Inc. (Giner) and then it ends up at the National Renewable Energy Laboratory (NREL) for scale-up.
- The approach contains useful characterization techniques. However, additional detail, such as the methodology of analyzing particle size, would be appreciated. Many techniques that show particle size require very dilute solutions. The ink may have to be diluted to determine the average particle size, and it is not certain that the homogenization techniques used would affect the ink in the same way if the ink were more concentrated. The project should provide additional information regarding this technique and justification that the results are applicable to the concentrations of inks used in preparation of real MEA electrodes. Furthermore, there may be additional analyses that can help to improve the understanding of the materials. As this is a narrowly focused project, a deeper dive into all the properties of the ink may be useful. For example, perhaps it is possible to quantify the magnitude of effect of solvent–ionomer interaction versus solvent–catalyst interaction on the final catalyst layer microstructure and homogeneity. Relatedly, a paper from the Tokyo Institute of Technology (*Journal of The Electrochemical Society* 166 (2) F89–F92 [2019]) has shown that certain solvents may degrade in the presence of catalyst. It would be interesting to know whether the team sees the same degradation with ethylene glycol and butanediol.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project does a very nice job by using constant stoic polarization curves with representative gas flow rates; it gave a good measure of progress toward DOE targets. It is surprising that solvents did have more of an impact on performance. It would be nice to compare the polarization curves and durability with the IPA (Nafion in 2-propanol/water) solvent MEAs since those catalyst layers were more significantly different in structure, as shown in the transmission electron microscopy images of slide 6. The EG/NPA (Nafion in ethylene glycol/Nafion in 1-propanol/water) images and polarization curves were actually very similar.
- The effects of solvents and mixing time were optimized under the guidance of rheology and particle size analyses. The project team examined MEA fabrication via both CCM and GDE and chose GDE for easy commercialization. Small MEAs prepared by Giner met several DOE 2020 targets on performance and durability, including mass activity, MEA performance at 800 MV, loss in catalyst activity, and performance at 0.8 A/cm^2. However, the rated power performance target was not met. While such a gap can be partially

attributed to the membrane, the property and structure of ionomer in the catalyst layer should be still the main contributor to relatively low current density, which needs further study and optimization. Some successes were seen for scaling up the process from small lab preparation to R2R.

- The formation of good films cast at high temperatures is noteworthy, but the film processing is not optimized. Treating at 180°C is above the temperature at which sulfonic groups come off of Nafion polymer, as can be seen by infrared spectroscopy of Nafion heated at different temperatures (see Peter Faguy et al. in the 1990s in the *Journal of Applied Electrochemistry*).
- The first project goal listed is to “Elucidate how solvents impact ionomer dispersion morphology, thus changing electrode structures and performance,” which has useful data that are yet to be connected. For example, the solvent’s effect on ionomer dispersion morphology has been partly studied through rheology, zeta potential, and particle size analysis. However, the results of the ink morphology have not yet been correlated directly to electrode structure and performance; for example, it would be useful to plot the results of the ink morphology studies with some quantifiable electrode structure metrics (e.g., electrochemical surface area [ECSA], gas transport resistance, total porosity, sulfonate poisoning of catalyst, catalyst layer ionic resistance, and current density at several cell voltages). Once each of these parameters is plotted, a sensitivity analysis may be performed to determine which characteristics of the ink are truly the most important in affecting the final electrochemical parameters. Additionally, while elemental mapping is interesting to view, subjective claims without a quantifiable direct relationship to performance should be made with caution. As an example, on slide 6, one of the bullet points says “better ionomer and Pt dispersion with EG and BUT” (Nafion in butanediol). It is unclear whether increased dispersion will necessarily lead to better performance; this is a matter of (among other effects) balancing an advantageous increase in protonic access to Pt sites and ionic conductivity of the cathode layer (through reduced tortuosity of the ionomer’s water channels) and a deleterious increase in sulfonate–Pt interactions that may have negative impacts on both catalyst activity and oxygen transport. If claiming that a particular electrode structure is more advantageous, the project should indicate the mechanisms by which it is. The project should also avoid using speculation, such as, on the same slide, “likely associated with higher elastic and viscous components of catalyst inks.” If this is the case, the project should provide evidence. For the goal of scalability, the methods to determine final ink structure at the small scale may not correlate to the large scale because of time limitations, such as milling for days and drying for days.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- The project teaming is well-considered and organized. LANL is responsible for ionomer dispersion preparation characterization because the ionomer material was originally synthesized there. Giner takes the main responsibility of investigating ink properties, fabricating, and testing MEAs, while the University of Connecticut supports the conduct of electrode structure characterization, and NREL helps with scale-up. The strengths of team partners are complementary and nicely arranged to achieve the project goals.
- Giner’s and the national laboratories’ work is well-coordinated and complementary.
- The results of the collaboration with the University of Connecticut are not quite clear in the presentation slides. It would be useful to outline exactly what kind of electrode characterizations are to be performed by this collaborator. The interactions with the Million Mile Fuel Cell Truck (M2FCT) national laboratories seem appropriate and useful. The results so far are a good foundation for work in the project’s future, especially NREL’s R2R capabilities.
- The team did have NREL as team member, but the work looked to be a repeat of the study using a different equipment. Some optimization needed to be done to obtain the same results. The project could have benefited from a collaborator with more analysis or modeling capabilities that could have given the team some correlation between observed performance differences and the structures and/or modeling.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is set to develop a new way to prepare catalyst ink to promote the application of a new ionomer. In general, new ionomer development and application have been quite difficult, but it is going to be very critical for future polymer electrolyte membrane fuel cell (PEMFC) development to meet DOE's goal for both passenger and commercial vehicle applications. To this end, this project indeed takes on high risks and challenges in a difficult topic with big impact.
- The project is quite relevant and has potential to provide a large impact on performance of PEMFC MEAs.
- Ionomer dispersion in both inks and electrodes is no doubt important. Some background evidence was provided to justify that solvent choice alone can affect fuel cell MEA electrode structure. However, there was relatively little discussion about how these structural changes specifically might affect efficiency and durability of the resultant MEA as a whole. Furthermore, for the purpose of establishing relevance, it would be useful to show how changing solvent alone might affect a voltage–loss–breakdown analysis. In other words, it is unclear which sources of overpotential are affected (and to what degree, specifically) by solvent choice.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Overall, the proposed future work is reasonable, considering the project status. It would be great to dedicate some additional effort to (1) investigating why the high current/power performance is poor and exploring potential countermeasures and (2) understanding how the solvents and fabrication methods might have affected catalyst durability (composition or ECSA change). The result could provide hints for further improvement toward heavy-duty applications.
- Future work appears to address the concerns outlined in the presentation.
- The optimization is needed, but the temperature range of curing needs to be between 140°C and 170°C.
- Unfortunately, there is not much time left for future work on this project, so the future work outlined is much more than can be accomplished by August 2021. The scope of future work quickly expanded to an all-encompassing catalyst layer optimization study rather than the original scope of studying the impacts of the solvent on the ionomer interaction with the catalyst layer.

Project strengths:

- Evidence is presented to show that solvent has an effect on both electrode structure and resultant MEA performance. Collaborations with M2FCT national laboratories are useful and appropriate for the strengths associated with each laboratory's capabilities. Obstacles were noted (such as cracking in the electrode structure at particular thicknesses and electrode drying times), and the project plans to overcome these obstacles and offers at least one method to do so (e.g., reduce thickness of the catalyst layer on the GDL).
- The project has a strong team with enough capabilities to perform the planned tasks and reach the project goals. It has a fairly straightforward technical approach.
- An important topic for making a good catalyst layer is catalyst film that is durable and like a bulk membrane, and this project addresses this.
- The project has an important approach—looking at solvent interactions with a catalyst layer—that has a potential for large impact.

Project weaknesses:

- The project states that part of the procedure is to ball mill inks for between three and five days. In addition, part of the procedure is to dry the electrode structure in a vacuum oven for five days at 150°C. This protocol is unrealistically time-consuming for scalable electrode fabrication, so the resultant structures may have a questionable relationship to real electrodes for use in industrial applications. The ink analysis was not stated to be at relevant concentrations (e.g., it seems that the ink may have to be diluted to be analyzed in the zetasizer). This may not be a weakness if the concentrations of ink used were the same that were employed during fabrication, but the project should indicate which is the case.

- The project focuses only on ink and MEA preparation processes, not covering the modification and improvement of the ionomer material itself. This may limit the opportunity to further improve performance and durability.
- The project quickly diverged from the study of solvent interaction to an all-encompassing study of catalyst layer construction.
- The researchers are not well-versed in the effects they are studying and need to examine the literature better.

Recommendations for additions/deletions to project scope:

- Relatively few solvents were chosen for study in this project. There is significant additional literature that addresses other solvents used with perfluorosulfonic acids that may be useful to consider. The project should add more specific electrochemical analyses (ECSA, gas transport resistance, total porosity, sulfonate poisoning of catalyst, catalyst layer ionic resistance, and current density at several cell voltages) versus particular ink and electrode parameters (particle size, ink viscosity, zeta potential, etc.) and perform sensitivity analysis on these parameters. As an additional note, acoustic particle size analysis can be a powerful tool for measuring particle sizes, even in relatively concentrated dispersions, and may be something to consider as an additional tool to confirm the results.
- The project should do a literature search of solvent casting with ethylene glycol (Martin), phase changes (Virginia Tech), and thermal stability (Peter Faguy).
- The project should consider adding countermeasures to improve high-power performance.
- There is very little budget and time left to act on any recommendations.

Project #FC-158: Fuel Cell Membrane Electrode Assemblies with Ultra-Low-Platinum Nanofiber Electrodes

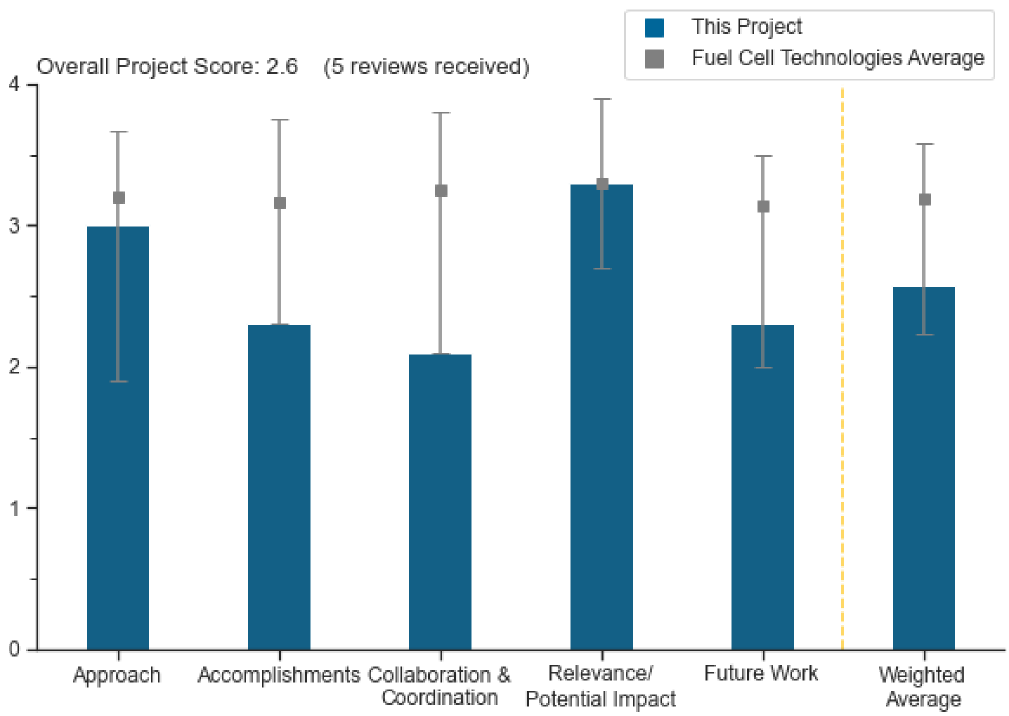
Peter Pintauro, Vanderbilt University

DOE Contract #	DE-EE0007653
Start and End Dates	1/1/2017 to 12/31/2021
Partners/Collaborators	Nissan Technical Center North America
Barriers Addressed	• High-current-density performance of polymer electrolyte membrane fuel cell membrane electrode assemblies is low for cathodes with low platinum loading

Project Goal and Brief Summary

Particle/polymer nanofiber mat electrodes are a promising alternative to conventional fuel cell electrode structures. This project seeks to better understand and further improve the performance and durability of low-platinum-loaded nanofiber mat fuel cell electrodes and membrane electrode assemblies (MEAs). Mat electrode MEAs with highly active oxygen reduction reaction catalysts for hydrogen–air fuel cells will be fabricated, characterized, and evaluated. The project will focus on nanofiber cathodes with commercial platinum–alloy catalysts containing various ionomer and blended polymer binders.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Using nanofibers of various configurations in the catalyst layer of MEAs is a novel and good approach, with excellent potential to improve performance over state-of-the-art catalyst layers. The project would benefit from some modeling work so that the mechanisms of the reported performance improvements could be better understood.

- Preparing structured electrodes through nanofibers can provide an optimal combination of protonic and mass transport resistances. The principal investigator (PI) has used platinum loadings that are relevant for automotive and heavy-duty fuel cell systems. The single-nozzle approach is not scalable. It would have been better if the project leaders had investigated options to scale up this technology by using multiple spray nozzles.
- The overall approach to improve catalyst layer performance is good. However, there are a number of areas of inconsistencies that make it hard to understand the technology improvements. For example, there is little understanding toward the effect of pre-compaction for 0.2 mg/cm^2 loading vs. 0.1 mg/cm^2. These loadings are not evaluated at the same compaction; hence, the benefits of this process cannot be understood. Similarly, a new binder is used in this year's process—one that is different from ones used in previous years—which does not adequately provide fundamental understanding of the binder's benefits.
- The project can still benefit from further systematic variation of compositions and process parameters, combined with Fuel Cell Consortium for Performance and Durability (FC-PAD) diagnostic and characterization tools, to correlate effects and enhance understanding of the underlying physics of the processes.
- Because there is no development of the basic materials (i.e., catalyst, catalyst support, or ionomer), the approach relies on assumptions that conventional methods of forming the catalyst layer create flaws (e.g., transport limitations) that warrant an alternative approach, and that the electrospinning approach would address that. There are several flaws in these assumptions. Also, using electrospun nanofibers brings its own challenges, such as higher contact resistance, pores and a residual carrier that take up valuable electrode volume, and potential higher processing cost.

Question 2: Accomplishments and progress

This project was rated **2.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- After showing initial promising performance in a relatively short period, it seems like progress has been more modest on the nanofiber approach. Interesting results continue to be shown at very low (40%) relative humidity (RH) at high current densities. Superior water retention due to the pore nanofiber structure was suggested (and apparently previously demonstrated by neutron radiography results). It would seem more work may be warranted to characterize this (and should include the high-frequency resistance and electrode conductivity measurements). On the same low-RH performance issue, more emphasis should be put on power density at usable voltages rather than "max power density," where the cell potential (V_{cell}) is too low to be practical. New work seems to focus on the new additive binder, which demonstrated improved performance on a conventional spray approach (not the project's nanofiber approach), raising performance to be very similar to that with the nanofiber electrodes. If this is so, perhaps there are no longer clear benefits to the nanofiber morphology.
- The maximum reported power density is better than the project's internal baseline. However, the MEA performance is not best-in-class compared to other DOE-funded projects.
- Progress toward DOE goals is almost impossible to determine since the operating conditions of the fuel cell tests are not those specified in the DOE targets. All of the polarization curves are operated at constant gas flow rates, not stoichiometrically controlled testing conditions. The stoichiometry at the project's reported maximum power point of 1.5 A/cm^2 is 4 × for air and 2.2 × for hydrogen—all this on a small, 5 cm^2 MEA—and results from testing procedures (i.e., performance duration at each data point) are not given. At a reasonable air stoic of 2.5 ×, all the polarization curves show less than 0.2 V of cell voltage. Nissan (shown on the budget slide) is a good teaming partner from a system level, but no polarization curve data from Nissan was reported.
- Progress toward overall DOE goals is harder to evaluate because the fuel cell tests are performed at constant flow and not at stoic. Any mass transport issue in the nanofiber is not apparent under the flow conditions.

- Unfortunately, there has not been much progress in the last two years. The project still cannot say for sure whether the approach provides any kind of benefit over the state-of-the-art method. The choice of baseline electrode (hand-sprayed electrode) is poor, with likely poor quality and reproducibility. MEA tests are done with small-active-area cells, and yet the project chose an operating condition that limits evaluation of high current density. The measurement quality and repeatability are unclear. The project should have followed DOE recommendations for testing and collaborated with an external partner to get proper evaluation and comparison with a state-of-the-art electrode, if the project team is not capable of that. The fact that there is no difference in performance or durability between electrospun fibers and hand-sprayed electrodes with hydrophobic additive further discredits the benefit of electrospun fibers. There is no characterization update of any insight regarding electrode structure after fuel cell operation, nor of what causes the claimed benefit.

Question 3: Collaboration and coordination

This project was rated **2.1** for its engagement with and coordination of project partners and interaction with other entities.

- The Oak Ridge National Laboratory imaging results are appreciated, but these are all beginning of life. Addition of post-accelerated-stress-test (post-AST) imaging would also be interesting.
- This project could benefit from a fuel cell system partner. Nissan is shown on the budget slide, but no validation data from Nissan are reported. Also, a partner that could model the transport mechanisms of the improved catalyst structures would be beneficial.
- It would have been better if the project had collaborated with companies to pursue the pilot-scale multiple-needle demonstrator, per the team’s response to the 2019 reviewer comments.
- Collaborations outside of the national laboratories are not apparent. Since the electrospinning collaboration has ended, it is not clear how the project can scale up this technology. There is no apparent interest in testing the MEAs at locations other than Nissan.
- There appears to have been some collaboration in prior years but none this year. The low score reflects the low collaboration in spite of being one of the FC-PAD (Million Mile Fuel Cell Truck [M2FCT]) projects. The project should have plenty of access to national laboratory resources and yet did not utilize them.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- High-performance, stable, low-platinum-group-metal (low-PGM) loaded robust electrodes are key to programmatic success. Further progress is still needed in the nanofiber electrode high-power-density performance, but the electrode has shown some promise in stability and low-RH performance. High performance at low RH is also an enabler, given that target power density is tied to the $Q/\Delta T$ (inlet temperature difference) metric (driving higher temperature, which results in reduced RH). The project should further identify the reasons for this exhibited low-RH performance.
- High efficiency and durability remain the priorities of fuel cell research and development. This is an approach that potentially addresses the challenges.
- The concept of incorporating nanofibers into the catalyst layer is a good one and does have potential.
- The project supports overall DOE goals to improve performance and durability of MEAs for light- and heavy-duty vehicle applications. However, testing should be beyond the understanding of subscale MEAs under constant flow. Even the catalyst layer structure analysis stops with scanning electron microscopy (SEM) at high magnification. There are no high-magnification transmission electron microscopy (TEM) data to help researchers understand the catalyst–nanofiber interactions and structure. Similarly, there are no fundamental data to help researchers understand the fiber–membrane interactions. The focus seems to be only on evaluating different ink compositions and coating methods. A more comprehensive study to understand the benefits and interactions of the nanofiber with catalyst layer components in the MEA should be the focus for the last part of this project.
- The impact of this project toward the DOE goals is limited. The performance of these MEAs is subpar compared to best-in-class, and there is currently no active work on scaling up this technology.

Question 5: Proposed future work

This project was rated **2.3** for effective and logical planning.

- Little time remains in the project for what seems to be a rather lengthy list of proposed future work. Half of that focuses on the new binder additive with sprayed electrodes. This additive does appear interesting, but the work on sprayed electrodes does not appear to be in scope. If it is, it may be worth demonstrating the repeatability of the results, as this spray method may show high variation. It would be good to see more systematic parameter and process variation, combined with FC-PAD diagnostics, to further identify nanofiber mechanistic impacts on performance, RH dependence, and voltage stability with both beginning-of-life and end-of-life samples.
- Future work should focus on comprehensive analysis of catalyst layer interactions between ionomer–binder–catalyst for an identified set of materials. Any further investigation on optimizing additive content, new catalysts, and new coating methods should be stopped until a full understanding of existing material is published.
- The project should report fuel cell performance under constant, DOE-specified stoichiometry operating conditions.
- The project should focus on a binary alloy catalyst for cathodes and the pilot-scale multiple-needle electrospinner.
- Very little time is left in the project. No clear plan exists to identify the approach's benefit or the source of the benefit, which will leave the project ending without much value to the community.

Project strengths:

- The project has a novel concept in tuning properties of catalyst layers, which does have good potential to improve conductivity and mass transport in catalyst layers.
- The PI has a strong background in nanofiber technology. The project can still take greater advantage of FC-PAD's characterization capability, which is a key attribute.
- The project understanding of the electrospinning process is a strength.
- Moderate success equals moderate strength.
- The project strength is the approach to catalyst layer deposition using a nanofiber spray method. However, the project should have focused on understanding the benefits of this method by limiting the material set that was investigated. Changing the ionomer additive every year without getting a full picture of the catalyst layer interactions was not beneficial to the community. A trial-and-error approach is not a valuable return on investment for DOE.

Project weaknesses:

- The project did not involve other national laboratory partners or the greater research community to understand the benefits of the nanofiber technology. The project team should not have given an industrial-style optimization effort a "go" without understanding the benefits of this approach. Fuel cell testing at constant flow is a weakness and does not allow the community to evaluate the progress for light- or heavy-duty vehicle application. This year's progress does not seem to include any contribution from Nissan Technical Center North America.
- The team has the capability but has not yet used it sufficiently to fully characterize performance (local O_2 transport resistance, mass transport, and electrode and membrane conductivity). Although much work has been done to improve the spray electrode performance, how these electrodes perform compared to state-of-the-art electrodes remains unclear. Process variation is also still in question.
- The project did not follow DOE test recommendations. The team did not have the capability to evaluate materials properly and did not reach out for help. Collaboration was limited.
- There is no active scale-up pathway.
- Determining the progress toward DOE targets and goals is difficult.

Recommendations for additions/deletions to project scope:

- It would be good to see greater characterization of nanofiber (and now additive, binder, and spray electrode) morphologies and linkages to their observed performance. More systematic parametric variation is recommended to elucidate nanofiber electrode mechanisms and benefits.
- DOE should stop all future optimization work on this project, and the PI should focus only on extensive catalyst layer structural analysis and interactions of the additive and ionomer in the nanofiber with the catalyst and membrane. Future projects should identify a limited set of materials and focus all resources on understanding the fundamental interactions within that limited set of materials and comparing findings with the state-of-the-art MEA.
- The project should provide a polarization curve at fixed stoichiometry on an MEA with an active area of 50 cm^2.
- Optimizing additive content should be deleted from the scope. Working with original equipment manufacturers to conduct stack-level testing should be added, if possible.

Project #FC-160: ElectroCat 2.0 (Electrocatalysis Consortium)

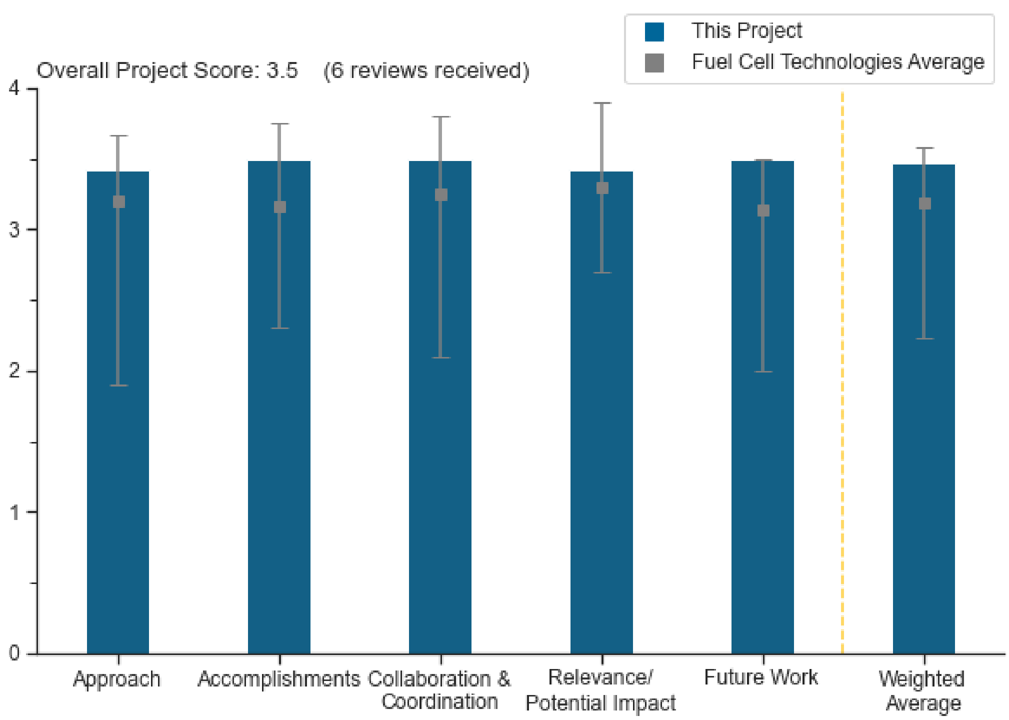
Deborah Myers, Argonne National Laboratory, and Piotr Zelenay, Los Alamos National Laboratory

DOE Contract #	Multiple
Start and End Dates	10/1/21–9/30/24
Partners/Collaborators	National Renewable Energy Laboratory, Oak Ridge National Laboratory
Barriers Addressed	• Cost (catalyst) • Activity (catalyst, membrane electrode assembly) • Durability (catalyst, membrane electrode assembly) • Power density (membrane electrode assembly)

Project Goal and Brief Summary

The Electrocatalysis Consortium (ElectroCat), created as part of the Energy Materials Network, aims to accelerate the development of next-generation catalysts and electrodes that are free of the platinum group metals (PGMs) currently required for good performance and durability. ElectroCat has focused its efforts on oxygen reduction reaction (ORR) catalysis for polymer electrolyte membrane fuel cell (PEMFCs) and has established a portfolio of unique synthesis, experimental, characterization, and modeling capabilities. ElectroCat 2.0 will increase focus on improving catalyst durability, investigating electrode engineering, and further advancing high-throughput catalyst synthesis and characterization capabilities coupled with machine learning while still working to improve catalyst performance. The Consortium has also expanded its catalyst portfolio to include the development of PGM-free catalysts for low temperature electrolysis.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The ElectroCat 2.0 team has continued the very well-integrated, thorough, and structured approach established in the first ElectroCat project. The combination of the combinatorial and high-throughput approaches with machine learning and density functional theory (DFT)/medium-duty modeling is very powerful. The use of extensive characterization approaches and the creation of new ones support a relatively strong pace in increased understanding. The neural network modeling and U.S. Department of Energy approach has been used to achieve significant results, with almost a doubling of the mass activity. Nevertheless, it is interesting that, despite several years of this structured approach, the catalyst system is still capable of significant surprises. For instance, the dual-zone process effect on performance is surprisingly poor, and durability is surprisingly good.
- The high-throughput and machine learning tasks have made significant advancements, and it is encouraging to observe the framework solidifying to the point where there appear to be sufficient data to generate useful predictions. It would be encouraging in future years to see whether the machine learning can predict synthesis/catalysts with performance/durability metrics that improve over the parametric studies used in generating the training data. Given the importance of the alkaline ionomer and membrane conductivity, the project would benefit from partnerships with multiple polymer electrolyte developers. The alkaline electrolyte membrane (AEM) electrolyzer effort would benefit from a greater amount of technical-assessment-driven targets and material-specific objectives based on performance and durability analysis, rather than cell performance goals. The x-ray spectroscopy, electron microscopy, and DFT modeling continue to be key assets to this project.
- ElectroCat 2.0 is (cautiously) welcome to address low-cost catalysts for electrolysis; however, there is very little publicity on this new effort. The Office of Energy Efficiency and Renewable Energy public relations does not mention ElectroCat 2.0, nor does the ElectroCat website. The integration of machine learning with experimental efforts is a good strategy. There is tightly coupled multiscale modeling in this effort to provide physical interpretations of optimization. A new LANL–NREL effort may contribute here. The direct comparison of the four high-throughput systems would be valuable. The table on slide 31 is difficult to map to Systems 1–3b on slide 15. Validation of DFT predictions with experimental data is limited. The fact that there are some experimental motivations is understood, but the results need to come back to these to demonstrate causality, for example, catalyst durability decay constant as a function of pH.
- The project appears to be on track and making important advances in the field of PGM-free catalysts. In particular, optimization of both activity and durability in parallel form an important approach to ensure that useful catalysts are developed, and the team is clearly adopting that strategy. A minor criticism of the work is that it is not clear how the fuel cell and electrolysis aspects of the projects are related or how they leverage each other; it seems these are entirely separate projects.
- The project is structured to focus on hydrogen–oxygen performance for heavy-duty transportation and electrolyzer stacks. Performance goals were met for hydrogen–oxygen, but decay is very high after 20,000 cycles. Development progress and spending are on schedule, and milestones have been met for the hydrogen–oxygen effort. The hydrogen–air tests are a significant concern because of the significant degradation after 10,000 cycles. The ultimate requirement is a hydrogen–air membrane electrode assembly. The team performed significant new machine learning efforts. The catalyst performance in the electrolyzer mode is very poor.
- There is a good mixture of performance-oriented work and fundamental scientific investigation and methods.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The work is structured via well-defined milestones that are on track or have been exceeded, with excellent progress since 2019. The team has already exceeded the September 30, 2021, target. The durability improvement of the dual-zone catalyst is impressive, and understanding this will undoubtedly lead to further improvements. The team is making some good progress on a hypothesis that is still to be proven. The establishment of the Pourbaix-like diagram is a very good addition to the knowledge base and provides an effective approach to understanding stability of the catalyst systems. The oxygen-limiting current method for characterization of bulk-electrode transport is a useful addition to the characterization techniques.

- The team has made excellent progress here in terms of new catalyst synthesis techniques and new high-throughput data generators, coupled with artificial intelligence (AI) and physical models. The dual-zone and post-treatment catalysts should provide a wealth of information about a mechanism that can be studied using high-throughput systems, AI, and physical models. The dual-zone catalyst appears to have higher resistance than the single-zone catalyst. Since this does not appear in the high-frequency resistance measurements, it may be localized to the electrode. It is unclear whether this is the topic of "reduced cathode proton resistance," as mentioned for the future work on slide 41. If NH_4Cl is a pore former, then a before and after study of micro- and meso-porosity is of interest.
- Overall, the project appears to be making progress toward the end-of-consortium goals, although the gap on durability is probably most significant at this point. The publication and dissemination of work appears to be excellent.
- The project is on track with its proposed goals based on the data presented. The dual-zone discovery seems to be a potential breakthrough in this field if a better understanding of the mechanism for improved durability can be elucidated.
- The fuel cell performance of the current project catalysts currently lags behind several other projects, as well as prior-generation catalysts from the team. The activity metrics have excessive catalyst loadings (7 mg/cm^2) that are not viable for generating satisfactory power density. Excellent stability has been demonstrated, but with a low-activity catalyst. The insights from the high-throughput testing and machine learning will yield significant advancements in site density and stability. Initial progress has been made in setting benchmarks for PGM-free oxygen evolution reaction (OER) catalysts for AEM electrolyzers.
- Significant progress has been made in PEMFC development, but there are weaknesses that need to be addressed—particularly, performance of the catalyst in the electrolyzer setting. The cell voltage of 2.0 V at 600 mA/cm^2 is too high. Much more focus should be put on the study conditions for the electrolyzer performance if the project is ever going to achieve a goal of an 80,000-hour lifetime. An early understanding of the fundamental mechanisms associated with the IrO_2 anode's operation in the electrolyzer should be used to guide the catalyst development.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The final team, facilities, and equipment required to complete this project are in place, ready, and available. The personnel are qualified, as demonstrated by the successful completion of previous projects and by their publications. This project has full commitment from senior management and corporate officers of partners. Ample facilities are available to support and complete this work.
- The consortium is a strong group of top-notch researchers and institutions. The research and development (R&D) plan uses the strengths of each institution. It would probably be impossible to assemble a better R&D team for this project or a team with better capabilities; however, the consortium seems to lack involvement of "end users" for the catalysts. This may be understandable because the PGM-free technology is far from commercialization outside of niche applications, but other DOE consortiums have more involvement from fuel cell original equipment manufacturers (OEMs).
- The project has a great deal of collaboration and provides critical support to the ElectroCat funding opportunity announcement (FOA) projects. Within the team, there does not seem to be very much coordination between the catalyst development and the electrode development. It would be good to have more coordination between those efforts.
- The work of the national labs in the consortium appears to be well-coordinated. ElectroCat is engaged in numerous collaborations.

- The team appears to be working with a variety of partners and organizations. For the electrolysis work, the team should consider working with some of the other (non-national-laboratory) teams developing AEMs: the University of Delaware, Georgia Tech, Rensselaer Polytechnic Institute (RPI), and others.
- The mention of external collaborators was very sparse in this presentation (granted, 2020 was a challenging year for collaboration). It would be of interest to see the way that external FOA projects have contributed to the core ElectroCat mission.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is the leading effort to obtain a low-cost electrocatalyst for ORRs, and now OERs, in the United States. For this reason, this project is crucial to the success of fuel cells in low-cost applications. ORR is much more important than OER for mobile applications, and stationary applications may be better suited to high-temperature systems. For this reason, the original mission to develop ORR catalysts should be given as much priority as possible.
- Although progress has been achieved in PGM-free catalysts, allowing the eventual applicability to high current density and high power density, durable applications are still in doubt. PGM-free catalysts are now at the point where they may find application areas, but the relevance to transportation applications is still to be determined. It is, however, necessary work and should be continued. The addition of the electrolyzer activity is also relevant.
- It is important to have this effort on low-technology-readiness-level materials and technologies that could be very impactful in the long term. The transition to greater emphasis on hydrogen production is timely. At the same time, the overall momentum in the advancement of PGM-free PEMFC catalysts within this project and the other ElectroCat projects is still high, and significant efforts should continue to be devoted to them.
- Reducing PMG loading is critically important to the successful commercialization of PEMFCs and electrolyzers, as well as the reduction of IrO_2 on the anode in the electrolyzer.
- The work is addressing the challenging area of PGM-free catalysts for ORR fuel cells and OER electrolytes.
- The PGM-free fuel cell catalyst development aligns well with DOE's long-term goals for fuel cell cost reduction, but the potential results from this project are likely a long way off with respect to achieving the million-mile performance targets of 1.07 A/cm^2 at 0.7 V. Most truck manufacturers are pursuing quite high PGM loadings, and PGM-free catalysts do not currently appear to be of interest for heavy-duty transportation. However, since the purpose of the consortium is more focused on R&D and discovery, the team is making significant potential impacts in that regard. For the electrolysis part of the consortium, it was difficult to understand how the work performed was related to the electrolyzer stack goals.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The proposed future work is clear and makes sense. The use of probe molecules for characterization could yield further interesting results on active site structure and mechanisms for degradation. It will be interesting to see further characterization of the dual-site catalyst and the team's discoveries.
- Emphasis on durability and durability mechanisms for fuel cell ORR is important and well-placed. Researchers on the electrolysis work should consider collaborating with some of the other (non-national-laboratory) teams that are developing AEMs: the University of Delaware, Georgia Tech, RPI, and others. Also, the team should more clearly define the gaps for alkaline OER catalysts and state whether the main issue is integration with membranes. It seems the hydrogen evolution reaction may be a bigger challenge than OER for alkaline systems.
- In the dual-zone-synthesis technique, it appears that a mitigation strategy has been developed before a comprehensive understanding has been achieved. The project should marshal all of its resources to take advantage of this good fortune.

- The future work is good; however, more effort should be dedicated toward understanding perovskite material operation under OER.
- The proposed future work appears well-planned.
- The future work on the AEM electrolyzers was not well-defined and missed specifics and a clear framework/organization.

Project strengths:

- The R&D team is very strong. The project is well-managed and appears to be on track with the proposed milestones. The project has uncovered scientifically interesting discoveries that have the potential to significantly improve the understanding, performance, and durability of PGM-free fuel cell catalysts.
- There is excellent progress in synthesis, modeling, and characterization of new catalysts, as well as good synergy across all components. The project has excellent capabilities for addressing OER catalysts.
- This project is very systematic and comprehensive, and it has aligned efforts to improve the catalyst activity and durability/stability. Extensive characterization and catalyst-level modeling are incorporated. Overall, this is a very strong team.
- The high-throughput synthesis and testing, coupled with machine learning, are key areas of innovation and strengths of the project. The characterization and analytical methods are also key strengths.
- This project has many strengths, but there is much to do. This project group is capable of conducting the R&D for PGM-free catalysts. Scale-up and stability verification are likely to present significant challenges.

Project weaknesses:

- It would be encouraging to see more OEM involvement with the consortium. The electrolysis part of the project seems to integrate poorly with the fuel cell work.
- The key weakness is the current fuel cell performance of the project’s catalyst, requiring high loadings to achieve activity targets.
- There is concern that the study of OER will be a distraction from the central goal of a low-cost ORR catalyst. The synergy between the two efforts seems minimal. There would be two potential reasons to pivot to OER: (1) ORR is very successful, and OER is a spinoff project, or (2) progress toward an ORR catalyst is slowing down, or there is no foreseeable pathway to commercialization. The former does not appear to be the case, and it is to be hoped that the latter is also not true. Finally, the integration of external FOA projects could be improved.
- The stability of the catalyst needs to be significantly improved.

Recommendations for additions/deletions to project scope:

- A recommended addition to the project would be more OEM involvement to help guide targets for potential applications. The electrolysis catalyst development is important, but it should probably be a separate project.
- The project should consider bringing in additional team members who have a good understanding of electrolyzer performance.
- Caution is recommended in adding OER to the scope of this consortium.

Project #FC-163: Fuel Cell Systems Analysis

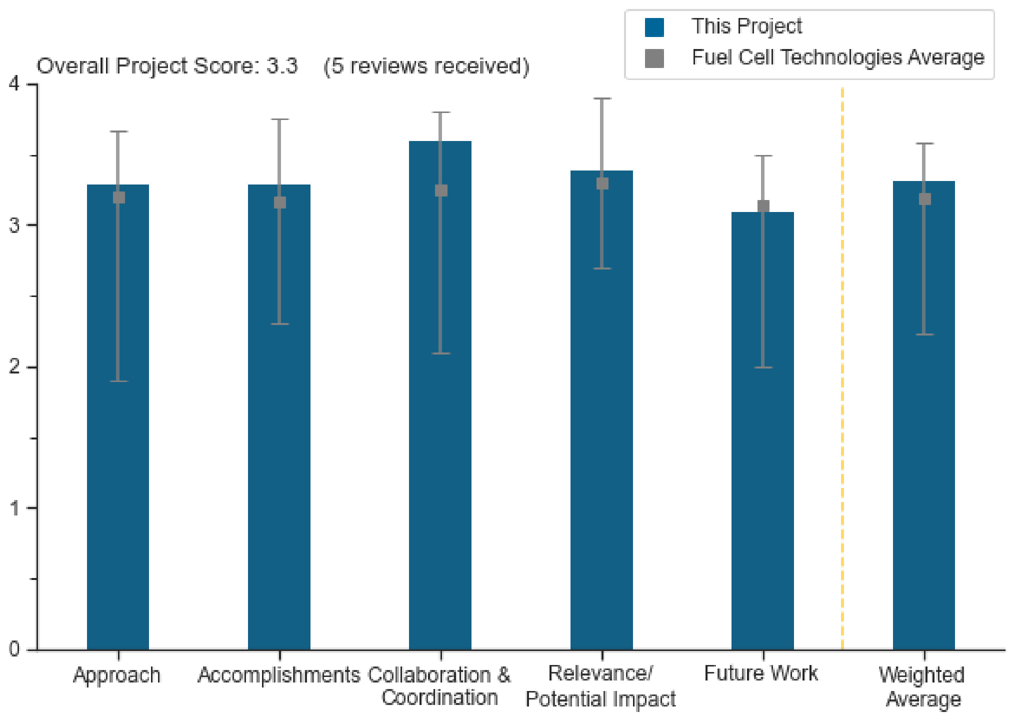
Brian James, Strategic Analysis, Inc.

DOE Contract #	DE-EE0007600
Start and End Dates	9/30/2016 to 9/30/2021
Partners/Collaborators	National Renewable Energy Laboratory, Argonne National Laboratory
Barriers Addressed	• System cost. Demonstrates impact of technical targets and barriers on system cost

Project Goal and Brief Summary

This project seeks to estimate current and future costs (for years 2020 and 2025) of automotive, bus, and truck fuel cell systems at high manufacturing rates. Analyses conducted project the impact of technology improvements on system cost, identify low-cost pathways to achieve U.S. Department of Energy (DOE) transportation fuel cell cost goals, benchmark fuel cell systems against production vehicle power systems, and identify fuel cell system cost drivers to facilitate Hydrogen and Fuel Cell Technologies Office (HFTO) programmatic decisions.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is solid, working closely with Argonne National Laboratory (ANL) on the systems modeling and the incorporation of information as it becomes available. The project appears to extensively "validate" the approach and the numbers through one-to-one interactions with manufacturers. In some areas, the analysis may suffer slightly from not enough visibility into manufacturers' approaches. Each manufacturer will have a different combination of tradeoffs that the company uses to achieve results, and this analysis is only one view that may not reflect any approach actually used. On the whole, however, the model seems to come out approximately "correct." The stack oversizing approach is one area that does not seem like the best approach. More model analysis is required to justify or change this approach. Incorporating the graphite plate as a validated option is a good approach; it might also be good to run a sensitivity analysis that incorporates a potentially viable metal plate option. It will be important to include other degradation modes, such as start-up and shutdown. The removal of a humidifier may not be the most cost-effective approach when looking at the cost tradeoff (assuming an impact on performance and durability).

- Strategic Analysis, Inc.'s (SA's) design for manufacturing and assembly (DFMA) approach has been shown to be sound, and the team is working with relevant stakeholders and the fuel cell community to properly address the DOE-provided project goals. While not working directly on technologies that could reduce the barriers, the project's cost analysis plays a necessary role in assessing HFTO's progress toward overall goals.
- SA's approach remains appropriate and good. A continuous close interaction with component suppliers and system developers is key to fairly accurate cost estimations.
- The SA team attempts to create a comprehensive fuel cell model to predict where costs are most intensive and where researchers should focus development costs to save money. The model is also useful for setting DOE performance goals. The model seems to be appropriately detailed for accurate analysis. The durability predictions could be very important, but the degradation mechanisms are not fully understood, so it is hard to model. The modeling of the cell monitoring systems could also be very useful to manufacturers. The major problem with the modeling approach is that it cannot be validated because it is based on high-volume manufacturing that has yet to occur.
- The project takes a consistent approach to annually update and indicate durability complications in the cost analysis. Research and development (R&D) focus has shifted to heavy-duty vehicles (HDVs). Therefore, project resources should also focus on HDVs, rather than light-duty vehicles (LDVs). HDV customers are conscious of total cost of ownership (TCO) rather than the cost of the fuel cell system. It is recommended that the project use TCO to identify cost actions for fuel cell designs.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The main focus in the past year was the DOE-driven request to assess the cost impact of durability, a difficult task. SA did as well as could be expected, given the uncertainties and relatively immaturity of fuel cell use in HDVs. In addition, the team updated all of the LDV, medium-duty vehicle (MDV), and HDV fuel cell statuses and performed cost assessments of various durability enablers (e.g., cell voltage monitoring, high-frequency resistance, and total harmonic distortion). The team completed quite a list of accomplishments and progress for a year.
- The SA team was able to incorporate extensive pricing details into the model and appears to have worked hard to bring accuracy to the numbers (the back-up information is impressive). The work is somewhat discouraging, as it predicts an increase in costs per kilowatt for longer endurance. The results almost suggest that additional innovations are needed to lower costs.
- The work done on HDVs is a real need. Unlike LDVs, TCO of HDVs is the key driver and thus should be the focus. Moreover, as the market share is less than that of LDVs, information on the corresponding market share, in addition to the number of produced systems, could be provided. For clarity, it would be good to be reminded as to whether the annual production rates refer to the total of fuel cell systems produced in the United States or to a single fuel cell system manufacturer, which would lead to even more difficult cost targets that need to be achieved. The final 10% cost decrease titled "miscellaneous" may be better detailed.
- This work is essential to guiding the overall DOE work on achieving cost-effective fuel cell systems.
- The durability-adjusted cost analysis shows more appropriate development direction, such as the tradeoff between Pt loading reduction and durability.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- SA worked effectively with the National Renewable Energy Laboratory (NREL) and ANL to obtain information for the SA model. The researchers were also able to populate their model with information from companies such as Celeroton. The project team got feedback on the model from multiple sources, including Gannon & Scott and Cell Centric Canada. The overall approach to collaboration and coordination is thorough.
- The team has excellent collaboration with NREL and ANL. There are a good number of collaborators providing pertinent input and review, as well as a very extensive list of additional collaborations for each component.
- SA is doing a great job of collaborating, mainly with the ANL systems analysis project and NREL, but also expanding with many component and system developers, suppliers, and end users. The team's interaction with the Million Mile Fuel Cell Truck (M2FCT) effort is expected in the next period.
- SA's close interaction with the ANL systems analysis project is important and effective. The team also provided an extensive list of collaborations, as required for project effectiveness.
- There is effective collaboration on the fuel cell system analysis, including durability impact.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project provides a powerful tool to forecast the costs of fuel cell systems for LDVs, MDVs, and HDVs. The tool allows systematic updates based on achievements of other projects, industry interviews, and modeling refinements. It contributes to identifying fuel cell system cost drivers to help DOE refine and update the critical issues to be addressed in future funding opportunity announcements.
- The project plays a necessary role in providing a status update to DOE on the key cost metric. Thus, the project is of greater benefit and relevance to HFTO and subprogram managers than to the direct advancement of the technology. The project also has indirect value in identifying promising technology enablers or areas and proposals of limited potential benefit.
- This project is essential to finding feasible solutions to meet DOE targets.
- The model clearly points to technology areas where improvements are needed to meet future cost targets for 2025 of automotive, bus, and truck fuel cell systems. The key unknown is whether the model is correct and whether it is possible to reach the projected cost targets; however, the study provides a useful direction. The disconnect with the industry might be whether industry would use this model or whether any company making 100,000 fuel cells a year has its own model.
- The R&D focus is now shifting from LDV to HDV applications.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- Given the significant cost impact of durability, the intent to continue to investigate ways to incorporate durability into cost models is appropriate. The project should continue to assess the potential cost impact/benefit of the various fuel cell projects funded by the U.S. DRIVE Partnership. Advanced coating of bipolar plates, membrane electrode assembly deposition techniques, and manufacturing control processes were mentioned, but should also be extended where relevant to any new U.S. DRIVE projects. Given the large cost sensitivity of various requirement-driven targets (e.g., thermal, power, end-of-life degradation, efficiency), it is thought to be worthwhile to more broadly explore the requirement-driven space and develop a more general and flexible cost vs. "x" functional relationship that can be more readily applicable to high-level TCO and technoeconomic studies. It is clear that a simple "$/kW" metric does not adequately describe this. Sensitivity studies are useful but, alone, are not likely sufficient.

- The proposed future work is reasonable. In this project, there will always be additional work to be done to improve the model and incorporate new approaches. It would be difficult to fully outline these.
- The proposed future work is in line with the project objectives.
- It is appropriate to update manufacturing quality processes for the MDV/HDV system cost.
- The future work is reasonable. The goal is to essentially continue to refine the model. There are some concerns about investigating technologies such as aluminum bipolar plates, as research along these lines has been attempted for years with no success (aluminum is tough).

Project strengths:

- The project has an excellent approach to providing current and future cost projections through great collaboration with ANL and NREL teams, who have broad expertise. The project has employed a stable calculation methodology, as well as transparency on its approach and data.
- This is a rigorous detailed model, with accurate inputs from industry. It can be used to target areas for cost reduction for manufacturing at a high volume.
- The project has provided consistent cost analysis updates. New approaches are properly implemented (e.g., durability and manufacturing adjustments).
- The team's extensive fuel cell cost analysis history, expertise in cost assessment, and extent of collaborations provide for success.
- The analytical collaborative approach is the project's greatest strength.

Project weaknesses:

- In the past, it would have been recommended that the project have access to state-of-the-art materials, but that was effectively addressed with the Fuel Cell Consortium for Performance and Durability (FC-PAD) partner projects (and continuing with M2FCT) and strengthened collaboration with ANL's system analysis project. Still, the team would benefit from greater feedback on durability, especially from fuel cell applications that have demonstrated high durability.
- The model is not validated and has no way to be validated, as that would require manufacturing at 100,000 units/year, plus full cooperation from private companies making 100,000 units/year. It is also not clear that a company with enough resources to make 100,000 units/year would use this model, rather than having its (the company's) own modeling resources. The model also has no way to incorporate truly disruptive technologies, such as membranes that do not require humidification.
- The project may not always have "true" data with which to work, owing to confidentiality issues.
- The main project weakness is the lack of comparison with real performance and cost data of systems.
- There are no significant weaknesses.

Recommendations for additions/deletions to project scope:

- The focus of the project could remain mostly on HDVs/MDVs in the short term by extending to additional applications, such as coaches and trains using comparable fuel cell systems. Additionally, close collaboration with M2FCT is recommended to rapidly integrate that consortium's findings into this cost analysis.
- The project would benefit from researching factors such as the effect of catalyst loading on durability, instead of stack oversizing; start-up/shut-down degradation; freeze-start requirement cost implications; precious metal commodity price sensitivity studies; recycling requirements and greenhouse gas emissions vs. material costs implications; and cost implications of materials that may be restricted in the future because of negative environmental impacts.
- The project should increase focus on a general functional cost model that can be readily used for high-level TCO/technoeconomic analysis—for example, cost as a function of end-of-life power, effective overall efficiency, lifetime, thermal rejection, or technology progress.

- For fuel cell system cost analysis of HDVs, TCO should be used for design suggestions, e.g., proper Pt loading and efficiency.
- It is most important for SA to continue cooperation with industry partners to refine the model.

Project #FC-167: Fiscal Year 2020 Small Business Innovation Research Phase IIA: Multi-Functional Catalyst Support

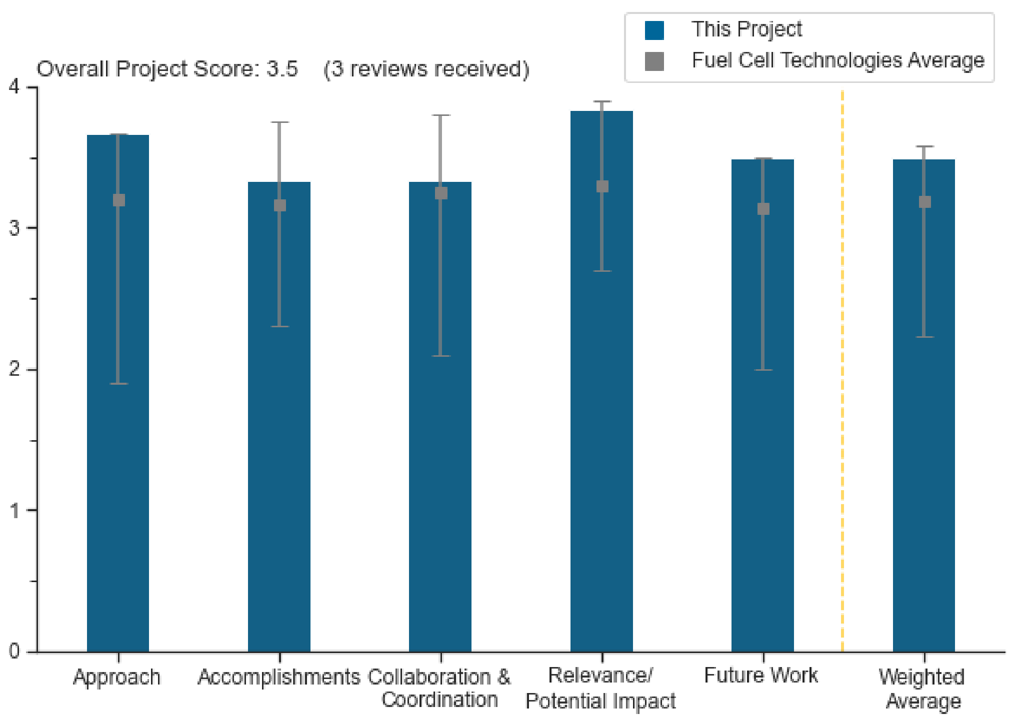
Minette Ocampo, pH Matter, LLC

DOE Contract #	DE-SC0017144
Start and End Dates	05/22/2018 to 05/20/2022
Partners/Collaborators	Giner, Inc., National Renewable Energy Laboratory, Shyam Kocha Consulting
Barriers Addressed	• Cost: enhance the platinum catalyst activity (and durability) to reduce its loading levels • Durability: optimize the interaction between the catalyst and the support material to improve chemical and thermal stability. • Performance: demonstrate improved performance in membrane electrode assemblies

Project Goal and Brief Summary

In Phase II of this project, the research team developed a multi-functional catalyst support (MFCS) approach for high platinum-group-metal (PGM) loading. In the present phase, researchers aim to use this approach to further develop catalysts and to demonstrate catalyst performance and durability requirements in membrane electrode assemblies (MEAs) for heavy-duty polymer electrolyte membrane (PEM) fuel cell applications. The project will optimize the MFCS to enable higher platinum loading, higher power, and extended durability performance for heavy-duty applications. Heavy-duty accelerated stress testing will be performed to evaluate catalyst durability and demonstrate the U.S. Department of Energy's (DOE's) 2025 Million Mile Fuel Cell Truck (M2FCT) target of 1.07 A/cm^2 at 0.7 V.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project takes a rational approach to achieving good activity and durability in a catalyst. The project has a larger batch size and more reliable data than most research and development projects.
- Developing durable PGM catalysts is an essential step to achieving DOE's goals for transportation fuels. The general approach of optimizing the porosity of the carbon support is a widely used method to decrease catalyst loading due to agglomeration and migration. The details of the technology development are proprietary, so it is difficult to extensively evaluate the fine details of the research and development approach.
- This project leverages previous project results to address DOE heavy-duty vehicle PEM targets.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- This project tested a large number of catalysts and supports under several DOE protocols and made progress in achieving the DOE targets for durability and performance. It is difficult to assess whether a single formulation meets the DOE targets, as so many catalysts were evaluated.
- The project has demonstrated catalysts with reasonably good performance and durability in MEA testing. However, it is not clear whether the intended features of the catalyst have been achieved. More characterization focusing on those benefits would be useful. The absolute performance is still trailing commercial Pt/high-surface-area carbon catalysts.
- Within the first year of the project, the team has nearly met DOE's 2025 M2FCT MEA targets.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- Collaborations are excellent, as they include Giner, Inc., National Renewable Energy Laboratory, and catalyst manufacturers. The research is well collaborated.
- Collaboration among project partners appears sufficient, although there is not much collaboration with other groups. More collaboration with national laboratories may help to obtain better insights about the catalyst structure and performance.
- Not much collaboration was reported during this project period.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is very relevant to the DOE Hydrogen and Fuel Cell Technologies Office mission, as catalyst development is key to reducing the cost of fuel cell systems. The potential impact is moderately high, but there is tremendous competition from larger catalyst manufacturers.
- Higher-activity and durable cathodes using low-PGM catalysts are a high priority for PEM fuel cells.
- This project is on track to meet DOE's 2025 M2FCT MEA targets.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The proposed future work is reasonable. Extensive future testing in realistic field conditions is necessary to evaluate the long-term durability and performance of the catalysts. The researchers should also further optimize the catalyst loading.

- The proposed future work is appropriate. The researchers should seek more collaboration with national laboratories for characterization to better understand the catalyst structure and features. Providing samples to MEA integrators would help bridge the materials to commercialization.
- This project is tightly focused on preparing high-performance MEAs for commercial deployment.

Project strengths:

- This project has excellent teaming—good collaboration between catalyst developers, fuel cell manufacturers, and national laboratories—and a logical development approach.
- Strengths include efforts to scale the catalyst process and the team's know-how.
- This project is meeting aggressive project targets.

Project weaknesses:

- It is not clear whether the graphitized supports will be cost-effective or easy for the project team to scale.
- The project does not include characterization to identify and confirm features.
- It is difficult to evaluate the materials development approach, as it is proprietary.

Recommendations for additions/deletions to project scope:

- The catalysts should be benchmarked against newer formulations and highly graphitized supports.

Project #FC-170: ElectroCat: Durable Manganese-Based Platinum-Group-Metal-Free Catalysts for Polymer Electrolyte Membrane Fuel Cells

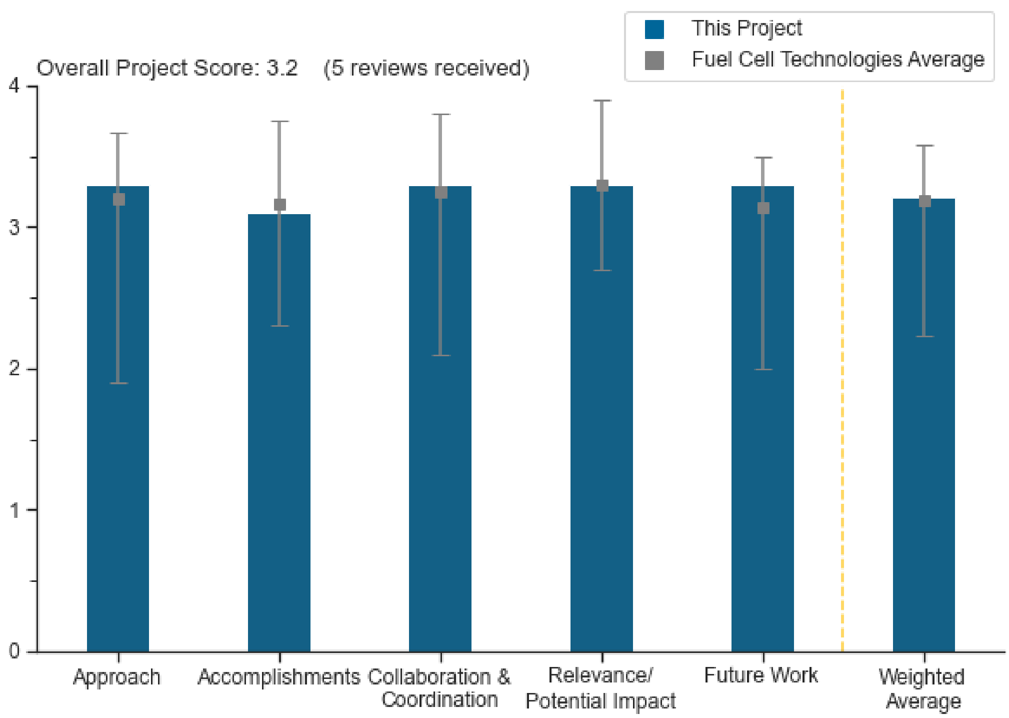
Hui Xu, Giner, Inc.

DOE Contract #	DE-EE0008075
Start and End Dates	10/1/2017 to 8/30/2021
Partners/Collaborators	University of Buffalo, University of Pittsburgh, General Motors, Indiana University, Compact Membrane Systems, Northeastern University
Barriers Addressed	• Durability (catalyst, membrane electrode assembly) • Cost (catalyst, membrane electrode assembly)

Project Goal and Brief Summary

The project objective is to develop a Mn-based platinum-group-metal-free (PGM-free) catalyst and membrane electrode assembly (MEA) as a replacement for current PGM catalysts. The developed catalyst and MEA will have lower cost and lower cost volatility, improved corrosion performance, improved de-metalation performance, and reduced membrane degradation compared to the baseline. The developed catalyst and MEA will be tested on a development fuel cell stack.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project objectives are clearly outlined; the technical approaches are scientifically solid and appropriate for achieving the project objective. The identified critical barriers are being effectively addressed. The tasks and experiments are well-designed and are integrated with other relevant efforts.
- The team approach toward developing Mn-based non-PGM oxygen reduction reaction (ORR) catalysts is good to excellent. The researchers are using an appropriate balance of modeling, physical characterization, and electrochemical characterization to guide their work. Additionally, the team is appropriately emphasizing durability in MEA under relevant conditions, a key barrier for commercial viability of non-PGM ORR catalysts.
- Overall, the approach seems appropriate. The team is developing better catalysts, testing them in appropriate platforms, and doing work on fundamental understanding of the catalysts' performance and degradation.
- This is a good, solid approach for developing PGM-free catalyst materials with new development strategies. It is a step-by-step approach. It remained a little bit unclear what iterative process may be used if the envisioned steps are not as successful as expected.
- The approach is focused on achieving U.S. Department of Energy metrics on activity and durability.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- It seems that the team has made excellent advances toward the outlined project objectives (and contributed to the DOE Hydrogen Program [the Program] goals as well) through well-defined and measurable performance indicators (such as electrocatalytic activity and durability). For example, it has been demonstrated that the designed Mn-based PGM-free catalysts have met the DOE catalyst activity target of >0.044 A/cm^2 at 0.9 V (iR-free) in an MEA test with the durability extended by 50%. The accomplishments to date suggest that the project has made considerable progress in addressing critical barriers to achieving DOE goals.
- The team has continued to make good to very good progress toward advancing the activity and hydrogen–air performance of the Mn-based non-PEM catalysts, with significant year-over-year advancement from 2020 to 2021. Determination of the importance of using forming gas to enable reduction of MnO toward better-dispersed single-atom Mn catalysts and space confinement (ordered structure) seems to be a key advancement.
- The project has met, or is on track with regard to, targets and milestones. The project made good progress on relevant catalyst development parameter studies and performance metrics. It is unclear what the flow conditions were for the in situ experiments. Stoichiometric flow rates or giving information about fixed flow rates together with cell size when showing current density would be more meaningful. Most important for comparison with PGM-based MEAs are the 150 kPa data sets. There is strong dependence of the catalyst on cell size (i.e., likely channel length) and relative humidity (RH). There is progress of degradation through post-treatment. Specifically, the durability of the material within an MEA structure will need improvement.
- The team has made consistent and excellent progress on the beginning-of-life catalyst activity. However, clear challenges for durability remain at this point as the project nears its end.
- The team has made excellent progress toward activity goals in comparison to where the project started. In particular, an excellent improvement in activity was achieved as a result of implementation of new synthetic procedures. Significant progress has been made toward fundamental understanding of the origin of the catalyst's electrocatalytic activity. However, the catalyst has not met the DOE activity target (0.044 A/cm^2) in MEA tests. Unfortunately, improvement in durability via the catalyst post-treatment with benzimidazole led to a loss in activity. The most serious durability problem is related to Mn oxidation due to Mn affinity to oxygen. This will be difficult to mitigate in the presence of air.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- There appears to have excellent collaboration and coordination among a strong technical team. Of note is the good alignment between electrochemical characterization and physical characterization and synthesis efforts.
- An excellent collaboration has been established, both within the team and with external partners, such as ElectroCat, Indiana University–Purdue University Indianapolis, Northeastern University, and Compact Membrane Systems.
- The project management team effectively engages and coordinates the activities of the four project partners: Giner, Inc., University of Buffalo, University of Pittsburgh, and General Motors. Well-coordinated collaboration has been demonstrated between the partners.
- The core project consists of a combination of industry partners and four universities. The project uses the ElectroCat consortium well.
- It appears the involvement of partners and work with ElectroCat is sufficient.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Some of the barriers that face the Hydrogen and Fuel Cell Technologies Office are the high cost, limited availability, and durability of PGM catalysts. The development of durable, PGM-free catalysts is critical to the Program and has potential to significantly advance progress toward DOE research, development, and demonstration goals and objectives. The project supports and advances progress toward Program goals and objectives and also supports the HydroGEN Consortium mission. The project has good potential to advance the discovery and development of novel materials for efficient water-splitting systems, which will enable meeting the DOE ultimate hydrogen production goal of $2/kg H_2.
- The relevance and potential impact are fair. While this project had made excellent progress toward addressing activity and performance, durability remains a significant challenge with non-PGM catalysts. Demetallation of highly active Fe or Mn atomically dispersed catalysts under relevant cyclic testing in air remains a key barrier. Oxidative stability of the carbon-based matrix also remains a fundamental and perhaps insurmountable barrier for these types of non-PGM ORR catalysts. These durability barriers are certainly challenging in light of passenger vehicle application requirements and are even more so with the evolution of focus of polymer electrolyte membrane fuel cells to heavy-duty vehicles. These concerns are not unique to this project but are related to the non-PGM ORR approach in general.
- This project has high potential impact; PGM-free ORR catalysts are needed to significantly reduce the cost of fuel cells.
- This program aligns well Program objectives. However, it is unlikely that this project will be a game-changer for DOE. The project makes contributions to understanding how materials work, which is also important.
- The team is directly addressing the challenge of PGM-free catalysts for ORR.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The project's future work is directly aligned at addressing the key barrier of simultaneously having high activity/performance and durability. The approach of further understanding the degradation physically and mechanistically is appropriate. The stated strategy of "reduc[ing] Mn oxidation and demetallation" is appropriate, but it is unclear how this would be accomplished.

- Degradation and MEA performance in hydrogen–air were adequately picked as the key topics for future work. Finding the right strategies for improving performance and durability is a common challenge with PGM-free catalyst materials.
- The project will end on August 31, 2021. The planned activities for the next few months are adequate to complete the remaining tasks and, if successfully implemented, to achieve the project objectives.
- The future work is focused on achieving durability and activity targets simultaneously.
- This project appears to be coming to a close. If it were not, a more detailed plan for reducing catalyst degradation would be important.

Project strengths:

- The development of PGM-free catalysts is an important topic. It may have great impacts on the cost and the commercial viability of the technology. The concept of the new catalysts was well-conceived, and the technical approaches are scientifically sound. The tasks, experiments, and milestones are designed well and in a logical manner by incorporating appropriate decision points and considering potential barriers to achieving project goals. Also, alternate pathways are provided to mitigate potential risks.
- The project strength is in the combination of fundamental tools, such as density functional theory and extensive experimental validation, to provide fundamental insights into the catalyst's performance. The team is very creative in solving problems.
- The team consists of highly capable researchers with an excellent balance of fundamental material development, characterization, and modeling. The team is following a unique approach of focusing on Mn rather than Fe as the active center, which is important for maintaining membrane durability.
- The project has a good systematic approach that considers important aspects of catalyst design and MEA integration.

Project weaknesses:

_The project work, accomplishments, team, and approach are all very good. The primary weakness is that, owing to the long-standing durability concerns, the prospects of non-PGM ORR catalysts in commercial applications remain remote.

- MEA performance seems to be very dependent on RH and cell size. Understanding these barriers and counteracting them seems very important to further advancing the performance of this catalyst system.
- The weakness of this project is in selecting a Mn-based catalyst, which is susceptive to oxidation in the presence of oxygen.

Recommendations for additions/deletions to project scope:

- Operation of MEAs at stoichiometric conditions would allow more relevant comparison to realistic operation.

Project #FC-172: ElectroCat: Highly Active and Durable Platinum-Group-Metal-Free Oxygen Reduction Reaction Electrocatalysts through the Synergy of Active Sites

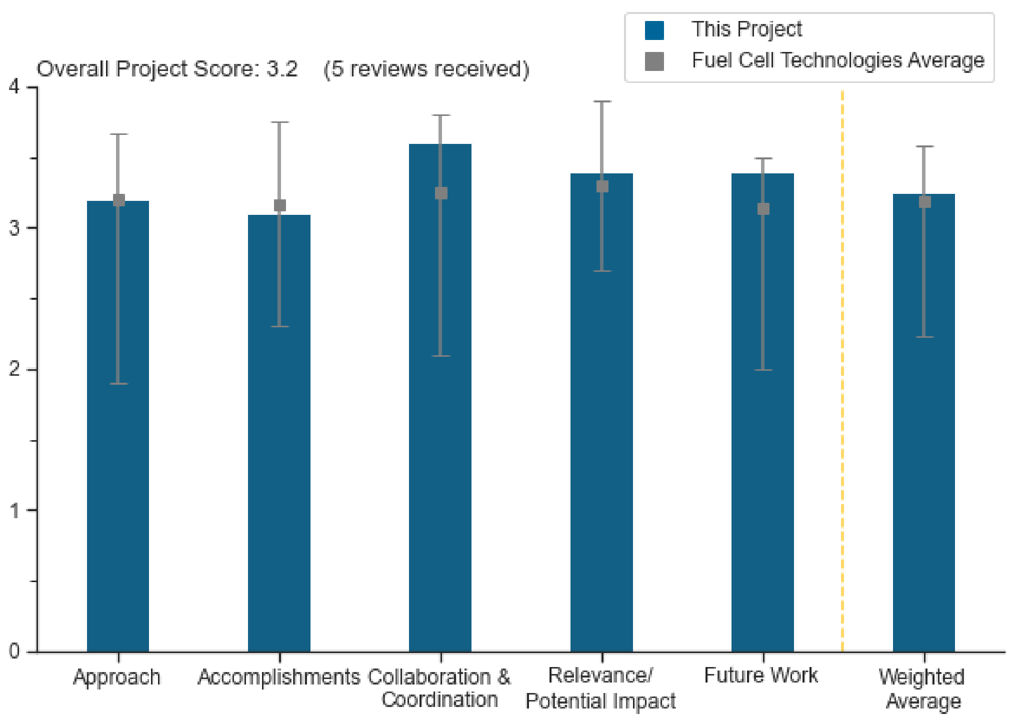
Yuyan Shao, Pacific Northwest National Laboratory

DOE Contract #	DE-EE0001647
Start and End Dates	10/1/2017 to 9/30/2022
Partners/Collaborators	Washington University in St. Louis, University of Maryland, Ballard Power Systems Inc., Oregon State University, Electrocatalysis Consortium (ElectroCat)
Barriers Addressed	• Cost (catalyst) • Activity (catalyst, membrane electrode assembly) • Durability (catalyst, membrane electrode assembly)

Project Goal and Brief Summary

The project objective is to improve the activity and durability of platinum-group-metal-free (PGM-free) oxygen reduction reaction (ORR) catalysts through dual active sites for enhanced oxygen reduction and hydrogen peroxide (H_2O_2) decomposition. Materials and synthesis innovations include (1) dual active sites for ORR and H_2O_2 and (2) thermal shock activation for high activity through increased active site density. The catalysts developed will lower cost, reduce H_2O_2 formation by 50%, maintain the activity level, and double the durability compared to baseline platinum catalysts.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is a generally sound approach that uses the creation of a knowledge base for the development of a new catalyst material. In this case, the team attempts to identify mechanisms for degradation of non-Fe-PGM-free catalysts. With this fundamental understanding, the group wanted to identify non-Fe-based dual active sites that improve durability. This is a feasible approach, given the right diagnostic techniques are used and the required information can be acquired.
- Dual active sites, a non-Fe-PGM-free catalyst, and a radical scavenger are good approaches. A non-Fe-PGM-free catalyst is a critical path forward for PGM-free catalysts to avoid the Fenton reaction on the membrane. The scavenger can help to enhance the stability of the PGM-free catalysts.
- Developing an understanding related to the performance and durability of PGM-free catalysts is important to their long-term development and use. The incorporation of radical scavengers into the PGM-free catalysts seems to show a benefit. Developing non-Fe-based catalysts may be important to membrane durability.
- The project differentiates itself from other work funded by the U.S. Department of Energy by putting more effort into understanding durability of PGM-free catalysts, including development of less active but more stable cobalt-based materials. In particular, in situ characterization of degradation, such as measuring carbon dioxide evolution during operation, is an important and insightful approach. The only negative aspect of the approach is that it seemed to be limited in terms of the modeling effort. The team reported demetallation of Fe versus Co, but it seems that a larger number of potential active sites and methods of oxygen attack or oxygen species could have been examined.
- This is a well-organized approach with systematic identification of the milestones and the go/no-go events.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team had a successful demonstration of synthesis of clean FeN_X. There was a systematic evaluation of degradation with a focus on radical attack and demetallation, as well as quantified demetallation with acid attack and effect of hydrogen peroxide formation on degradation (artificially introduced hydrogen peroxide). The team's application of x-ray photoelectron spectroscopy (XPS) is very informative. The Co-N-C development (non-Fe-PGM-free catalyst) is successful, but prepared samples had poor activity. Co-N-C has superior durability to Fe-N-C. The team members explained why Co-N-C is more resistant to demetallation. They determined radical scavenger $TaTiO_X$ and identified optimum composition. Finally, they found a way to use Fe-N-C and benefit from its superior activity compared to Co-N-C, which appears to be a very important finding.
- The team presented some nice results to show the effect of demetallation and oxygen attack on ORR performance, as well as the improved stability with cobalt metal centers and radical scavengers. This information will be very useful to future researchers who are developing the next generation of PGM-free catalysts. The only negatives regarding the accomplishments were that there could have been a greater modeling effort and that characterization could have included adsorption and spectroscopy of active site markers, such as NO. This could have provided more information about degradation, the nature of the active site, and how it changes over time.
- Progress was seen in developing higher-durability catalyst materials when compared to Fe-based catalysts. The milestones were either completed on time or are still in progress. The analysis focuses on diagnostics and ex situ work. More device testing, specifically at stoichiometric flow rates, would be of interest in understanding the state of membrane electrode assembly (MEA) integration and potential of the catalyst materials.
- The project demonstrated that the catalyst layer picks up oxygen during the acid treatments. It would also be nice to measure the relative hydrophobicity change of the catalyst, as PGM-free catalyst layers are typically thick, with more hydrophilic layers; and the thicker they are, the more important flooding will be.

The durability improvement of Co-N-C is good, whereas the poor durability of Fe-N-C should possibly be compared to other developers in the area that are showing much better durability. It is important to know whether this difference is due to the fact that Fe-N-C is a low-durability catalyst or whether the durability of Co-N-C has in fact improved. The use of $TaTiO_X$ is interesting. This compound should potentially be examined in higher-technology-readiness-level (TRL) systems (e.g., Pt/C) to see whether it has a good effect on catalyst and membrane durability.

- Although good progress was made for the Co-N-C catalyst, achieving 22 mA/cm^2 at 0.90 V in H_2/O_2, it is still far from meeting the DOE target of 44 mA/cm^2, 150 mA/cm^2 at 0.80 V in H_2/air. The stability is even worse, with no MEA stability results provided—only rotating disk electrode (RDE) results. The dual catalyst synergistic effect was not shown in the presentation, and it was unclear why no MEA stability results were shown if the scavenger approach was working. The new scavenger $TaTiO_X$ developed showed good RDE performance but no MEA performance.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- There is a sound mix of national laboratories, industry, and universities, supported by the ElectroCat consortium. There is a large team with distinct capabilities and clearly defined roles.
- The project is making excellent use of the ElectroCat capabilities. The project collaboration is an excellent set of partners: Pacific Northwest National Laboratory, Ballard Power Systems, Inc., University of Maryland, Washington University, and Oregon State. It is unclear what the no-cost partners are providing.
- The rating would have been outstanding if an industrial partner were included. The national laboratories, academic researchers, and no-cost partners all bring excellent technical strengths to the project.
- There are more collaborators involved in the project this year, and the team worked closely with ElectroCat.
- The project had a strong and diverse team, and there were no obvious weaknesses with the collaboration.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Relative to other ElectroCat projects, this project has a greater potential impact because of the focus on understanding durability for PGM-free catalysts. Poor durability is probably the largest hurdle that PGM-free catalysts need to overcome to be more useful in real-world systems. This project also included an industry participant, Ballard Power Systems, Inc., that is interested in commercializing PGM-free electrodes, which helps the project stand out in terms of potential impact. The only negative is that PGM-free catalysts' relevance to DOE's new focus on heavy-duty vehicles was not clearly communicated.
- This project has high potential impact, as reducing the cost of fuel cells significantly will require PGM-free ORR catalysts. It is difficult to compete with Pt for these systems, so higher loadings and thicker catalyst layers are required. The system currently lacks the performance and durability to be able to compete with PGM systems. This project specifically targets improving degradation aspects by designing a new type of PGM-free catalyst.
- PGM-free catalysts are critical for polymer electrolyte membrane fuel cell (PEMFC) commercialization since a PGM-free catalyst can significantly reduce the cost of PEMFC systems.
- The project is developing more active, more durable PGM-free electrocatalysts and appears to be making good progress. Performance is still far away from being competitive with Pt.
- This is an extremely important project if PGM-free catalysts are to be successful.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- There are good future work plans related to the precise identification of various degradation mechanisms and relationships to operation conditions, as well as demonstration of new radical scavengers in single fuel cells to improve durability.
- The future work addresses the missing links in the previous work. Future work aims at moving toward the demonstration of the novel catalyst materials in MEA devices through performance and degradation testing. Furthermore, the testing of additional radical scavengers may improve degradation behavior.
- The team proposes designing experiments to differentiate acid leaching from radical attack; however, there were no details regarding how these experiments would be done. More details would have increased confidence that the future work will be fruitful. The MEA experiments were proposed to achieve milestones, so adding the new radical scavengers to MEAs will be interesting.
- Each type of FeNx moiety was surprising, but discussion of these moieties was not found in the presentation. An explanation is needed as to why different FeNx moieties are important. It would also be good to know where the large MEAs are going to be tested and what Washington University's capabilities are.
- The project should focus on the mass activity and 0.80 V performance to meet the project goal.

Project strengths:

- This project had strong diagnostics and ex situ analysis. The team showed proof of principle that the degradation behavior of MEAs can be improved through the chosen approach.
- The main strength of this project was the focus on durability and understanding of PGM-free catalyst degradation.
- The project's strength is developing the fundamental understanding related to the degradation mechanism and understanding the importance of a radical scavenger.
- The dual active site (M-N-C and scavenger) is a unique approach. The use of non-Fe catalysts, which can avoid the Fenton reaction, is a plus. The work on the degradation mechanism is critically needed.
- There are excellent research capabilities at all the universities. There is a detailed approach to understanding issues. The project is well-organized.

Project weaknesses:

- Seeing more in situ test results that are comparable to the methods that are used by other ElectroCat collaborators would be beneficial. The proposed future work seems to promise this, which is great.
- The progress on both activity and degradation mechanisms seems slow and does not meet the milestones yet. The reported work on degradation mechanisms is not very clear as to the understanding of the degradation root causes.
- PGM-free is far from being competitive with Pt. The path to competitive performance is unclear.
- The project needs an industrial partner and/or a testing laboratory that works at an industrial scale, e.g., 10 cell stacks or greater.
- The project did not seem to put extensive effort into the modeling of degradation mechanisms.

Recommendations for additions/deletions to project scope:

- Using the radical scavenger with higher-TRL materials (Pt) and incorporating it into membranes to see its effect would be a nice addition to the project. It is unclear whether this radical scavenger is durable over long periods.
- A greater modeling effort could be useful for improving degradation mechanisms. Also, adsorption and spectroscopy of active site markers, such as NO, could provide more information about degradation and the nature of the active site and how it changes over time.

- The team needs to take a systematic approach to studying the degradation mechanism. The team also needs to focus on the new scavenger, $TaTiO_X$.
- More MEA device work should be included, as promised in the Proposed Future Work section.
- The project should get an industrial partner.

Project #FC-302: ElectroCat: Developing Platinum-Group-Metal-Free Catalysts for Oxygen Reduction Reaction in Acid: Beyond the Single Metal Site

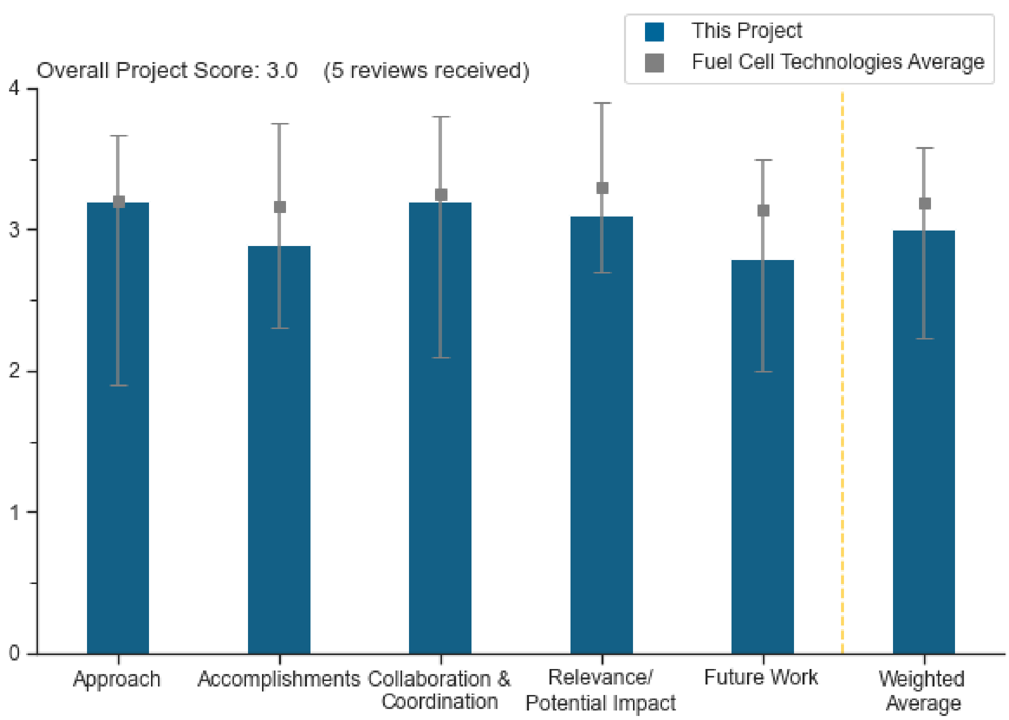
Qingying Jia, Northeastern University

DOE Contract #	DE-EE0008416
Start and End Dates	10/1/18 to 9/30/21
Partners/Collaborators	Lawrence Berkeley National Laboratory, Northeastern University
Barriers Addressed	• Performance in polymer electrolyte membrane fuel cells • Durability in polymer electrolyte membrane fuel cells

Project Goal and Brief Summary

Northeastern University seeks to develop platinum-group-metal-free (PGM-free) oxygen reduction reaction (ORR) catalysts with high activity and durability in polymer electrolyte membrane fuel cells (PEMFCs). These PGM-free ORR catalysts are developed via the following concurrent pathways: (1) M_X-N-C catalyst development featured with multiple metal centers (MMCs) and (2) M_X-N-C catalyst synthesis using surface deposition methods. These catalysts are developed to attain the following performance targets: (1) 0.035 A/cm^2 at 0.9 V in an hydrogen–oxygen PEMFC (1.0 bar partial pressure, 80°C); (2) loss in activity ≤40% after 30,000 square wave cycles with steps between 0.6 V (3 s) and 0.95 V (3 s), and (3) power density of 0.5 W/cm^2 in a hydrogen–air PEMFC with a membrane electrode assembly (MEA) size ≥50 cm^2.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project is developing novel strategies for active site formation via chemical vapor deposition (CVD), strategies that form active sites in accessible surfaces of the supports for higher Fe utilization and potentially high site density. The MMC approach is intriguing. The half-wave voltage of the cobalt version provides encouraging results. The project's focus on active-site quantification is good and part of a scientific approach rich with characterization. It is good that the project is exploring alternative, high-risk approaches such as the ion-beam-assisted deposition (IBAD) concept for active site formation, although it was not successful. The MEA modeling of the catalyst kinetics with two Tafel slopes is questionable and requires additional validation. It is easy to conflate mass transport overpotential with a Tafel slope change, especially with high loadings. It is unclear whether the modeling would be coupled to improvements in catalyst morphology or electrode fabrication.
- The project uses a wide array of synthesis techniques, characterization techniques, and site-density-measurement methods to develop PGM-free catalysts. The plan and methodology are strong in this regard. The only negative with the approach is that it seems that significant effort went into developing and characterizing high-activity materials that have extremely poor durability. It would be beneficial if more effort were placed on durable catalysts or on understanding the degradation mechanism.
- The synthesis approach uses multiple techniques, which is nice to see; however, this appears to be mostly a shotgun approach, as opposed to being based on scientific hypothesis and theory. The project is using characterization techniques to understand the fundamental reasons for improving activity, which is good.
- This project has a good approach to increasing the activity of PGM-free catalysts. It aims to create MMCs to increase activity through high turnover frequency and active-site density. It is unclear why it is beneficial to avoid pyrolysis. In any case, the group plans to use several alternative synthesis routes to achieve the project development goals, which may increase the chances of reaching the research goals.
- The demonstrated project approach of screening multiple synthetic routes to achieving high-performing and durable PGM-free catalysts, rather than an application program toward MEA performance, is consistent with basic science. It is not clear why the targets specified by the project are lower than the DOE targets.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project had successful synthesis at a low temperature. Fe-metal-based materials show the highest performance. There was also a successful wet impregnation with MMC precursors. The team completed a detailed analysis to understand the nature of the resulting catalyst materials, had a successful transmetalation of Fe with Zn, and achieved high catalyst activity, although it was somewhat unclear from the presentation how this translates into MEA performance. It would be good to see more standardized MEA testing at various operating conditions, such as relative humidity (RH) and stoichiometric flow rates in hydrogen–air. Finally, there was very interesting voltage breakdown modeling for PGM-free MEA material sets.
- The team clearly conducted a large amount of work and, based on slide 19, is very close to the project goals listed. However, it was difficult to understand whether the project is on schedule and achieving milestones in a timely manner. A Gantt chart or table showing milestones is needed to communicate that. There were technical and audio issues during the presentation that may have contributed to difficulty with understanding whether the project is on track.
- The team demonstrated a CVD synthetic route to achieving highly active FeNC catalysts with high site density as an approach toward achieving performance goals; however, stability of obtained catalysts is not sufficient. The CVD process is not described well specific to its pros and cons, particularly, uniformity/ geometry spacing in the CVD chamber, which often results in non-scalable or non-uniform products.
- The project's progress has been reasonably good in terms of exploring various accessible approaches to active-site characterization and quantification. The catalyst activity is becoming good, achieving a first scan

oxygen current of 33 mA cm^{-2} at 0.9 V high-frequency-resistance-free, although with a high loading of 6 mg cm^{-2}. Several of the project targets have not been evaluated, and the fuel cell characterization of the catalyst appears to be limited (it is likely that these are outcomes of COVID-19 challenges).

- MMCs do not appear to show competitive activity with other PGM-free catalysts (e.g., MN_4). In fact, they are far from competitive. Unless a path is known for better performance, it seems like this path is not going anywhere. The FeNC-CVD shows poor durability. Understanding the degradation mechanism might be important. Improving site density might give better beginning-of-life (BOL) performance; however, unless the rapid degradation is prevented, the improved site density is not going to make a catalyst that is useful. The team should improve the site density after a stable catalyst is developed. The modeling seems fine, but without a more active and durable catalyst, it is not helping this project make a commercializable material. The isotherm degradation appears to give a more stable catalyst, but it appears still to lose significant activity from the other materials and in the initial cycles. It seems like the modeling and characterization should be applied to the post-cycled material to understand the stable structure.

Question 3: Collaboration and coordination

This project was rated **3.2** for its engagement with and coordination of project partners and interaction with other entities.

- The project is adequately leveraging several collaborations within the Electrocatalysis Consortium (ElectroCat) and externally.
- The project has an excellent team that contributed strengths of each individual institution to make the team strong. Slide 16 communicates this very clearly.
- The collaboration consists of Northeastern University and Lawrence Berkeley National Laboratory (LBNL), with ties to industry and contribution from ElectroCat.
- The team made use of ElectroCat, plus other partners.
- The partnership with LBNL seems limited. Other collaborations are not presented, or work is isolated to Northeastern University or an IBAD subcontractor.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project has a high potential impact, as PGM-free ORR catalysts are needed to significantly reduce fuel cell costs. It is difficult to compete with platinum for these systems; therefore, higher loadings and thicker catalyst layers are required. If this approach leads to higher activity in PGM-free systems, various barriers to reducing costs of fuel cell systems may be overcome.
- The project's focus on novel approaches to creating active sites is critical to advancing PGM-free catalysts. Advances in increasing active-site density are necessary for realizing adequate PGM-free performance to compete with PGM catalysts.
- The project is helping to advance state-of-the-art PGM-free catalysts. PGM-free catalysts could help lower the cost of PEMFCs with further development. The only weakness is that DOE has shifted focus to heavy-duty fuel cells, and the PGM-free materials seem a long way off from the performance required for that application. Furthermore, original equipment manufacturers do not seem interested in PGM-free catalysts.
- PGM-free is far from competitive with Pt, and the path to competitive performance is unclear. Since a stable material is made from the isothermal carbonization, it seems like developing that material at BOL with a high site density is a preferred path.
- As presented, this project has minimal visibility in the short-term impact on advancing progress toward the DOE research, development, and demonstration durability goals.

Question 5: Proposed future work

This project was rated **2.8** for effective and logical planning.

- The proposed future work is logical for achieving most of the project objectives. It is not clear whether the project objectives will be obtained concurrently with the same catalyst. For example, the team is close on the activity target, but the performance lasts for only three cycles. It was not communicated clearly how many cycles the project needs to achieve or which of the catalysts could achieve both activity and durability targets. Also, more details regarding how the team will improve understanding of the $Fe\text{-}N_4$ degradation mechanism would be useful.
- The future work aligns fairly well with the relevant and listed remaining challenges and barriers. However, the future work may need to be expanded to include an MEA integration aspect. Moving from the development of a catalyst material to a functional electrode requires the consideration of many variables. This process is highly important for novel PGM-free catalyst materials to the device level. This is currently missing entirely from the proposed work.
- The ongoing work on the MMCs with Fe is worthwhile, but it is unclear whether the work can yield a single FeCo active site or two separate sites with Co and Fe.
- The researchers should focus on achieving stability of the resulting formulation and batch consistency, and they should specify their approaches in greater detail, providing justifications toward every approach. There are too many global statements in slide 17, resulting in questioning of the reality of these far-reaching goals. Additional background should be provided on the demonstrated exchange of experiences with project partners and collaborators in choosing one or another route and justifying the focus of the next budget period.
- The proposed work on understanding the degradation mechanism seems important. Increasing the site density might make for a better BOL catalyst, but unless the performance can be maintained by improving the durability, that seems like a fruitless goal.

Project strengths:

- The project has a strong team and is using a wide array of synthesis techniques, characterization techniques, and site density measurement methods to develop PGM-free catalysts.
- The project uses the Northeastern University team's extensive experience in surface modification techniques and catalyst synthesis. A variety of options are demonstrated, with thorough assessment of resulting formulations.
- The project is developing more active and durable PGM-free electrocatalysts and appears to be making good progress. The strength of the project is developing stable materials post-cycling (isothermal carbonization). The team should use extensive characterization to understand that structure, then synthesize that as an initial material.
- The clear strength of the project is the innovation in catalyst synthesis and active-site characterization.
- This project has a strong approach, backed with extensive diagnostic capabilities and sound methods.

Project weaknesses:

- The project does not have any obvious weaknesses, although the translation of the catalysts to electrodes in fuel cells could be given more consideration in the future.
- The engineering challenges of the proposed synthetic routes are not worked out specific to uniformity, cleanliness, etc. The project runs as if it were funded by the Office of Basic Energy Sciences and not the Hydrogen and Fuel Cell Technologies Office.
- The main weakness with the project is the communication of the milestones and whether they are being achieved on time concurrently with the same catalysts.
- The project is missing a device-level proof of concept and development.
- The performance is still far away from being competitive with Pt.

Recommendations for additions/deletions to project scope:

- It is recommended that the project drop the IBAD scope; focus on decreasing activity loss after the accelerated stress test with one transition metal, not two; and clarify the role of porosity with obtained formulations.
- The project should add an MEA integration aspect that makes strong use of the modeling capabilities combined with hydrogen–air performance at relevant stoichiometric flow rates to understand limitations and optimize an MEA-level device that contains the developed catalyst materials.
- The isotherm degradation appears to give a more stable catalyst, but it appears still to lose significant activity from the other materials and in the initial cycles. It seems like the modeling and characterization should be applied to the post-cycled material to understand the stable structure.
- More details and introduction of creative techniques to improve the understanding of $Fe-N_4$ degradation mechanisms are recommended.

Project #FC-303: ElectroCat: Mesoporous Carbon-Based Platinum-Group-Metal-Free Catalyst Cathodes

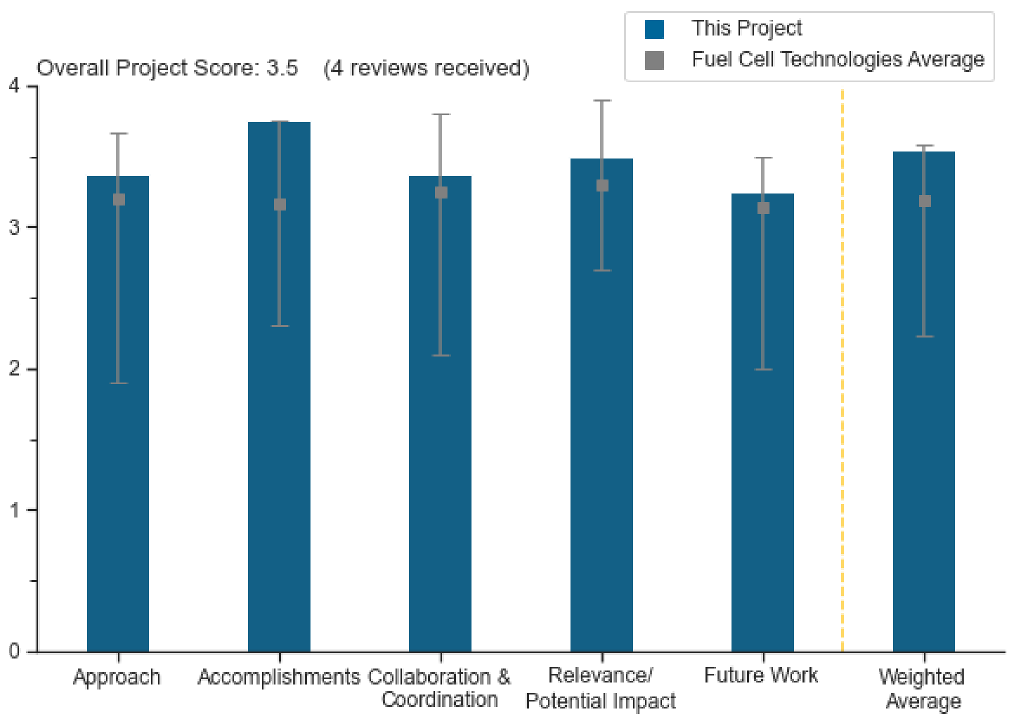
Jian Xie, Indiana University–Purdue University Indianapolis

DOE Contract #	DE-EE0008417
Start and End Dates	10/1/18 to 12/31/21
Partners/Collaborators	University at Buffalo, United Technologies Research Center, Electrocatalysis Consortium
Barriers Addressed	• Performance • Cost • Durability

Project Goal and Brief Summary

Indiana University–Purdue University Indianapolis (IUPUI) will use controllable synthesis to design and develop advanced hierarchically porous carbon sphere M-N-C catalysts for platinum-group-metal-free (PGM-free) cathodes in polymer electrolyte membrane fuel cells. The project team also aims to develop membrane electrode assemblies (MEAs) using the novel ionomer–catalyst interface by controlling the surface charges on catalyst particles to obtain improved catalyst activity, utilization, and high-current-density performance. The project goals are addressed on both intra-particle and inter-particle levels, respectively, via the following approaches: (1) develop high-performance PGM-free catalysts with a mesopore structure and (2) construct an ideal Nafion™ ionomer–catalyst interface within a catalyst layer of MEAs.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is very good in overcoming some of the most important barriers that exist for PGM-free catalyst material sets. The thickness and lower activity of the catalyst layer, when compared to Pt catalysts, create a number of challenges tackled by the project approach through investigation of morphology and interfaces, combined with optimization and characterization.
- The novel aspect of catalyst development in this project is the tuning of the particle structure and internal porosity for higher activity of a zeolitic imidazolate framework (ZIF)-derived catalyst from the University at Buffalo. The process is yielding very high activity. The performance with alternative metals (Mn, Cr, Ce) is very encouraging. Although the electrode integration, particularly the ionomer–catalyst interface, is outlined as a key aspect of the project, there does not seem to be an approach or tasks specifically addressing that interface or the ionomer integration. IUPUI's coating system is preparing catalyst-coated-membrane MEAs, producing uniform dense electrodes without large aggregates and with high activity. These results are likely due to the high concentration of well-dispersed catalysts at the membrane interface. It is not clear why relative humidity (RH) between 50% and 100% has no impact on performance and performance is higher at 50% RH, which raises some concern in regard to the testing, as the results are inconsistent with the expected effects of RH with thin and thick electrodes.
- Improving catalyst accessibility to improve activity is a great approach. Hierarchical porosities should result in better performance. It would be good to see more in-depth study of the correlation between pore structure and activity by using the Electrocatalysis Consortium's (ElectroCat's) capabilities existing in the national laboratories.
- The approach is to design interfaces and catalysts and is quite comprehensive, which also means it might be tough to understand and optimize. The use of rational design and the inherent built-in feedbacks are good, although it is not clear how things will evolve with time, as most of the focus appears to be more on initial performance. The ZnO template is a good idea, but it is not clear whether these structures are maintained during testing and operating conditions. There is not a clear pathway to surface area and loadings that are high enough that mass transport does not become limiting at higher current densities, as shown in the flooding at high RH. Modeling could help. The ink studies are not comprehensive and just seemingly correlative.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Progress is very impressive. Even at 65% completion, the project has met or exceeded most of the end-of-project goals, especially those related to both catalyst activity and MEA performance. The fuel cell hydrogen–oxygen performance of >50 mA/cm^2 (current density) at 0.9 V iR-free is indeed very impressive. The 500 mW/cm^2 power density at 0.67 V in hydrogen–air at 150 kPa is also very impressive.
- The project met or exceeded all targets and milestones with respect to project goals and DOE metrics. Impressive hydrogen–air performance was conducted at 150 kPa. There is a good comparison to current PGM-based cells and their typical operating conditions in the laboratory. Independent hydrogen–air performance is very impressive with regard to RH ranging from 50% to 100%. This seems to indicate that the approach works. The work is combined with advanced microscopy and other diagnostic methods, as it should be, to allow better insight into the reasons this approach works.
- The project is making excellent progress in terms of catalyst activity and PGM-free cathode fuel cell performance.
- The accomplishments in catalyst activity appear good in terms of meeting project goals, with the exception of stability. It is not clear whether CO_2 has evolved from the amorphous carbon that results at end of life or just from the graphitized carbon. It is not clear how pore volume is measured and whether that measurement is accurate for the operating conditions. It is not clear what the estimated surface area of the catalysts is or what pores are active, especially under different RH. The overall porosity and thickness of the different catalyst layers were also not presented. This is especially important with respect to the cracks,

as those may dominate the response. It is not clear why cracks would increase with the ionomer–carbon (I:C) ratio if the ionomer is acting more like a binder. More analysis is required. The optimization is relatively trivial and simple, especially compared to the catalyst design, and so the objectives and focus must be realistic.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- The core project consists of a combination of university and industry partners that complement each other. The project seems to make good use of ElectroCat.
- There appears to be good collaboration between the University at Buffalo and IUPUI, and ElectroCat laboratory support is being used.
- Collaboration between IUPUI and the University at Buffalo is excellent. However, the project could engage ElectroCat better to develop a better fundamental understanding of how catalyst porosity affects catalyst activity and how MEA porosity affects MEA performance.
- Coordination within ElectroCat appears good, although publications seem to be mainly from Gang Wu and collaborators, with none from the principal investigator.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- High-potential-impact, PGM-free, oxygen reduction reaction catalysts are needed to significantly reduce the cost of fuel cells. For these systems, competing with Pt is difficult; therefore, higher loadings and thicker catalyst layers are required. Moving away from Fe-based systems is difficult, but since iron can contaminate the membrane, the PGM-free system could be of significant benefit with regard to degradation processes as well.
- The development of new PGM-free catalysts with high activity is well-aligned with the DOE goals and objectives.
- The project is meeting beginning-of-life technical targets for non-PGM systems. Stability needs to be improved, but initial results hold promise of impact; however, for heavy-duty, efficiency needs make it crucial to get higher performance at higher voltages.
- Potential impact is high. It would be good to see the project move to larger-area cells (perhaps 25 or 50 cm^2) and operate them closer to 2.0 stoichiometry of air.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Future work is good and fits well into the continuation of the project.
- The focus on durability is great. However, the project should engage ElectroCat better to improve the understanding of both performance and durability. Understanding mechanisms and processes that correlate porosity to performance and durability will be very valuable for the community.
- A greater future emphasis on stabilizing the PGM-free catalyst’s performance would be good. The project is lacking studies focused on degradation, which is becoming the leading challenge for these PGM-free catalysts.
- The project is wrapping up. Focusing more on understanding than on fabrication of new materials is recommended. Stability, in particular, should be a focus. Delta-V analysis should be conducted to understand the nature of the losses.

Project strengths:

- Performance is very impressive. Preliminary durability data are also impressive. This is a great team making excellent progress.
- The project has strong achievements. Operating at relevant hydrogen–air operating conditions allows easy comparison of results and demonstrates the accomplishments well.
- The project has a good design for initial catalyst activity, including multiple approaches. Overall progress and results in terms of activity are good.
- A notable strength of the project is the high catalyst and electrode beginning-of-life activity.

Project weaknesses:

- Durability aspects of the system need to be improved. The future work addresses these aspects.
- Rational design for the ink does not really exist. The project focuses only on changing the I:C ratio and seeing the impact on performance. It is entirely correlative, with not much understanding. The work on durability is nascent in terms of understanding the mechanism loss. Additional accelerated stress tests, such as open circuit voltage hold tests or some RH cycling, could be informative.
- The key weakness is the limited emphasis on durability, beyond applying accelerated stress test characterization.
- There are not enough systematic or fundamental studies that correlate catalyst and MEA properties to performance.

Recommendations for additions/deletions to project scope:

- The project team should consider the following:
  - MEA performance increases with decreasing I:C ratio (down to 0.5), whereas mesopores are optimized at I:C = 0.6. The project needs to add better MEA characterization to figure out mass transport resistance and try to correlate it to MEA pore structure.
  - The project needs to add correlating hierarchical porosity to accessibility, i.e., characterizing the post-treatment effect on the micro/meso porosity and correlate that to accessibility.
  - It is important to make 100% sure that there is no Pt contamination on the cathode (x-ray fluorescence [XRF] can be used). Maybe the project can use two 211 membranes instead of one 212, to make analysis easier, and check for Pt on the cathode side of end-of-test MEAs.
- For even better comparison to PGM systems, it would be necessary also to operate with stoichiometric flow rates during the experiment. It would also be important to clearly identify what role the hierarchical structure plays in achieving the measured performances.
- Carbon corrosion and CO_2 coming out of the system should be measured. Modeling is recommended to understand the losses in the system.

Project #FC-305: Active and Durable Platinum-Group-Metal-Free Cathodic Electrocatalysts for Fuel Cell Application

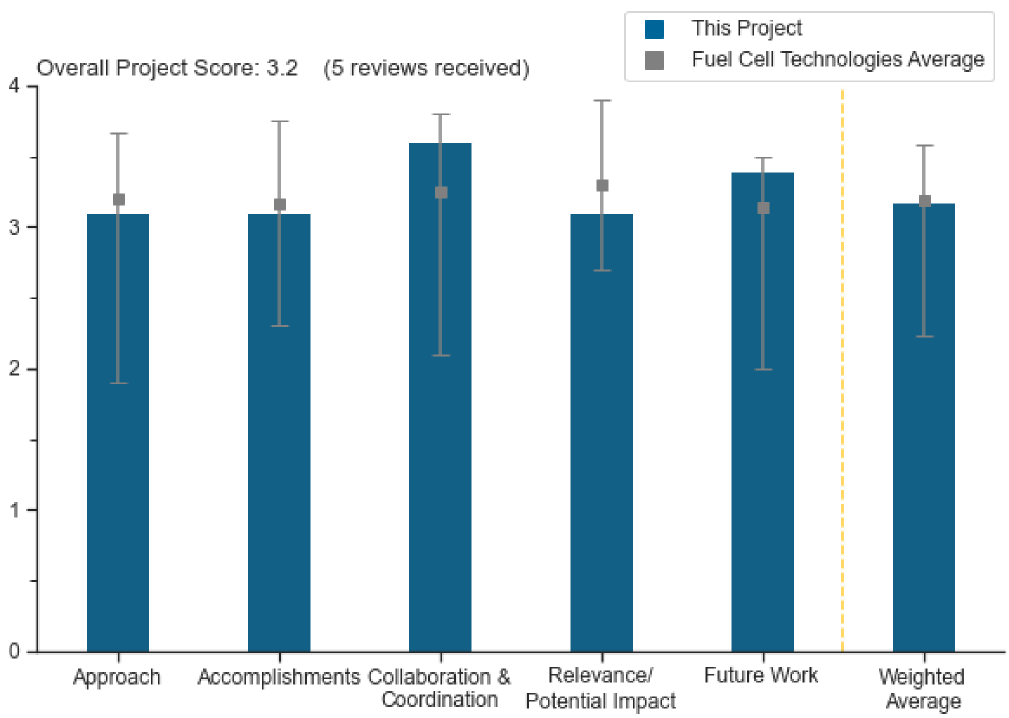
Alexey Serov, Pajarito Powder

DOE Contract #	DE-EE0008419
Start and End Dates	1/2/2019 to 12/31/2021
Partners/Collaborators	IRD Fuel Cells, University of Hawaii, Natural Energy Institute
Barriers Addressed	• Increase activity of platinum-group-metal-free (PGM-free) oxygen reduction reaction (ORR) catalysts • Decrease cost of PGM-free catalyst manufacturing • Increase durability of PGM-free catalysts

Project Goal and Brief Summary

The project objectives are to (1) develop platinum-group-metal-free (PGM-free) electrocatalysts for oxygen reduction reaction (ORR), (2) scale up production of the catalysts to 50 g batches, (3) integrate PGM-free catalysts into industrial state-of-the-art membrane electrode assemblies (MEAs), and (4) comprehensively evaluate the catalysts using electrochemical methods. The project addresses existing barriers by (1) increasing the activity of PGM-free ORR catalysts, (2) decreasing the cost of PGM-free catalyst manufacturing, and (3) increasing PGM-free catalyst durability. Improved understanding of the electrochemical processes relevant to PGM-free materials in mass-produced MEAs will allow commercial manufacturers to develop inexpensive, highly active, and stable PGM-free ORR catalysts that demonstrate performance levels required by the U.S. Department of Energy.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The focus of this project is the development of a scalable method for synthesis and manufacturing of PGM-free electrocatalysts (Fe-N-C types) for ORR for polymer electrolyte membrane fuel cell (PEMFC) applications. PGM-free ORR catalysts are integrated into industrial-quality MEAs through cathodic catalyst layer design (optimization of ionomer type and loading, deposition method, and type and concentration of additives). The team studied the electrode thickness to increase performance.
- The approach for this project was more on the applied end (versus the fundamental end) of the spectrum. This makes the project unique compared to other Electrocatalysis Consortium (ElectroCat) projects, which is positive, because the project puts more effort into getting these materials to function in an MEA. The MEA development approach taken was logical. The main criticism of the project approach is that there is a high risk that the catalyst activity and durability trails PGM catalysts by so much that the materials and our fundamental understanding may need to drastically improve before useful MEAs can be produced.
- The team has taken a systematic approach, starting with catalysts and proceeding to MEAs, then to using the electrochemical method to characterize the MEA performance, and then to elucidating the other important parameters, such as mass activity, current density, and catalyst stability. It was unclear whether the go/no-go decision point was for Year 1 or Year 2. The use of pore formers to increase the catalysts' surface area is a good approach.
- The team uses a method of preparing PGM-free ORR catalysts that is somewhat different from the most popular methods currently used in this space, such as metal–organic frameworks. The nature of the approach is essentially the same as others, i.e., using Fe- and N-based precursors plus pore formers. The pore former selected by the team appears large compared to others, which could contribute to performance on par with them. Silicon was used in the precursor, which would trigger the undesirable use of hydrogen fluoride for removal. The authors could be more specific about this. Ultimately, durability is the key challenge in PGM-free ORR catalysts in the acidic electrolyte. There was no clear path or hypothesis from the presentation to articulate how to address this challenge.
- The approach is focused on achieving activity and durability targets for PGM-free electrocatalysts.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team has conducted a sufficient number of experiments, from catalyst preparation to testing. The result is also good, on par with other state-of-the-art catalysts in this field. The team also successfully met the go/no-go decision criteria. The durability, though improved, appears to remain the Achilles' heel for this type of PGM-free ORR catalyst.
- The progress was slow because of the pandemic. The team achieved the project targets and the go/no-go ElectroCat target: demonstrate 0.044 A/cm^2 at 0.9 V (iR-free, H_2/O_2 configuration, 1 bar O_2, 80ºC, 100% RH). The team scaled up manufacturing capabilities of the catalyst.
- The biggest accomplishment from the work appears to be the demonstration of an MEA with a PGM-free catalyst that survives 30,000 cycles reasonably well, although still below DOE targets. The project also developed an interesting machine learning tool to determine the importance of MEA factors on resistance. Such a tool would definitely be useful to guide development of electrodes and MEAs with PGM-free catalysts. The downside with the project accomplishments is that the materials developed and the MEAs have very low performance relative to DOE targets. Very little was provided on characterization of the PGM-free materials or on the details of how they were made. The fundamental insights provided by other ElectroCat projects were lacking in this project.
- Significant progress has been made toward project goals and optimization of the catalyst layer design. Although the trend in durability improvement looks very promising, performance at 0.8 A/cm^2 is low.

- The surface area of catalysts using the PF-1 and PF-2 pore formers did not provide either Brunauer–Emmett–Teller (BET) or mercury intrusion porosimetry (MIP) data; it is hard to judge whether these pore formers work as designed, particularly for mesopores. An understanding of the porosimetry of the catalyst and MEA is important, as the mesopore plays a critical role in catalyst and MEA performance. The electrode layer is too thick to have good performance and is the root cause of the low performance. MIP is needed to analyze pore size distribution and pore volume to correlate performance and structure properly (slide 10). Proton conductivity was improved by the use of low-equivalent-weight (EW=720) ionomer and additives, and it is not apparent which one played the major roles here (slide 10). Clarity is needed on how the H+ conductivity of the catalyst layer was measured and whether it was measured by high-frequency resistance. It is strongly suggested that MEA durability, the current loss at 0.80 V, and voltage loss at 0.80 A/cm^2 be provided. It seems losses between 60 and 119 mV are quite significant. There is some interesting progress on ORR mechanisms, but the team should make a clearer and better summary.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- The key personnel are fully qualified to manage this project, as demonstrated by their publications on work in this and related fields, and the proposal clearly and completely defines the roles and contributions of each team member, including the financial support of partners.
- The project team is diverse and led by a respected, world-class scientist. There were no significant weaknesses in the team.
- The project had a very well-coordinated effort between Pajarito Powder, University of Hawaii, IRD Fuel Cells, and ElectroCat.
- The team is working closely with ElectroCat.
- The team showed good collaboration between themselves and with key partners.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Eliminating the PGM while maintaining the current level of specific power, power density, peak energy efficiency, and durability will significantly accelerate the deployment of fuel cell systems.
- The project is critical to the Hydrogen and Fuel Cell Technologies Office and has potential to significantly advance PEMFC commercialization toward DOE research, development, and demonstration goals and objectives. The industrial company that participated in this project is critically needed to accelerate the progress of the PEMFC commercialization.
- The biggest potential impact from the work was the demonstration that PGM-free MEAs with reasonably good durability can be produced, providing hope for further PGM-free MEA development. The modeling tools could also prove impactful for the industry. The biggest concern with potential impact is that DOE has switched focus to heavy-duty vehicle applications, and the materials and MEAs developed on this project are not competitive with the new DOE targets and objectives. The project did not yet investigate the mechanisms for degradation that may make the project more impactful.
- The fuel cell application is now shifting toward use in heavy-duty vehicles, in which the durability requirement becomes more stringent. The PGM-free ORR catalyst becomes less relevant unless some major breakthrough can be achieved.
- The project is relevant to DOE goals on commercialization of PGM-free fuel cells. However, performance of PGM-free catalysts is not sufficient to make a transformational impact in the fuel cell community.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The project team proposes logical next steps to meet the proposed project objectives. The post-accelerated-stress-test (post-AST) characterization could provide interesting insight to degradation of PGM-free catalysts in an MEA.
- Proposed future work is well-organized and feasible. Machine learning is a good approach for rational design of the catalysts and MEA structure.
- Proposed future work is focused on achieving DOE targets in activity and durability.
- The proposed work is well-presented and will lead to meeting the proposed milestones.
- Durability was identified as one of the future work areas, which is important. From a scientific point of view, it is not clear why MEA configuration can significantly improve durability.

Project strengths:

- The strength of this project is that it takes a systematic approach, from the catalyst to the MEA, with the goal to develop a scalable method for synthesis and manufacturing of PGM-free electrocatalysts (Fe-N-C types) for ORR for PEMFC application. This is particularly important for the PEMFC commercialization since the early involvement of the industrial partners will greatly promote the advancement of the PEMFC applications in transportation and other applications, such as renewable energy utilization and hydrogen at scale. The team has good collaboration with ElectroCat and other institutes.
- The project strength is in the combination of strong catalyst synthetic skills with thorough validation of the catalyst performance, use of novel theoretical tools such as machine learning, and modeling of full polarization curves to understand and expedite the design of new materials and catalyst layers.
- The team focuses on the commercialization of the project catalysts and has the venue and capability to do so. It will be exciting to discover fuel cell applications that can serve as early adopters of this type of catalyst. The team also works diligently to address not only the catalyst but also the MEA aspect of the development, which helps to validate the approach. The team demonstrates the capability to produce larger quantities of catalyst.
- This project is unique in comparison with other ElectroCat projects because it puts more effort into getting PGM-free materials to function in an MEA. The durability data to 30,000 cycles was nice to see. The machine learning model was a strong point as well. The project had a strong principal investigator and team.
- There is a clear focus on scale-up and catalyst manufacturing.

Project weaknesses:

- The project does not contribute greatly to the fundamental understanding of how to improve PGM-free catalysts to the point where they could be competitive with PGM catalysts.
- The team has difficulty in controlling the particle size; the porosity of the particles will have a negative impact on long-term stability.
- The project team made good progress but needs to accelerate the effort to meet the project goals and DOE targets. The project status shows that the team met the project milestone but still needs to make great effort to meet the end goals.
- More focus should be given to catalyst durability improvement.
- Fe-N-C electrocatalysts are not new.

Recommendations for additions/deletions to project scope:

- The planned post-AST testing could provide interesting insight as to why the MEA degrades. If the techniques planned do not fully explain the degradation, the team should consider expanding the array of techniques to include electrochemical diagnostics, energy dispersive x-ray spectroscopy (EDX) mapping, pore measurements, or more advanced techniques.

- The proposed team is doing a good job.
- As the project ends in six months, there is not enough time to change its scope.

Project #FC-307: Cyclic Olefin Copolymer-Based Alkaline Exchange Polymers and Reinforced Membranes

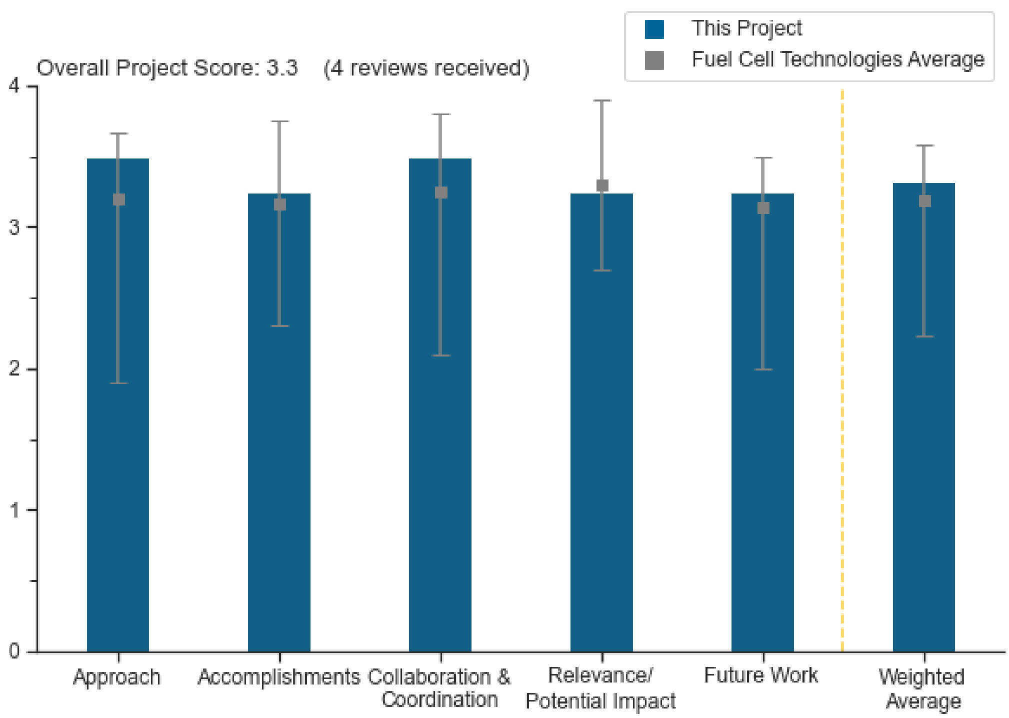
Chulsung Bae, Rensselaer Polytechnic Institute

DOE Contract #	DE-EE0008432
Start and End Dates	4/1/2019 to 4/30/22
Partners/Collaborators	Los Alamos National Laboratory
Barriers Addressed	• Performance • Cost • Durability

Project Goal and Brief Summary

In this project, Rensselaer Polytechnic Institute (RPI) will develop a series of innovative cyclic olefin copolymer (COC)-based alkaline exchange membranes (AEMs) that would overcome the challenges of the state-of-the-art AEM. Specifically, the project team plans to (1) develop COCs with tunable backbone rigidity, (2) incorporate alkyl chain-tethered quaternary ammoniums of different structures into the polymer by simple post-functionalization method, (3) impregnate the anionic polymers into a mechanically stable matrix (reinforced AEM), and (4) demonstrate the membranes' performance and durability in fuel cells using platinum-based and platinum-group-metal-free (PGM-free) catalysts. The reinforcement of AEM will allow RPI to produce thinner (e.g., 10–25 µm) membranes, affording lower area-specific resistance and better water management in MEAs, particularly with a PGM-free catalyst.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach of combining ethylene and norbornene has the potential to access low-cost, durable AEMs. The project strategy is a very clever idea: incorporating a non-functional phenyl ring onto the norbornene monomer to enable metallocene catalyst polymerization, followed by functionalization of the phenyl group. The team is focused on the important parameters necessary to advance AEM technology.
- The project is making saturated hydrocarbon and reinforced membranes for high-performance AEMs by using low-cost monomers and polymers, no heteroatom (oxygen or nitrogen) in the backbone, high alkaline chemical stability, tunable rigidity (by varying the ratio of ethylene and norbornene/cyclic olefins in the backbone), and pore-filling reinforcement for enhancing durability and extending lifetime of MEAs.
- The team is making good progress. The work is feasible and will likely be successful.
- This is good work, but the U.S. Department of Energy is now funding at least three aliphatic AEM projects, and the clear advantages or differences between the projects are indistinguishable.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The progress made by the principal investigator's group is good. The researchers were able to make some really nice progress in developing very nice reinforcement of their AEM. This was also highlighted by the impressive improvement in mechanical properties. Fuel cell performance is good, but it is unclear whether the fuel cell performance is tied to the specific humidification of the cathode and anode.
- The RPI team has shown the feasibility of the synthetic approach, as well as made prototype fuel cell membranes. The researchers are target-driven while still developing the necessary system understanding. Focused performance, mechanical strength, and chemical durability show a well-rounded approach.
- The project has prepared membranes, used reinforcement composite, characterized membranes, and studied hydrogen oxidation reaction catalyst electrodes.
- Some of the targets could be more suited to future applications. For example, peak power density is nice, but it is not really an important practical value. A much better metric would be voltage at 1.0 A/cm^2. The current DOE target is 0.65 V at 1.0 A/cm^2 at steady state (it should be at least a one-hour test). The researchers already seem to meet that target in the pol curves, but it is not clear how stable the performance is, especially given that the membrane is drying out, given the increase in high-frequency resistance shown on slide 12. Additionally, some of the performance variables could be moved closer to reality. For example, the anode flow rate is 1.4 L/min, which is huge, because it is likely to avoid anode flooding. It is also worth noting here that the overall performance with these materials is below the state of the art, and that should be addressed.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- There is good collaboration between RPI and Los Alamos National Laboratory (LANL), with good division of labor; the synthesis is mostly at RPI, and the characterization is mostly at LANL.
- The collaboration at this stage of this effort is perfect.
- Collaborations between RPI and LANL are complementary, and the team structure is productive.
- The collaboration seems fine.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The operating environments for AEM fuel cells or electrolyzers are very challenging; however, this team has the potential to address many of these issues. If successful, the RPI technology has the potential to meet many, if not all, of the DOE targets.
- There have been great improvements in AEM technology, but more is needed in terms of CO_2 tolerance and highly active non-PGM catalysts with good stability, and this project is targeting these needs.
- This is good work, but it is in a crowded area. The current results here are similar to the other aliphatic projects, and it is difficult to declare which project is better than the other at this point.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The most relevant future work should be the following:
    - Mechanical property improvement by pore-filling reinforcement and use of higher-molecular-weight cyclic olefin copolymer polymers
    - Evaluation of the AEM performance in a fuel cell long-term test with minimal recoverable and unrecoverable loss
    - Pore fillers for strength and water in membrane optimization.
- Durability will be the next focus, as it should be, to give an idea of the stability of this material. It is interesting that this material was not utilized as the ionomer since it may be a good candidate; perhaps this is something that should be evaluated.
- The proposed work is fine.
- The future work is clear and on point with DOE targets. However, there are very ambitious goals, such as a catalyst layer and AEM compatibility, that will likely exceed the time allotted in this project. The optimization work is not clearly defined. There are multiple layers of polymer composition, crosslinking, support, and process conditions that will be challenging to complete.

Project strengths:

- A key strength of this approach is the ability to incorporate a true commodity monomer (ethylene) into a highly engineered ionomer polymer. Not only does this lower ionomer cost, but ethylene units are thought to be among the most chemically stable in an alkaline environment. The RPI–LANL team comprises some of the most recognized experts in the AEM field. Their understanding of the critical barriers and strategies to address these barriers is of the highest caliber.
- The current strength of this project is the very good reinforced membrane development. The chemistry work is good but is not unique, as many researchers are developing these types of polymers.
- The project has a good team with complementary skills. The project builds well from what is known in the literature. The team is capable of executing all of the aspects of the project.
- There is good synthesis at RPI and characterization at LANL.

Project weaknesses:

- While a very clever approach, optimizing membrane copolymer ratios, crosslink density, support type, membrane thickness, and other properties will be challenging. There are many very good AEM candidates in the literature. More work is needed to demonstrate that this approach has the potential for superior performance, durability, and cost.
- More investigation into this material as an ionomer should be pursed since the material has little aryl groups that have been found to adsorb onto the catalyst with time, affecting durability.

- The team says mechanical properties are being improved, but the characterization of membrane strength is not clear. The relative ranking of membrane strength at 50% relative humidity by stress–strain is useful but does not apply to strength in fuel cell operating conditions, which have much higher water levels.

Recommendations for additions/deletions to project scope:

- This team should focus on membrane optimization, crosslinking, and hydration issues by using a standard anode and cathode catalyst for fuel cell performance comparisons. Any other catalyst work seems a diversion.
- The project should make targets to align better with those laid out in Simon T. Thompson et al., *Journal of The Electrochemical Society* 167 084514 (2020). The project should push the team to be more ambitious with its performance and durability goals, as others have already achieved much better than the final project goals here.
- Ionomer investigation would be beneficial.

Project #FC-308: Advanced Anion Exchange Membranes with Tunable Water Transport for Platinum-Group-Metal-Free Anion Exchange Membrane Fuel Cells

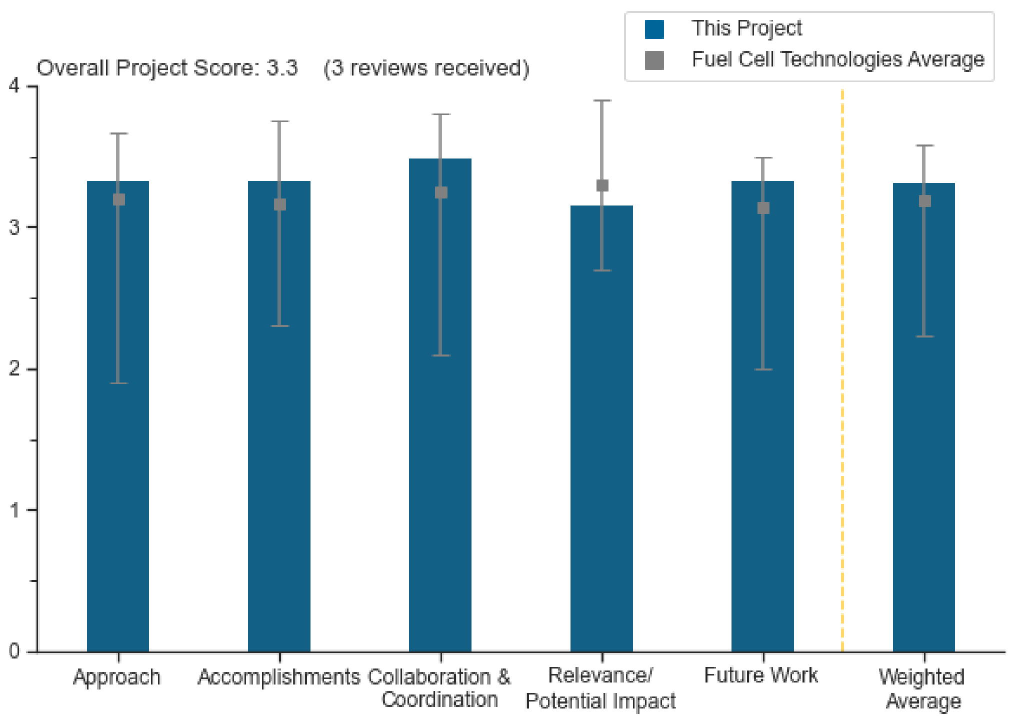
Michael Hickner, The Pennsylvania State University

DOE Contract #	DE-EE0008433
Start and End Dates	10/1/2018 to 3/31/2022
Partners/Collaborators	Pennsylvania State University, University of South Carolina, National Renewable Energy Laboratory, 3M Company
Barriers Addressed	• Durability • Cost • Performance

Project Goal and Brief Summary

This project will enable high-performance, long-lifetime, low-platinum-group-metal (low-PGM) (PGM loading ≤0.125 mg/cm^2) anion exchange membrane fuel cells (AEMFCs) through (1) synthesis and fabrication of novel thin, mechanically supported anion exchange membranes (AEMs) and electrode ionomers with validated outstanding water transport properties and stability, (2) integration of these new polymers with high-performing low-PGM and PGM-free catalysts and electrodes, and (3) precise control over the distribution of water in operating cells. What makes this project exceptional are the team's capabilities in new material synthesis to tune water transport and the world-leading knowledge in membrane integration with electrodes to achieve the current world-record performance in AEMFCs.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Membrane-making using stable saturated hydrocarbons, using a catalyst specific to AEM, improving cell performance, and using neutron diffraction to study and optimize polymer and water management are approaches that cover all targets.
- The project's focus on large-scale batches and repeatability is important, and it is a valuable part of the approach. The work to focus on such issues should be commended.
- This is good work, but there are now at least three aliphatic AEM projects that the U.S. Department of Energy is funding, and the clear advantages or differences between the projects are indistinguishable.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The performance results are excellent and above the targets in the milestones. The durability testing, which is what the milestones focus on, are written for 60°C, while this team is showing testing at 80°C, a more challenging temperature. The team is showing 0.69%/100 hours, which translates to 13.8%/2000 hours, which is above the goal of 10%—but again, the work is at a higher temperature. Also, this rate is projected from the first few hundred hours, not actually shown. Overall, this project appears to be on track to hit the final project milestones.
- All targets have been met except the neutron studies, which are behind because the pandemic shut down the National Institute of Standards and Technology (NIST) facility.
- The performance and durability shown were impressive and a good step forward. However, the performance does look similar to Paul Kohl's (Georgia Tech) materials.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- This appears to be a well-integrated team with appropriate partnering.
- All team members share different tasks, such as synthesis at The Pennsylvania State University, catalysts at 3M Company, and characterization at the National Renewable Energy Laboratory and NIST.
- The partners right now are sufficient.

Question 4: Relevance/potential impact

This project was rated **3.2** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is demonstrating steady progress on making the changes needed to advance AEMs: stable saturated hydrocarbon membranes, a catalyst specific to AEM fuel cells, stable cell performance, and water management. The effects of carbon dioxide (CO_2) and high-performance stable non-PGM catalysts still need work.
- This is good work but in a crowded area. The current results here are like those of the other aliphatic projects, and it cannot be declared which project is better than the other at this point.
- The AEM performance is good, but there is still PGM in the electrodes, and then there is the CO_2 issue to address. The likelihood of AEMFCs ever beating polymer electrolyte membrane fuel cells remains in pretty serious question. This is not a negative for this project.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The future work suggested by the team is relevant.
    - The project will synthesize larger-scale batches of polymer to facilitate membrane testing; this is mostly complete, but more material will be filled in as needed.
    - The project will measure water transport in membranes using pulse field gradient–nuclear magnetic resonance (PFG-NMR) and connect to cell water transport observations using water balance measurements.
    - The project will fabricate expanded polytetrafluoroethylene (ePTFE)-supported membranes for cell testing.
    - The project will finalize cell testing electrodes and conditions for demonstration of 2000-hour lifetime end-of-project goals.
    - Someone has to step up on effects of CO_2.
- The future work is reasonable and focused on proving out the final milestone.
- The progress made in measuring the water diffusion and relating it back to fuel cell performance was interesting. In addition, investigation of this material as an ionomer should be pursued since the material has little aryl groups that have been found to adsorb onto the catalyst with time, affecting durability. Perhaps looking at polyethylene instead of PTFE support could reveal better ionomer impregnation.

Project strengths:

- This project has delivered some very nice fuel cell performance and durability, which is very promising.
- This project has good teaming and good progress, except for the NIST water studies.

Project weaknesses:

- There are none, but someone must address CO_2—maybe examine a CO_2-rejecting membrane backbone.
- One weakness is that the material is only being used as a membrane; it should also be looked at as an ionomer. It would be interesting to see if the performance is primarily due to the GT ionomer or not.

Recommendations for additions/deletions to project scope:

- Reviewers did not provide comments in response to this question.

Project #FC-309: Polymerized Ionic Liquid Block Copolymer/Ionic Liquid Composite Ionomers for High-Current-Density Performance

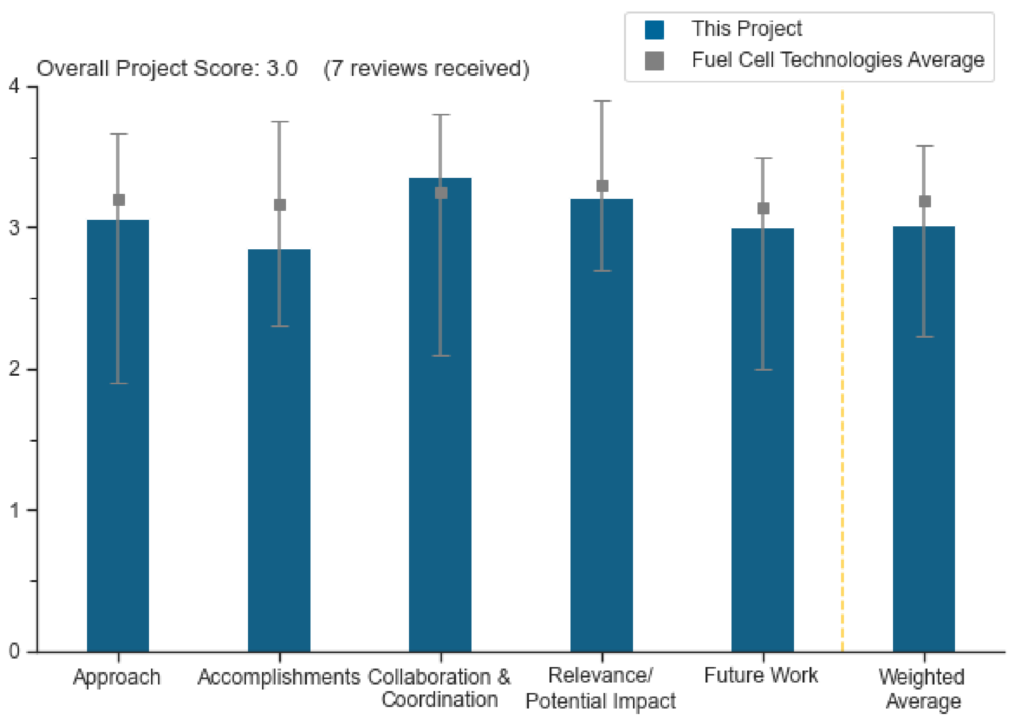
Joshua Snyder, Drexel University

DOE Contract #	DE-EE0008434
Start and End Dates	10/1/2018 to 12/31/2021
Partners/Collaborators	Drexel, Texas A&M, General Motors, National Renewable Energy Laboratory
Barriers Addressed	• O_2 transport through ionomer films • Ionomer adsorption on catalyst • Inaccessible catalyst in porous carbon • Distribution and retention of IL in catalyst layer • Humidity tolerance at HCD

Project Goal and Brief Summary

The project's goal is to develop a polymerized ionic liquid block copolymer/ionic liquid (PILBCP/IL) composite ionomer to replace traditional perfluorosulfonic acid (PFSA)-based ionomers and address their associated limitations. The expected outcomes include (1) development of a cathode that meets U.S. Department of Energy targets for low and high current density (HCD) and (2) improved understanding of how interface engineering affects HCD performance. The project will develop the PILBCP/IL ionomer and then develop and study membrane electrode assembly (MEA) performance and durability. The project addresses the primary technical barriers associated with (1) oxygen transport through ionomer thin films, (2) ionomer-specific adsorption onto the catalyst, (3) inaccessible catalyst in porous carbon supports, (4) distribution and retention of IL in catalyst layers, and (5) humidity tolerance at HCD (Pt utilization).

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The objectives of this project are to improve the performance of fuel cell cathode catalyst layers through reduced sulfonate interactions and lower oxygen transport resistance. The project appears well-suited to prove its hypotheses, and replacing incumbent PFSA ionomers is an interesting concept.
- The approach of using ILs and PILBCPs to enhance electrode performance is innovative and promising. The strong focus on PILBCP synthesis and MEA integration and testing, coupled with fundamental electrochemical studies, makes this a durable approach.
- The approach of using ILs to try to improve Pt utilization and decrease ionomer–catalyst-poisoning-type interactions has potential to improve performance and durability of oxygen reduction reaction catalysts. Tethering ILs to a polymer should help retain the IL in the catalyst layer. The approach of using a block copolymer that also contains a proton-conducting block should alleviate dilution effects and maintain high proton conductivity in the catalyst layer. Slide 14 suggests that the IL can penetrate into the pores of porous carbon supports to provide proton transport to catalyst particles within the pores; however, once the IL is immobilized by tethering to a polymeric backbone, it is unclear whether it will be able to enter these pores. The results shown appear to be for Pt/Vulcan. The project does not appear to be investigating different types of carbons to determine the impacts of carbon support porosity on the tethered IL's benefits or comparing the tethered IL's benefits to use of porous carbon supports to decrease catalyst–Nafion interactions.
- The development alternative ionomer to Nafion is meaningful, and the PILBCP/IL composite ionomer is novel.
- The project has an interesting and novel approach to improving cathode performance.
- While the concept seems applicable, the insolubility in normal solvents and use of Pt/Vulcan are major drawbacks to the approach.
- This presentation was hard to follow. It is clear that the goal is to develop a replacement for PFSA ionomers, but then there is a fair amount about PILBCP–Nafion mixed ionomers. One can see how this could be interesting to look at from a fundamental point of view, but considering the goal is to move away from PFSA, the mixed ionomers seemed to be a big focus of the presentation.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The main accomplishment over the last year appears to be in the free IL MEA tests, where IL additives to fuel cell cathodes have demonstrated enhanced performance over the Pt dissolution accelerated stress test (AST). Though degradation rates are maintained, this should help with mechanistic understanding of catalyst degradation. The hypothesis that the polymerized IL does not disperse well in the catalyst ink is supported with good evidence, and the approach of mixing with Nafion to demonstrate progress was a good idea. It is unfortunate that more progress in the polymer work did not meet with any success. There is certainly more to do in durability testing, as indicated.
- The project has met its 2020 go/no-go milestone, with lower Pt loadings than the target, and appears to be on track toward meeting the 2021 target for performance. The project has shown improvements in performance of mass activity, specific activity, and performance at rated power for Pt/Vulcan carbon electrodes using the IL and tethered IL.
- The project has accomplished the following: (1) PILBCP synthesis has been well-progressed, (2) results of specific adsorption in PILBCP–Nafion mixed ionomers are very informative, (3) the microkinetic model is interesting, (4) the new ionomer clearly demonstrated improved performance, but whether IL can be toxic to the catalyst has not been thoroughly studied, and (5) interaction of catalyst with new ionomer in the electrode can be better understood using high-resolution transmission electron microscopy (TEM).
- The higher Pt utilization with high-surface-area carbon at low relative humidity in the presence of free IL is a good result.

- Several questions remain in terms of the combinations of IL, polymerized ionic liquid (PIL), and Nafion. Studies on oxygen transport, pressure, and poisoning of catalysts are needed.
- There does not appear to be substantial progress in the synthesis of PILBCPs in the past year. Most of the work involved mixing PILBCPs with Nafion and demonstrating that the PILBCP can reduce Nafion adsorption and thereby enhance kinetics and transport. The performance enhancement achieved by the mixing of Nafion with PILBCP looks impressive, but the performance of the baseline MEA based on Nafion without PILBCP looks too low. It is not clear whether these materials are truly enabling improved performance over the state of the art.
- This presentation was somewhat hard to follow. It seems like the initial year's milestone was hit, but it is unclear whether the researchers are expecting to meet the final milestone or think this material platform is a no-go.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- There is excellent collaboration in this project, with strong contributions in ILs from Drexel University and great MEA capabilities at the National Renewable Energy Laboratory (NREL) and General Motors (GM). The roles of NREL vs. GM in MEA analysis should be clarified.
- Collaborations within the project appear to be working effectively. Plans to engage with the Million Mile Fuel Cell Truck (M2FCT) consortium will provide more collaboration and access to additional analytical techniques for characterization. Collaboration with Lawrence Berkeley National Laboratory in the area of thin-film polymer morphology and interactions of the tethered IL with the catalyst could be beneficial.
- The collaboration with NREL is a key enabler of the project, although it is somewhat unclear whether GM has participated in the project yet. The principal investigator (PI) did indicate GM's effort was focused at the end, which makes sense.
- The PI has great collaboration with GM, NREL, and Texas A&M University.
- A capable team has contributed to the progress to date.
- The collaboration appears good.

Question 4: Relevance/potential impact

This project was rated **3.2** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is highly relevant to the goals of the Hydrogen and Fuel Cell Technologies Office (HFTO). This innovative approach to improving electrode performance through development and incorporation of novel materials is a great fit for HFTO and is likely to have substantial impact on the field.
- This work is relevant and has a high potential impact. From preliminary studies, addition of IL can enhance catalyst activity and improve durability. Tethering may limit these impacts in terms of the type of carbon support used. These studies also provide insight into tailoring catalyst surface interactions to improve performance.
- The project is relevant to HFTO in that the ionomer developed can improve power density of polymer electrolyte membrane fuel cells. The long-term durability should be better studied for a higher impact. However, on the slide relating to relevance (slide 5), the table was left empty.
- The work in this project is innovative and potentially high-impact to M2FCT goals.
- A cathode that meets DOE performance targets is needed.
- While the work is focused on PFSA-free ionomers, the testing is all done with Nafion membranes. Also, the slide relating to relevance was mostly left blank.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The project appears to be in no-cost-extension territory to meet its final goals. The focus on durability and 50 cm^2 diagnostics is appropriate.
- Durability testing is very important, especially given the possible mobility of the IL.
- Clearly defined future work has been shown.
- The proposed future work looks reasonable but could have been described in more detail. It seems like all of the future work is on MEA testing. Further work on the PILBCP chemistry would seem worthwhile.
- Durability testing and MEA performance are clearly priorities, but it would have been helpful to have more clarity and language here around what has been learned and how that informs plans going forward.
- Future work should be expanded to look at different carbons. It may be possible to trap free IL in the carbon pores by capping the pores with Nafion or the tethered IL. More durability studies and studies looking for leaching of the IL and decomposition of the tethered IL polymer are needed.
- While durability is important right now, performance is too low to be meaningful to fuel cell performance goals. Durability testing of the IL, PIL, and combinations must be done separately to establish the degradation mechanism.

Project strengths:

- This project provides a highly innovative approach to advancing fuel cell performance and decreasing cost. The dual focus on materials development and MEA testing is a key strength.
- The combination of synthetic capabilities of Drexel University and Texas A&M University with the diagnostic capabilities at NREL and GM is a strength.
- The project has innovative ideas of developing a PILBCP/IL ionomer, a great team has been assembled, and great progress has been achieved.
- The project's innovative approach and excellent collaboration are effective for investigating the concept in relevant systems.
- Novel approach to cathode improvement.
- This project has interesting results.

Project weaknesses:

- Project weaknesses include the following: (1) long-term impact of IL on the catalyst and electrode structures has not been studied, (2) electrode optimization using the new ionomer has not been thoroughly investigated, and (3) PILBCP ionomer–catalyst interaction in the electrode is not shown.
- There are plans to focus on Vulcan carbon in the future work, which is a weakness. The combination of free IL with block copolymer IL and Nafion has potential with porous carbons, as the free IL can access the pores and Nafion and block copolymers may cap the pores, limiting or preventing loss of the free IL.
- There does not seem to have been much recent progress in PILBCP development; most of the progress has been in MEA studies.
- Polymerization work has not appeared promising, and dispersion of the ionomer in catalyst inks has met with initial poor results (though this is a challenging topic).
- There is an insufficient consistency in understanding the effects of IL and PIL mixtures on degradation and performance.

Recommendations for additions/deletions to project scope:

- Recommendations include the following: (1) gas permeability and water uptake of the ionomer-cast thin film can be characterized, and (2) this new ionomer can be used for heavy-duty vehicle application, increasing Pt loading and extensive AST (e.g., 90,000 hours).

- The project should monitor changes to the microstructure of the composite layer of Nafion and PILBCP during, before, and/or after AST.
- The project should expand leaching studies and investigation of IL composites with new advanced porous carbon supports.
- The PI should engage NREL rheology/catalyst ink experts to understand and explore the PIL behavior in inks.
- The project should attempt to quantify coverage of catalysts and the catalyst–electrolyte interface, as well as capacitance. Durability testing of the IL, PIL, and combinations must be done separately to establish the degradation mechanism.

Project #FC-310: Composite Polymer Electrolyte Membranes from Electrospun Crosslinkable Poly(Phenylene Sulfonic Acid)s

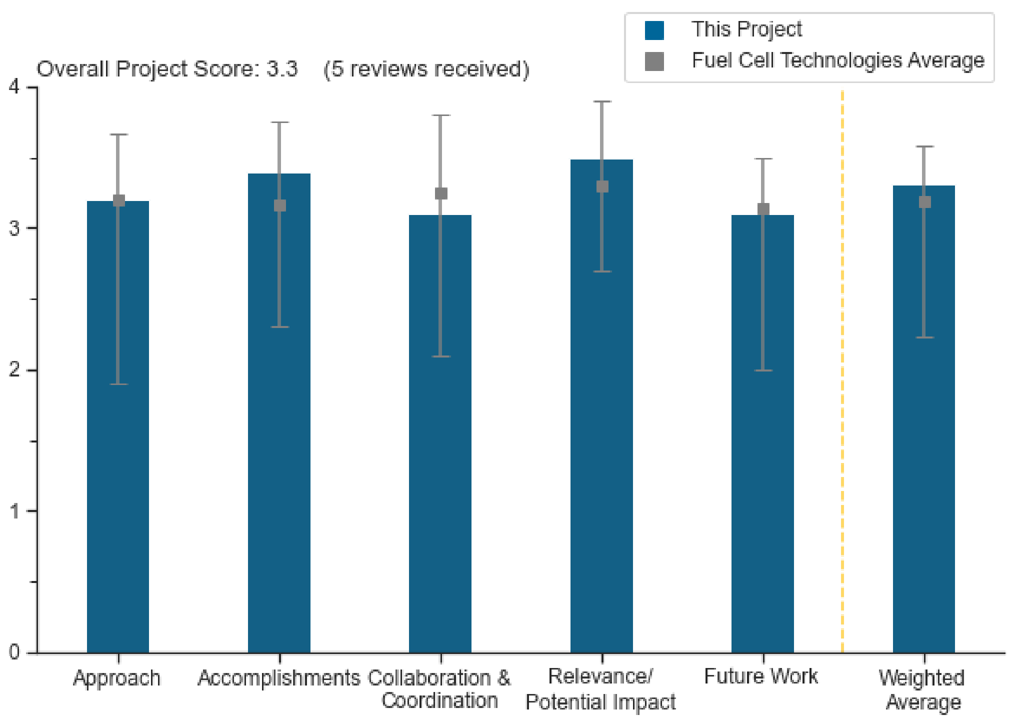
Ryszard Wycisk, Vanderbilt University

DOE Contract #	DE-EE0008435
Start and End Dates	1/9/2019 to 12/31/2021
Partners/Collaborators	Vanderbilt University
Barriers Addressed	• High cost of PFSA membranes • Low proton conductivity at reduced humidity (water partial pressure) • Performance drop above 80°C

Project Goal and Brief Summary

The project objective is to fabricate a novel electrospun, non-perfluorosulfonic acid (non-PFSA) fuel cell membrane that meets all 2020 technical targets in the Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRD&D Plan). The project approach is to develop and fabricate a robust, low-cost composite all-hydrocarbon membrane via dual-fiber co-electrospinning of a crosslinkable poly(phenylene sulfonic acid) (cPPSA) and poly(phenyl sulfone) (PPSU) mixture mat, followed by mat densification via solvent-vapor-induced softening of PPSU fibers and thermal crosslinking. The project addresses the barriers of (1) the high cost of PFSA membranes, (2) low proton conductivity at reduced humidity (water partial pressure), and (3) performance drop above 80°C.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Looking at novel polymers and new methods to make ionomer composites is definitely important. The polyphylene ionomer and electrospinning ideas are worth investigating. The presenter himself correctly identified the core issues with the approach: (1) reproducible synthesis, (2) electrospinning with minimal use of carriers and loss of conductivity, and (3) ionomer integration to create robust membranes. He is fundamentally right. This means the project team has many variables with which to work, and therefore, the research will be complex, which in the end creates a risk of not achieving its goals.
- The data focused on the application of electrospun materials for the fabrication of fuel cell membranes. Preparation of precursor materials is a critical step in this process and clearly identified in Tasks 1–3. The next three tasks address electrospinning. The last two tasks address membrane optimization and fuel cell testing. The systematic organization of the project and progress depend on the success of the previous group of tasks. It is not clear what plans the organization had if any of the first three tasks should reach their expected objectives.
- This is a good approach to improving the mechanical properties of rigid rod sulfonated polyphenylene (SPP), which is brittle and soluble in water.
- The Vanderbilt team has a clear, target-driven approach. Building on the success of the SPP is a credible candidate for realistic hydrocarbon membranes. Electrospinning reinforced fibers has the potential to result in high-quality, commercially viable membranes. However, it seems electrospinning is relied on to the exclusion of other approaches. The new technology in this project is the technique to crosslink the SPP.
- The justification for the PPSA was missing. It is not clear why this poly(aromatic) hydrocarbon polymer electrolyte membrane (PEM) would be more advantageous than sulfated polyether ether ether ketone (PEEK) or PPSU. It is clear that high ion exchange capacity (IEC) values can be attained with PPSA, as two sulfonic acid groups can be installed per phenyl or biphenyl, allowing for high ionic conductivity under low relative humidity (RH) conditions, but the rigid rod nature of the polymer will inevitably lead to poor mechanical properties. Reinforcement is needed to make a mechanically robust hydrocarbon PEM. A clearer picture stating that high IEC is needed for low-RH operation and that the rigid rod poly(aromatic) backbone would prevent water dissolution would help the presentation. It is not clear whether the poly(phenylene) offers greater oxidative stability over PEEK or PPSU backbones because it does not contain ketone, sulfone, or ether functional groups.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There was good progress in developing membrane mats incorporating SPP.
- A good deal of progress has been made in preparing two reinforced cPPSA PEMs. The pore-filled cPPSA has very high ionic conductivity (450 mS/cm) and conducts protons near 100 mS/cm at 40% RH. The pore-filled approach gives PEMs with better conductivity and mechanical properties. The new pore-filled cPPSA products should be good candidates for 100°C–120°C temperature operation at low RH for heavy-duty vehicles. However, fuel cell performance and chemical stability studies (accelerated stress tests [ASTs]) are needed. These experiments should be done in the no-cost extension period, as the project has been partially delayed because of the COVID-19 pandemic. The following items are missing from the technical target goals: H_2 and O_2 crossover, area-specific resistance, AST, and cost for manufacturing membranes.
- Tasks 1 and 2 appear have achieved success. Task 3 demonstrated two approaches to composite cPPSA–PPSU membranes: dual electrospun and pore-filled PPSU. The data demonstrated that the pore-filled membrane has superior proton conductivity and tensile strength. A problem was reported: mechanical strength characteristics were worse than those obtained in budget period 1. The researchers did not offer a technical path to resolving this issue.
- The proton conductivity reported by the team at 80°C and 40% RH is very impressive. This is perhaps some of the best low-RH conductivity reported by a hydrocarbon membrane. Mechanical properties may

need more improvements. Strain at break of 15% or less is likely to be brittle and may suffer mechanical failure in handling or operation.

- There was good progress in developing membrane mats incorporating SPP.
- The research team synthesized the polymer and made some good mats. The project achieved decent proton conductivity and tensile properties for the items produced. All the accomplishments were very impressive. For this technology or approach to compete, it also has to meet cost, durability, and even higher performance metrics. None of those data were provided in the slides.

Question 3: Collaboration and coordination

This project was rated **3.1** for its engagement with and coordination of project partners and interaction with other entities.

- The project team leveraged knowledge from Professor Litt at Case Western Reserve University. There was a collaboration with Professor Litt prior to his death. There has been some discussion of testing the PEMs with Dr. Mukundan at Los Alamos National Laboratory (LANL). No interaction with industry or other national laboratory partners is clearly defined.
- The team consists entirely of Vanderbilt University researchers. Given the size of the award, this does not seem to be a fundamental problem. However, the teaming score can be no higher than “good” in this circumstance.
- Collaboration focused on academic researchers. No industrial partners were identified. The researchers reported they would seek an industrial partner/laboratory when optimization is concluded. This should not be a “throwing over the wall” approach to collaboration. The earlier an industrial partner or laboratory participates in a project, the more productive the research and development should be.
- An end user that currently buys membranes would be a great addition to the team, as the end user can provide feedback on the progress and commercial readiness of the technology.
- The team should collaborate with another entity to perform third-party analysis to measure conductivity and measure gas crossover.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The researchers have a good grasp of the importance of their successful demonstration of the technology. Reduced cost and better low-RH performance at higher temperatures would greatly benefit most aspects of fuel cell applications.
- New PEM architectures that conduct protons with low resistance over a wide humidity range, as well as being mechanically robust, are important to the MYRD&D Plan. The project accomplishments and remaining activities are aligned with this plan.
- The SPP approach has the potential to advance the state of the art of hydrocarbon PEMs. For this reason, the project has a high potential impact. Material properties and accelerated durability are necessary for this approach to demonstrate its full relevance and impact.
- If an alternate to Nafion™ PFSA composite materials (currently in the market) is developed, it would be a significant contribution.
- The conductivity of the rigid SPP is one of the highest of all hydrocarbons, and this project improves the mechanical properties. However, there are some concerns that these mats will have issues with gas crossover since the film is really not totally dense (it appears to have some voids). Moreover, the mats are made of fibers that are at the opposite ends of hydrophobic/hydrophilic extremes. With such large differences in a material not covalently bonded, there is a large concern about mechanical stability in RH cycling, which is an AST. Also, these types of structures are typically stable toward highly oxidative environments, which leads to durability concerns. These potential issues will limit the impact of this material until proven otherwise.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The researchers identify three challenges and barriers. The first was a surprise, as it was missed in discussion of Tasks 1–3 and could be a showstopper. The second challenge was identified, and the researchers proposed an approach that appears reasonable. The third challenge states the problem but does not suggest a path to improvement. The future work addresses membrane electrode assemblies and their testing. If membrane challenges are resolved, this is a good approach, but it does not appear the challenges are part of future work. It is recommended the researchers take a step back and solve challenges or at least explain why they are going forward with fuel cell membrane electrode fabrication and testing to resolve the challenges identified.
- Regarding fuel cell testing and AST protocols, perhaps the researchers should look at the water uptake of this material at various temperatures to understand how high temperature and humid environments change the dimensions of the membranes. It would be beneficial to see the impact of this material in Fenton's reagent to determine whether the mat improves chemical stability as well.
- Running fuel cell performance and durability testing—proposed future work—are clearly important next steps; however, the plans for competing this work are unclear. The project does not state whether work will be done at Vanderbilt University, LANL, or another institution.
- The proposed future work primarily focuses on testing the cPPSA in fuel cell devices. The reinforced cPPSA will be the PEM, but it is not clear what electrode binders will be used. Additionally, AST needs to be done. This seems like a good deal of work to complete in six months with limited resources.
- There is much to do. This is all good basic research but has many thresholds to pass before being commercially ready. Some effort should be expended to consider specific tasks relevant to commercialization, such as cost analysis and durability testing.

Project strengths:

- Reinforced cPPSA PEMs have been prepared using two different strategies, co-dual fiber electrospinning and pore-filling. The team has demonstrated remarkably high proton conductivity (450 mS/cm at 90% RH and 100 mS/cm at 40% RH). The pore-filled membrane has good mechanical properties over 18 MPa and 15 strain at break at 50% RH. The new PEMs based upon reinforced cPPSA will be good candidates for membrane electrode assemblies that will operate at higher temperatures that have lower partial pressures of water (important for heavy-duty vehicles).
- Building on one of the most promising hydrocarbon membrane technologies (SPP) is a core strength of this project. The team is highly regarded, has many years of membrane development experience, and clearly understands the important targets for this technology. The proton conductivity presented by the team is quite impressive.
- The research is a good, sound alternative approach, addressing a critical issue in current PEM systems. The strong, highly qualified team has proven competence in this field.
- This is a very creative and technically strong research collaboration. It is good to see electrospinning technology moving forward.
- These materials show one of the highest proton conductivities at low RH of all materials, and this project has shown improvement in the mechanical properties of these materials.

Project weaknesses:

- Mechanical properties to date may be inadequate for truly competitive membranes. Electrospinning fabrication methods make sense for mechanical support but seem to be a "force-fit" in the dual-fiber case. There is no obvious advantage to making an ionomer fiber only to destroy it (i.e., melt or dissolve) later. Additional partners or Million Mile Fuel Cell Truck (M2FCT) laboratories should be enlisted for performance and durability evaluations.
- The largest weakness right now is understanding how humidity and temperature affect the mechanical properties. One of the automotive tests looks at repetitive low/high RH in a membrane electrode assembly

and monitor open circuit voltage loss; this would be a good demonstration of good mechanical–chemical behavior. Also, Fenton's test will give a basic understanding of the membrane's oxidative resistance.

- The project can benefit from a stronger rationale for the PPSA chemistry, especially since it is a non-trivial synthesis and has batch-to-batch consistency issues. Additional work is needed to substantiate the potential of reinforced cPPSA PEMs for fuel cell devices. This work includes gas crossover, fuel cell performance, and durability. The electron micrographs show some porous areas in the membrane, and these pores could cause large gas crossover rates.
- The project needs input from an industrial partner or testing laboratory. The project needs to have a discussion about moving electrospinning to high-rate production. Technically, the project needs to resolve the thermal crosslinking of PPSA ionomers as quickly as possible.
- The project is a long way from commercialization.

Recommendations for additions/deletions to project scope:

- The Vanderbilt team has done a nice job on this project, and clearly, electrospinning is a core strength of the team. However, expanding the potential supports to include expanded polytetrafluoroethylene (ePTFE) is suggested. If nothing else, it would be a good comparison.
- If the polymer system shows promise, there will be a need for much more work involving optimization, electrode attachment, and then preparation for commercial applications.
- The three challenges identified on Chart 14 of the presentation should be added to future work.

Project #FC-313: Novel Bifunctional Electrocatalysts, Supports, and Membranes for High-Performing and Durable Unitized Regenerative Fuel Cells

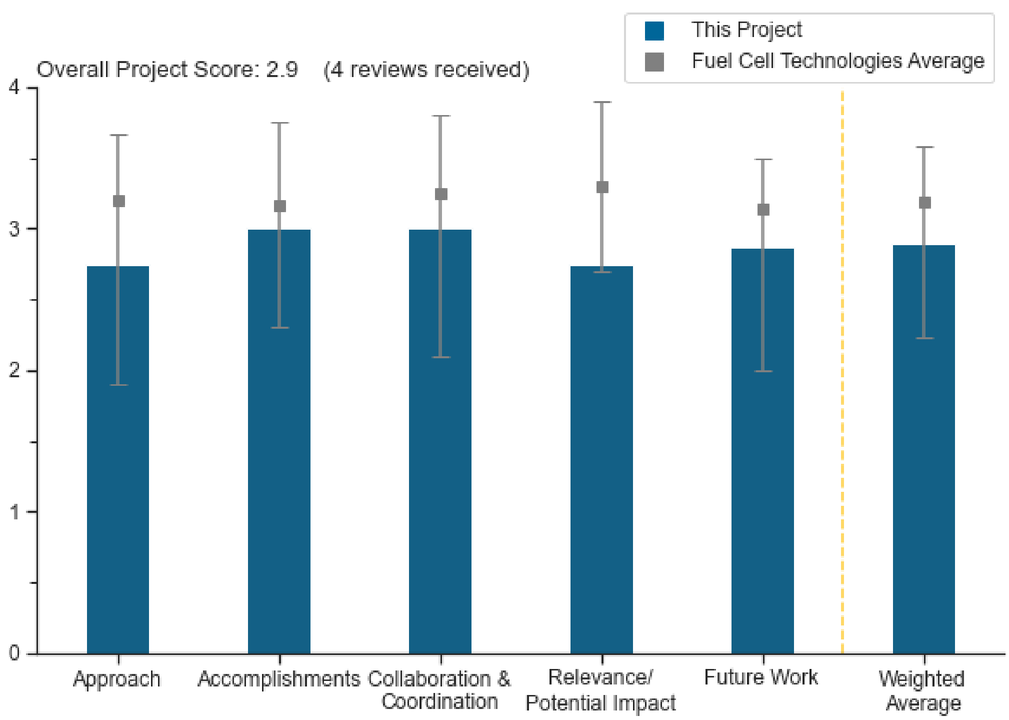
Nem Danilovic, Lawrence Berkeley National Laboratory

DOE Contract #	1.3.0.209
Start and End Dates	7/1/2019
Partners/Collaborators	Nel Hydrogen, Washington University in St. Louis, Ballard Power Systems, Pajarito Powder
Barriers Addressed	• No barriers specific to regenerative fuel cells • Optimization between fuel cell and electrolyzer barriers • Fuel cells (durability, cost, performance) • Hydrogen production (capital cost, system efficiency, and electricity cost)

Project Goal and Brief Summary

The main focus of this project is to demonstrate a highly efficient and stable unitized regenerative fuel cell (URFC) achieved through a novel membrane and supported electrocatalysts. The goal is to achieve 50% round-trip efficiency (RTE) utilizing advanced membranes and bifunctional oxygen evolution reaction/oxygen reduction reaction catalysts on engineered supports. Project tasks include (1) developing membrane/ionomer and catalyst supports, (2) integrating the membrane into a membrane electrode assembly (MEA) and integrating the bifunctional catalyst onto supports, (3) demonstrating MEA performance and durability in electrolysis testing, and (4) demonstrating MEA performance and durability in fuel cell testing.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **2.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach to move toward more fuel-cell-type materials should lead to increases in RTE. The use of a durability test cycling between fuel cell at ~0.55 V and electrolyzer at 1.55 V should provide an accelerated durability test and advance the field. The addition of work on the porous transport layer (PTL) should help improve performance, as modeling suggests mass transport losses at 1 A/cm^2 are due more to the PTL than to the catalyst layer. There is some question about the durability of the sulfonated poly[ether ether ketone] (SPEEK)-based membranes in electrolyzer operation, and it is not clear what steps are being investigated to improve chemical stability (whether the team is just relying on the base polymer, using current commercial additive packages such as CeO_2, or looking at other additives). Also, it appears membrane degradation testing has looked mainly at discrete mode. Longer durability testing of the membrane in electrolysis mode and cycling between electrolyzer mode and fuel cell mode should be a priority. The targeted current density of 1 A/cm^2 for both fuel cell and electrolyzer mode for the target efficiency seems arbitrary.
- The methods by which the team is investigating URFCs are reasonable; however, the approach is fairly broad, taking on essentially every component of the UFRC, from membranes to catalysts to PTLs to electrodes. This seems too broad a scope for such a limited budget, and it would have likely been more successful to focus on a smaller subset of components with the highest priority, for example, PTL and electrode strategies.
- This project primarily involves testing materials that are already developed, including commercially available materials, to find which combinations of materials give the best URFC performance and durability. The main materials/component development work is in the SPEEK membrane development. Catalyst support development is also mentioned, but no results were shown. Overall, there does not seem to be much novelty in the work being performed.
- The main weakness here lies in the way that the team has been designed, which naturally leads to mostly discrete testing of a fuel cell and then an electrolyzer. There is not much true URFC work here, and that is somewhat of an issue. Making the necessary sacrifices to enable both should be the root of a URFC project, and that is nowhere to be found here.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has demonstrated improvements in performance with supported Pt/Ir-TiO_2 and has achieved >50% RTE at 1 A/cm^2 (in oxygen). The project has met its milestones for 2021 and is on track to meet end-of-project targets. The project appears to have shifted some from catalyst support development to optimizing systems with commercial materials. It is not clear whether this is due to COVID-19 restrictions or whether doped TiO_2 materials being developed at Washington University in St. Louis showed poor promise. Development of an accelerated stress test (AST) matrix is an important advancement.
- The team's efforts with PTLs and electrodes have yielded good, useful results, but catalyst and membrane work has not shown any specific advances or progress. The investigation of constant gas versus constant electrode approaches are interesting and have shown some ability to increase RTE. The fuel cell conditions presented are a modest window of conditions that could be investigated and seem like they were run at very high stoichiometry, but it is not fully clear. A discussion of the fuel cell operating conditions presented and perhaps presenting how polarization changes as a function of conditions (stoichiometry and back pressure, in particular) would be insightful for overall operating considerations.
- The individual components seem to be performing well. Discrete systems are performing pretty well. Electrolyzer performance is greater than fuel cell performance, but both are fine. Sometimes, it is difficult to judge the accomplishments, as the cell set-up and conditions are often not given in the slides, making it hard to compare to what has been done before or to know whether the experiment done is practically relevant. It is not clear what the team means by "liquid water"—whether it is deionized water or a salt solution, as both would be "liquid water." Durability data are of very limited duration. Practical durability data should be at least 100 hours long.

- Some progress on SPEEK membrane development was reported, but this does not seem to enable a significant benefit for URFC technology. The down-selected membrane is a commercially available perfluorosulfonic acid membrane. Some work was performed on development of novel catalysts for URFCs, but no new results were shown this year. Instead, the catalyst work in the project seems to be focusing on comparing performance of commercially available catalysts. AST development was mentioned, but data are needed to demonstrate that the developed ASTs mimic real-world degradation modes.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- Collaborations within the project appear to be working well.
- The different collaborators all have well-defined roles and have experience in their support areas. The primary concern would be how broad the effort is and how effective the collaborations are. For the membrane synthesis and catalyst development tasks, there seems to be limited synergy with the more general UFRC fabrication and testing tasks.
- The team makes sense and is capable. It seems somewhat less desirable to have one institution on fuel cells (Ballard) and the other on electrolyzers (Nel Hydrogen). It would seem that this would lead to a bifurcated design for the electrodes, which cannot be present in a real URFC. This arrangement also leads to discrete testing dominating, which it obviously has. There is also not much catalyst work mentioned here. It is unclear what Pajarito Powder has done in this particular update.
- The team consists of several of the key players in URFCs. It is a capable team, but in some cases, it is hard to see how the team members are contributing to research and development (R&D). For instance, Nel Hydrogen and Ballard seem to be mainly testing commercially available membranes and catalysts to select the best materials. DOE-funded work should focus more on developing the science or developing new materials and less on screening commercial materials.

Question 4: Relevance/potential impact

This project was rated **2.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is in alignment with Hydrogen and Fuel Cell Technologies Office goals and objectives. Improving URFC performance and efficiency will result in increased utility of hydrogen storage as an energy storage option.
- The project seems to be addressing relevant objectives and needs.
- A more science-based approach would make this project more relevant and increase the potential for significant impact.
- Reversible fuel cells do not have well-defined targets, and oftentimes the primary competition for UFRCs would be independent fuel cell and electrolysis stacks. It is far from clear, and perhaps doubtful, that UFRCs will have application in anything beyond a few niche applications, although this is much less a comment on this specific project rather than the area of UFRCs in general. However, science outcomes still have potential value in the fuel cell and/or the electrolysis areas.

Question 5: Proposed future work

This project was rated **2.9** for effective and logical planning.

- Proposed future work addresses most of the challenges for URFCs. Concerns about the durability of the SPEEK-based membranes in electrolyzer operation and how it may handle the humidity changes in reversible mode need to be answered. Longer durability testing of the membrane in electrolysis mode and cycling between electrolyzer mode and fuel cell mode should be a priority.

- As the project is in its late stages, the proposed work is reasonable, but some areas, such as the further development or implementation of membranes and catalysts, seem unlikely to have much chance of meaningful outcomes.
- The proposed future work seems well-planned, but it involves too much demonstration and not enough R&D.
- It seems like the project would really benefit from switching to operating most of the time as a URFC, not discrete systems.

Project strengths:

- There is a strong team, a good principal investigator, and interesting science. The project addresses some gaps in the scientific community. The highest value is in the area of PTLs and in some of the electrode areas, particularly with constant electrode and constant gas comparisons of operating strategies.
- The team's experience in fuel cells and electrolyzers, with Nel Hydrogen and Ballard as partners, is a major strength.
- The team includes many of the key players in URFCs.
- There is a good team. It is making progress toward goals.

Project weaknesses:

- While hydrocarbon implementation in electrolyzers is an interesting area for research and would be great if achieved, the amount of effort in this project seems subcritical and a distraction from other topic areas. The late addition of catalyst development also seems like it serves to distract from the other, more fruitful, areas of investigation in the project. The project really is focused only on performance and not on durability at this point in time, and while this makes sense based on resources, it leaves significant gaps in what is likely the key area for devices.
- The work reported in the past year and the planned future work involve too much screening of existing materials and not enough novel R&D.
- The project is too focused on discrete tests. Experiments are pretty short-term. AST might work fine, but it is unclear whether it is really the correct one.
- Membrane durability aspects do not appear to be receiving the focus they require.

Recommendations for additions/deletions to project scope:

- Extensive work has already been performed on development of polymer electrolyte membranes for fuel cell applications. While there could be room for improvement in membranes, specifically for URFCs, the opportunities for improvements in catalysts and diffusion media are far greater, so it would be better to focus more resources on catalysts and diffusion media and fewer resources on membranes. The work scope associated with screening commercial materials should be reduced.
- The project should be more URFC-focused. It would be good to actually show that the AST is giving relevant information or information that is indicative of how a URFC might respond.
- It is recommended that the project increase work on membrane durability issues.
- With the project only months away from completion, there is not much time to coordinate large changes in scope across the team, but membranes, in particular reinforced membranes, seem to be an area that does not merit further investigation. Catalyst efforts also seem tangential at this point.

Project #FC-314: Efficient Reversible Operation and Stability of Novel Solid Oxide Cells

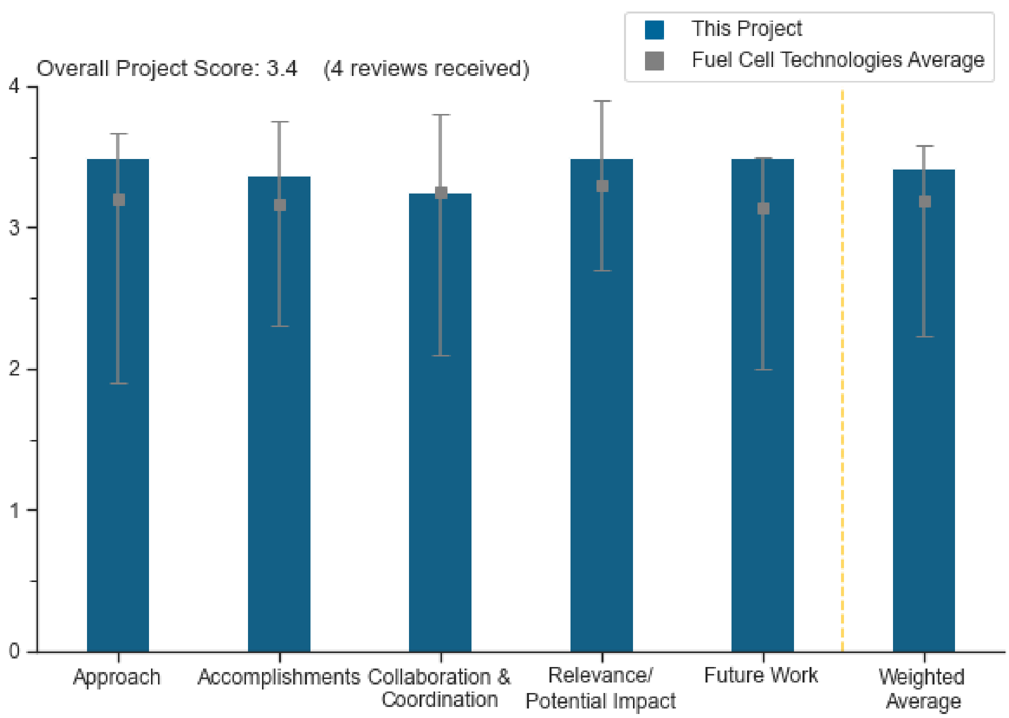
Scott Barnett, Northwestern University

DOE Contract #	DE-EE0008437
Start and End Dates	10/01/18 to 09/31/21
Partners/Collaborators	Colorado School of Mines
Barriers Addressed	• Durability • Performance

Project Goal and Brief Summary

This project will develop and test reversible solid oxide fuel cells (RSOFCs) for electrical energy storage applications, including system concepts for high efficiency. The RSOFCs will be designed to operate efficiently and durably in both fuel cell and electrolyzer modes. The project approach employs novel high-temperature cells with the potential for high power density, long-term stability, and high round-trip efficiency. The RSOFCs will be designed to achieve the low area-specific resistance (ASR <0.15 Ωcm^2) required for high round-trip efficiency at high current density (>1 A/cm^2). One focus is on durability improvement via a combination of materials development, mechanistic degradation model development, and accelerated stress testing to determine the factors that affect long-term stability, including reversible operation cycles. Multiple cell designs will be investigated. The team will also fabricate and test large-area cells and determine the effects of pressurized testing. System modeling (system concept development and technoeconomic analysis) will inform designs that can achieve cost and efficiency targets for renewable electricity storage.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project is set to develop RSOFCs with high current density, good long-term stability, and high round-trip efficiency. The project will also integrate experiments with system modeling and technoeconomic analysis to provide early feasibility evaluation. These approaches are unique and are critical to ensure that the project goals can be met.
- The pressure effect study was performed on the oxygen electrode side. In practice, pressurizing the hydrogen electrode side is equally important, considering the hydrogen pressurization for downstream storage. Therefore, this portion of the study can be considered in the future. Additionally, the positive effect of gadolinium-doped ceria (GDC) infiltration into the hydrogen electrode microstructure is interesting. A further mechanistic study is deserved. Finally, the need for thermal energy storage can be further discussed for the case of above-thermal-neutral operation.
- The project approach addresses the following key technical barriers: (1) development of RSOFCs allowing high round-trip efficiency, (2) ASR <0.15 Ωcm^2 (achieved in fiscal year 2020), (3) life testing of reversible operation to establish long-term stability, and (4) a reduced degradation rate of ≤6%/kh at 0.75 A cm^{-2}.
- This is a very sound approach.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- This project has made excellent progress; reversible cells were fabricated and tested to show reduced degradation, and a large-area-cell test facility was set up and successfully used to test solid oxide cells with 80 cm^2 active areas.
- The project has good results. However, a solid oxide electrolyzer (SOE) typically operates at around 1.3 V, which is the thermo-neutral point. The V-I (voltage–current density) curve in electrolysis mode should be extended at least up to this point. Likewise, the degradation data at 0.5 A/cm^2 should be increased to higher currents to operate at 1.25–1.3 V. Cell performance is very impressive.
- The project and milestones have progressed well, and go/no-go decision points have been met.
- The progress toward milestones is on track.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The project is led by Northwestern University (NU), with Colorado School of Mines (CSM) as the subcontractor. NU is conducting the experimental work, while CSM is leading the stack and system modeling and technoeconomic analysis. NU provides experimentally measured cell characteristics as input to CSM stack and system models, allowing for accurate prediction of expected system characteristics, while CSM provides input to NU regarding desired cell characteristics and operating parameters, ensuring that test results are relevant.
- NU provides experimentally measured cell characteristics as inputs to CSM stack and system models, allowing for accurate prediction of expected system characteristics. CSM provides input to NU regarding desired cell characteristics and operating parameters, ensuring that test results are relevant.
- The project is a collaboration between NU and CSM, with the former working on experimental and the latter working on theoretical analysis. Both are making good progress toward milestones.
- It would be better to have some industrial partner(s) collaborate on an advisory level.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Developing RSOFCs with high round-trip efficiency and long-term stability will provide an enabling technology for electrical energy storage. GDC infiltration into nickel–yttria-stabilized zirconia (Ni-YSZ) fuel electrodes has been shown to improve cell stability. Oxygen electrode performance under pressurization has been characterized and fully modeled, a large-area-cell test set-up has been assembled and fully vetted, and it will provide a unique testbed for observing effects of RSOFC operation.
- Developing RSOFCs for electrical energy storage with high (60%–90%) round-trip efficiency at ~ 1 A cm^{-2} is a very important part of hydrogen production and storage.
- Some good progress has been achieved on small-cell characterization, while long-term stability needs to be further demonstrated, especially on large-area cells.
- This project is very relevant to improving performance and reducing cost of SOE technology.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The proposed future work is on target, as it aims to further its studies of RSOFC degradation rates and mechanisms, develop procedures for electrode infiltration of large-area cells yielding uniformly low ASR, and continue to refine electrochemical model calibration as additional pressurized cell and 80 cm^2 cell experimental data become available.
- Further work is aimed at identifying main degradation mechanisms, developing preliminary models for both button cell and large-area single-cell tests, and developing procedures for electrode infiltration of large-area cells to yield uniformly low ASR. These studies are essential to developing efficient and durable RSOFCs for energy conversion and storage applications.
- The principal investigators clearly recognize the challenges of the project and have planned well to address them in the coming year.
- Further cell studies at even higher current densities and a stack demonstration are suggested.

Project strengths:

- This is a well-coordinated project with an integration of experimental and modeling efforts to address the critical barriers in RSOFCs for energy conversion and storage. Solid progress has been made, and the project milestones have been met.
- This project combines experimental and theoretical strengths of the two institutions to address the issues of RSOFCs. The two approaches could potentially converge to provide key engineering information to implement in solid oxide cell systems.
- The project is addressing the following key Hydrogen Program technical barriers: (1) development of solid oxide cells allowing high round-trip efficiency, (2) ASR <0.15 Ωcm^2, (3) life testing of reversible operation to establish long-term stability, and (4) a reduced degradation rate of ≤6%/kh at 0.75 A cm^{-2}.
- There is a great focus on cell performance and degradation. This cell can potentially reduce overall SOE system costs if it can operate at 1–1.5 A/cm^2.

Project weaknesses:

- GDC infiltration into Ni-YSZ has been shown to improve cell performance and durability; however, how to implement this approach for the stack fabrication should be identified and validated.
- The hydrogen storage tank model that is included with additional compressors and intercoolers does not seem well-defined. There is also the question of whether the high pressure will cause any potential problems for the cells during operation.

- The project needs more work on the DOE target current densities of 1–1.5 A/cm^2, with operations at 1.3 V.
- The long-term stability of cells needs to be further demonstrated to meet the cost goal.

Recommendations for additions/deletions to project scope:

- The project scope is well-defined, and no changes are necessary.
- It would be good to see a degradation/performance of at least 1.0 A/cm^2 operating point. The maximum round-trip efficiency is at 0.78 A/cm^2, and the total cost of ownership will also improve with higher operating currents.
- It is recommended that the hydrogen storage tank model be included with additional compressors and intercoolers. Information is needed about the desired properties, such as the volume and the pressure for hydrogen storage; the compressors and intercoolers; and the properties required for the compressors.
- Studying degradation mechanisms should be considered in the remainder of the project.

Project #FC-316: Durable, High-Performance Unitized Reversible Fuel Cells Based on Proton Conductors

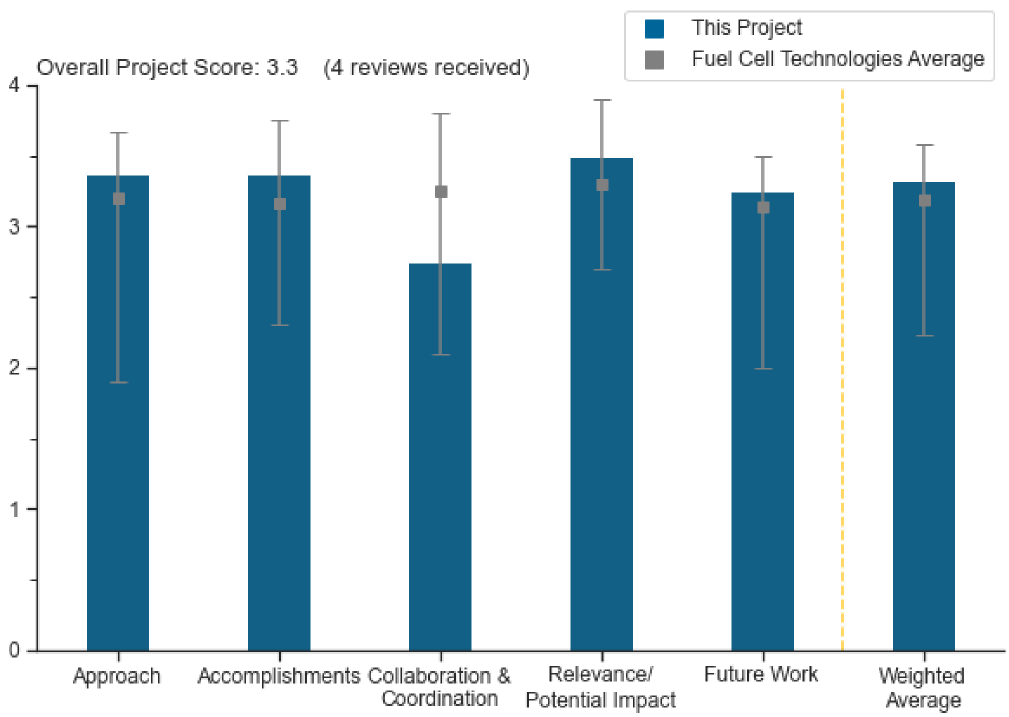
Meilin Liu, Georgia Institute of Technology

DOE Contract #	DE-EE0008439
Start and End Dates	1/1/2019 to 12/31/2021
Partners/Collaborators	N/A
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Operations and maintenance

Project Goal and Brief Summary

This project is developing a robust, highly efficient, and economically viable high-temperature unitized reversible fuel cell based on proton conductors for large-scale, co-located energy storage and power generation. Project activities focus on two main areas: (1) gaining better understanding of the degradation mechanism of cell and stack materials and interfaces, using various in situ, ex situ, and operando measurements guided by theoretical analysis; and (2) integrating nanostructured components into the cell design and interfaces between electrodes and electrolyte, which will be modified with active bi-functional catalysts and protection coatings to achieve >70% round-trip efficiency at 1 A/cm^2 in both operating modes.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is quite logical and orderly: (1) synthesize the electrode and electrolyte materials with desired particle size and morphology, (2) fabricate symmetrical cells and single cells, and (3) integrate nanostructured components into the cell design, and modify the electrodes with active bifunctional catalysts and protection coatings in single cells to achieve >70% round-trip efficiency.
- The project studies proton-conducting perovskites as key materials for intermediate-temperature solid-oxide-cell-based water electrolysis. Perovskite proton conductors allow the use of highly active perovskite oxygen electrodes, which ultimately elevate the overall performance and reduce the operating temperature. The demonstrated area-specific resistance (ASR) is very low for the temperature range studied, which is promising for achieving the cost and efficiency goals.
- Very good materials science is being performed in this project. Improved materials and a novel barrier layer approach have been developed to improve resistance to steam, while improving solid oxide electrolyzer cell performance, efficiency, and durability. Significant improvements have been demonstrated as materials formulations have been adapted. The work has led to performance levels that are at or exceed the state of the art. That said, it is a matter of question as to whether it is meaningful to measure round-trip efficiencies via testing at low reaction utilizations and whether button cell testing is the best way to assess durability, given that reactant utilization is extremely low and a number of important degradation mechanisms can occur at higher utilizations.
- Some aspects of stability and durability of this concept have been discussed in the slides and presentation (e.g., see slide 11). However, it is not very clear how this project addresses other aspects, such as mechanical durability related to operating condition changes (such as relative humidity changes after changing the operation mode) and chemical durability, focusing in particular on the many interfaces present. Perhaps the team could elaborate on how these durability aspects are considered.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The principal investigator (PI) is making good progress toward achieving round-trip efficiency and degradation rate on small button cells. Some density functional theory calculations have also been done to facilitate the understanding of the enhanced catalytic activity.
- The Georgia Institute of Technology (Georgia Tech) had significant accomplishments. The team completed a baseline study of air electrodes (ASR=0.02–0.03 Ω cm^2 under a bias of +0.2 V at 700°C with a durability test of 200 hours), developed fuel electrodes/catalysts with electrode polarization <0.07 V at 1 A cm^{-2}, and demonstrated 200-hour continuous operation of single cells at ≤700°C with >60% round-trip efficiency at 1 A cm^{-2} in both modes with a degradation rate of <2% per 500 hours.
- Very high-performance levels have been demonstrated, with reasonable stability at operating temperatures. Performance, durability, and faradaic efficiency levels still need to be improved at lower operating temperatures that are being targeted, but there is reason to believe that these improvements are possible. The characterization and analysis techniques being employed provide significant insights that will be leveraged in the future development of protonic ceramic electrolytes.
- It would be helpful to understand why the last milestone (>500 hours for a 1-inch button cell with <2% degradation, etc.) was chosen. Perhaps this will help in gaining fundamental understanding of the degradation mechanisms for this concept. If so, information about the type of characterization tools and methods used is also requested.

Question 3: Collaboration and coordination

This project was rated **2.8** for its engagement with and coordination of project partners and interaction with other entities.

- This is a collaborative project between Georgia Tech, Idaho National Laboratory (INL), and Phillips 66. The role of Georgia Tech is to develop materials sets, INL is to validate the metrics, and Phillips 66 is to develop a fabrication process and prototype.
- This project's partners for implementation include INL for validation of efficiency measurements and Phillips 66 for development of fabrication processes and prototype.
- This is a single-organization project. Collaborations with INL and Phillips 66 were mentioned, but no evidence (data) of any collaboration was presented. For example, if INL is validating performance levels that have been achieved at Georgia Tech, then it would have been useful to present comparative data. If Phillips 66 has been collaborating to scale up the fabrication to larger cell areas, then photographs of large cells could have been presented.
- It is not clear if and when the partners mentioned in slide 17 have been or will be involved in the implementation.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Proton-conducting solid oxide cells (SOCs) have the potential to operate at a 500°C–600°C range and, thus, to reduce cost and improve durability of SOC systems. However, some critical challenges need to be addressed before scaled-up demonstrations. The project addresses some of the challenges, such as oxygen electrode performance, which will contribute to the overall development of the technology. Other engineering challenges, such as electronic leakage, mechanical strength, and chemical reactivity of proton-conducting perovskites, will have to be addressed in the future.
- Development of reversible SOCs to achieve >70% round-trip efficiency at 1 A cm^{-2} in both solid oxide fuel cell mode and solid oxide electrolysis cell mode is a key element of DOE's energy production and storage targets.
- Excellent materials science is being performed on this project, and the performance and durability of protonic ceramic fuel cells and electrolyzers have been advanced. The work needs to be extended to larger cell areas and higher reactant utilizations before the potential impact of these new materials can be fully assessed.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The proposed future work is targeted to a successful completion. Georgia Tech will make efforts to understand electronic conducting behavior of $BaZr_{0.1}Ce_{0.7}Y_{0.1}Yb_{0.1}O_{3-\delta}$ (BZCYYb)-based electrolytes through conductivity and transference number measurements. The project will also develop new strategies to improve faradic efficiency, including optimization of operating conditions and development of new electrolyte materials with low electronic conductivity. The team will fabricate single cells with desired electrolyte, electrode, and catalyst coatings and run long-term stability tests.
- The PI has identified a key issue of electron leakage through the Ce-containing, proton-conducting perovskite electrolytes used by the project, and addressing this issue is proposed for future work. It is important work to be studied. It will be interesting to see whether the proposed barrier layer will lower the performance.
- The proposed future work does not clearly show how the remaining milestones, related to lower-temperature performance and durability, will be achieved. Larger-area single-cell testing with higher reactant utilizations will help assess the true status of the technology being developed and could provide a decent capstone to the project in its final project year.

Project strengths:

- Georgia Tech had the following significant accomplishments: (1) completed a baseline study of air electrodes (ASR=0.02–0.03 Ω cm^2 under a bias of +0.2 V at 700°C with a durability test of 200 hours), (2) developed fuel electrodes/catalysts with electrode polarization <0.07 V at 1 A cm^{-2}, and (3) demonstrated 200-hour continuous operation of single cells at ≤700°C with >60% round-trip efficiency at 1 A cm^{-2} in both modes, with a degradation rate of <2% per 500 hours.
- There are several characterization methodologies, leading to good understanding of the enhancement mechanisms. From a pure electrocatalytic activity perspective, the achieved ASR is a promising indicator for the materials studied.
- This project has excellent materials science with new materials and approaches, as well as state-of-the-art characterization and analysis techniques.
- The project focuses on a concept that has very high potential for advancement toward the DOE Hydrogen Program goals.

Project weaknesses:

- No progress is reported on developing large cells at Phillips 66. The reported results were all from small button cells. The thermal stability of the catalyst $BaCoO_3$ (BCO) is unknown. In general, BCO is not stable at elevated temperatures because of the loss of oxygen, forming less active brownmillerite or other BaCo-related oxides. The calculation of faradaic efficiency needs further examination, as it requires the analysis of hydrogen produced. The presentation did not elaborate on whether this is the case.
- The approach chooses to demonstrate certain durability targets (the milestones in slide 6) but could focus more on gaining fundamental understanding of possible failure modes and limitations associated with the materials selected/developed.
- There is an over-reliance on button cell testing (low reactant utilizations) for performance and durability demonstrations.

Recommendations for additions/deletions to project scope:

- There may not be sufficient resources available, but larger-area single-cell testing with meaningful reactant utilizations would provide a better assessment of where the technology stands.
- The project’s future work should cover the most pressing work.
- The team should continue the planned project effort.

Project #FC-317: Stationary Direct Methanol Fuel Cells Using Pure Methanol

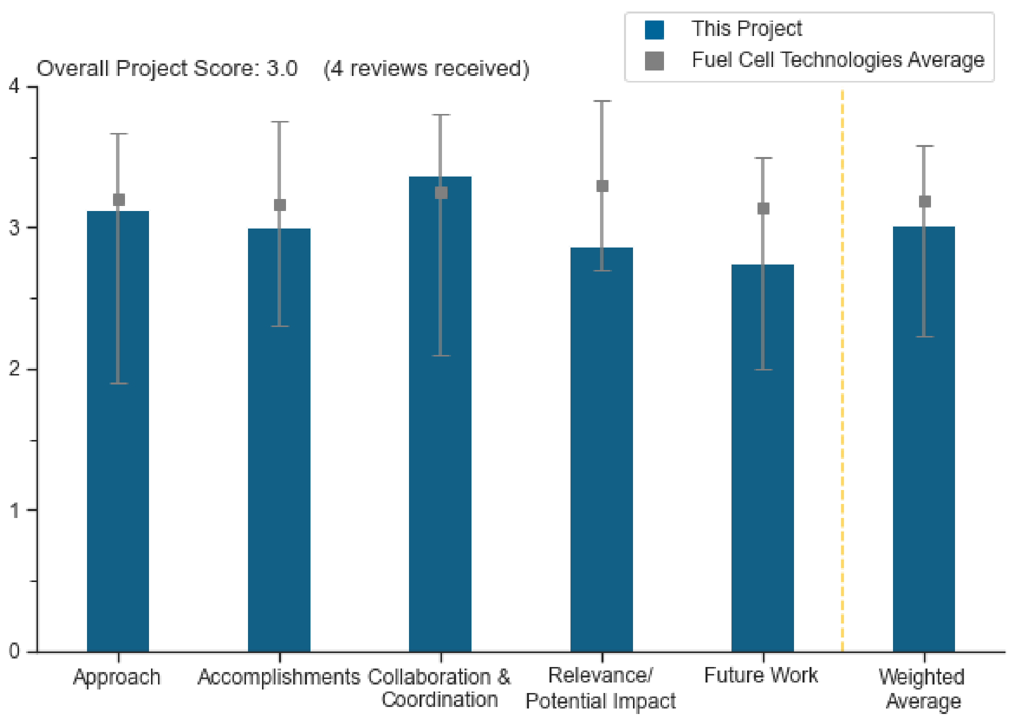
Xianglin Li, University of Kansas

DOE Contract #	DE-EE0008440
Start and End Dates	10/1/2018 to 3/31/2022
Partners/Collaborators	Kansas State University, University of Buffalo, Carnegie Mellon University
Barriers Addressed	• High platinum-group-metal catalyst loading • Catalyst poisoning by methanol • High fuel crossover

Project Goal and Brief Summary

The project goal is to develop stationary direct methanol fuel cells (DMFCs) using pure methanol as the fuel. The project will address three critical challenges from material to system levels: (1) reduce noble catalyst loading and cost, (2) enhance cathode tolerance of methanol poisoning, and (3) decrease methanol crossover. The end-of-project goal is to deliver a 50 cm^2 membrane electrode assembly (MEA) and prototype that produces peak power density of $\geq$300 mW/cm^2 with total loading of $\leq$3 $mgPGM/cm^2$. The project addresses the barriers of high-platinum-group-metal (high-PGM) catalyst loading, catalyst poisoning by methanol, and high fuel crossover.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach systematically builds on the expertise of four universities, with each university addressing a specific component. This type of project and this type of approach are usually difficult to complete because of the separation of the four research laboratories. The milestone status on chart 5 demonstrates that these four universities were able to coordinate their efforts, contribute their expertise, and successfully complete the milestones in the fifth through eighth quarters.
- Several advances in DMFCs are highlighted in this project. The non-PGM catalyst from the University of Buffalo appears to be an extension of the university's existing catalyst work into a new field, which is reasonable. MEA data is presented for this part of the project and appear to meet targets. It is less clear what the targets for the "ultra-low PtRu anode catalyst" are, and there is no discussion of what scale is necessary for MEA integration or the schedule for it. The electrode work at Carnegie Mellon comprises state-of-the-art techniques, but the MEA performance is one-third that of other partners, and it is unclear whether learnings will be meaningful. Modeling appears to be effective for understanding future materials development needs.
- Overall, it seems to be a good approach in terms of developing active anode catalysts and methanol-tolerant cathode catalysts. There has been no result demonstrating mitigation of methanol crossover, as such. The authors have proposed the idea of fabricating a graphene-based methanol crossover barrier layer.
- The project is broad, taking on many aspects of DMFC performance improvement, including anode and cathode catalyst development, electrode fabrication, and mass transfer considerations. The project is focused primarily on performance metrics but does not quantify all loss metrics, such as methanol crossover or parasitic power/water requirements, and does not address durability at all, which is certainly the most difficult hurdle in terms of making DMFCs relevant.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project exceeded the target performance while maintaining the PGM at the targeted level. Chart 6 shows the project surpassed literature-reported DMFCs with PGM-free cathodes. The chart was difficult to read because of the overlap of the performance and the target. The authors report that the air flow rate and the pressure are higher than the proposed operating conditions. The proposed operating conditions were not shown in the first 14 charts. The results indicate DMFC lifecycle cost approached the polymer electrolyte membrane fuel cell (PEMFC) target for Class III forklifts, and for Classes I, II, and III, the fuel cost is less. The research team claims DMFC has lower infrastructure costs; however, this does not appear to be consistent with chart 7; this should be explained. The researchers report Pt/Ru/TiO_2/O-NCNTs (nitrogen-doped carbon nanotubes with open-ended channels) have greater current density than commercial PtRu/C catalysts, but the experimental conditions were not reported. It is unclear at what voltage these data were collected. In chart 8, the Johnson Matthey (JM) PtRu/C has a greater mass activity than the Pt/Ru/TiO_2/O-NCNTs. Why the Pt/Ru/TiO_2/O-NCNTs have a greater current density, as claimed in Chart 9, could be better explained. It is unclear whether the sensitivity of the MEA in chart 10 to applied back pressure is unique to the MEA or cathode. If a platinum or platinum alloy catalyst on carbon replaced the PGM-free catalyst, it is unclear whether the same dependence on back pressure would be observed. It would be helpful to know if the back pressure dependence is a product of the MEA design. In chart 11, the researchers report that "additional spray in [gas diffusion electrode] offsets the ohmic loss." This raises questions as to whether:
    - The additional spray changed the catalyst loading
    - The porosity, particle size distribution, and pore size distribution of the catalyst layers fabricated by different methods were considered when comparing spray versus blade coating
    - Spray or blade coating produces the same wettability of the MEA components.

- It is unclear what methods were used to measure the capillary pressure. For two-phase flow, the contact angle is unknown. The conclusion seems correct. The project needs to explain the shape factor from chart 14.
- The go/no-go milestone has been achieved for power density at a given PGM loading. Synthesized anode durability targets in milestone M6 have not been reached or do not appear to have even been started/ discussed.
- Within any given area investigated, the progress is reasonable, although not notable in terms of achieving commercial relevance. The cell performance is good but not remarkable and requires very high temperatures that would lead to significant methanol evaporation losses at the cathode and environmental concerns. The anode catalyst development is struggling to meet quantities for 50 cm^2 testing when the target should be how to synthesize kilogram quantities or hundreds of square meters of MEAs.
- The project demonstrated the achievement of ~250 mW/cm^2 peak power density. However, it is not clear which material, process, or MEA testing operating condition developed as part of the project led to this improvement. Both the PtRu-based anode catalyst and non-PGM-based cathode catalyst are known in the literature. No specific improvement to the catalyst structure that would lead to activity improvement is demonstrated. Therefore, it is not clear why these two known catalysts would lead to higher power densities (approximately five times better than those reported in the literature). Methanol–air polarization curves demonstrated in this project still show a big drop in cell voltage (~150 mV at < 25 mA/cm^2), indicating that the anode kinetics and methanol crossover are still the major limiting factors in performance. Therefore, it is not clear what tangible benefits these new anode and cathode catalysts provided. Using peak current density and peak power density could be misleading in judging catalyst behavior. Also, the beginning-of-life performance is shown at high temperatures of 99.8°C and 300 kPa. Sustaining performance at these conditions is highly unlikely because of durability concerns. Better understanding of the catalyst kinetics and methanol crossover is required.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- The structure of this project was based on collaboration and coordination, with three team members providing outstanding results. The research collaboration was similarly outstanding. It would be great if more collaborative projects worked this well.
- The team is good, with diverse capabilities to focus on individual aspects of methanol fuel cell development.
- The demonstrated collaboration in this project is excellent. Bringing in a diverse set of collaborators magnifies the impact, and the collaborators chosen are preeminent scientists in the field. While there is reported contribution from all parties, it is not clear that the collaborators are intimately integrated in terms of materials-sharing.
- The team includes four universities, each with defined roles, but there are no industrial entities to move the project forward or a system designer that could commercialize DMFCs. This is likely due to the limited interest/viability of DMFCs in different markets.

Question 4: Relevance/potential impact

This project was rated **2.9** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The research reduced the noble catalyst cost for DMFCs and enhanced the cathode tolerance of methanol poisoning (already known for non-PGM catalysts, but the project results were very good). The researchers claim a decrease of the methanol crossover, but it is unclear what they did (on purpose) to achieve this. The results are good enough to move on to durability testing and stack testing.
- The technoeconomic analysis is questionable. It appears to assume significant cost reductions in the DMFC technology while allocating no similar optimism to reducing the cost of hydrogen in PEMFC technology, which is clearly one of DOE’s primary focuses. Given that DOE’s focus for fuel cell applications has

moved to the heavy-duty truck, this forklift-/drone-focused project may not fit in the mainstream of efforts. However, small efforts over a broader range of applications seem worthwhile, and the demonstrated expertise is valuable.

- This research is likely to have only indirect impacts on any DOE Hydrogen Program objectives or in the marketplace.

Question 5: Proposed future work

This project was rated **2.8** for effective and logical planning.

- Perhaps one of the team members could attempt to do a voltage loss breakdown analysis to understand the contribution of losses from anode kinetics, cathode kinetics, methanol crossover, transport losses, etc. This would better guide the team to put priorities on challenges to solve. The project should focus on mitigating methanol crossover, fuel and water management, durability, and better understanding of the anode kinetics needed.
- The reviewer agrees with the planned resolution on chart 17. What is missing is the stack testing; durability and decay testing of a 10-cell stack with 50 cm^2 active area per cell is necessary, along with start/stop testing. If this system is proposed for forklift trucks, operation at sub-zero temperatures will be required.
- Graphene-coated membranes have been attempted in a European project (DOLPHIN) and have not produced promising results. Blocking water essentially blocks proton transport, as the proton exists as a hydronium ion in fuel cell transport. It is not clear that there is any proposed work to utilize the synthesized anode catalyst in an MEA, as all MEA data appear to use JM PtRu and no indication of scale-up/utilization is present. Integration of all efforts should be explicitly incorporated in Year 3.
- The proposed future work is limited and not particularly compelling. The membrane work with graphene and polymer coatings is completely disconnected from the current project and serves only to further broaden an already overly broad approach to addressing meaningful advances in the DMFC space.

Project strengths:

- The overall strength is the assembly of very competent researchers who have the ability to collaborate and coordinate a very complex fuel cell research and development task. The performance has emphasized research in this effort.
- This is a broad, collaborative approach that comprises relevant experts to drive the DMFC field forward. Most milestones have been achieved, even with the tough working environment of 2020. Integration of modeling efforts informs future materials development outside the scope of the project.
- This is a good team with diverse capabilities to focus on individual aspects of methanol fuel cell development. There is good progress on the development of methanol-tolerant cathode non-PGM catalysts.
- DMFCs have been largely ignored in the research community, and it is good to have some presence in this space. Broad academic engagement may be a cost-efficient way to maintain some footprint.

Project weaknesses:

- It appears that the team members have focused on meeting the peak power density targets, which is good, but that has been achieved largely by operating the MEA at very high temperatures of ~100°C and high back pressures of 300 kPa. Such extreme conditions might momentarily help achieve the beginning-of-life performance targets. However, the relevance of these conditions for real-life operation is questionable. Also, no quantitative information is available on the major limiting factors of beginning-of-life performance to better guide research priorities. No progress has been reported toward decreasing methanol crossover or toward demonstrating durability.
- The future work is focused on making the MEA and MEA components better, which is good; however, the results are good enough for addressing the next level of complexity—stack testing and real-life operation. The reviewer agrees with the proposed future work and attacking the identified barriers.
- No emphasis on durability is a weakness, and the lack of component integration makes the good collaboration appear more siloed than it should be.

- The project is overly broad and not deep enough to have significant advances arise. The team lacks any sort of commercialization presence or a compelling case of commercial viability or interest.

Recommendations for additions/deletions to project scope:

- The researchers should identify a DMFC manufacturer or a test facility experienced in durability and stress testing of stacks as a testing collaborator.
- An assessment of durability should be present in Year 3, even if the stated focus is on beginning-of-life power.
- Rescoping will be difficult, but not expanding the project to include the membrane parts would make sense.

Project #FC-319: Low-Cost Gas Diffusion Layer Materials and Treatments for Durable High-Performance Polymer Electrolyte Membrane Fuel Cells

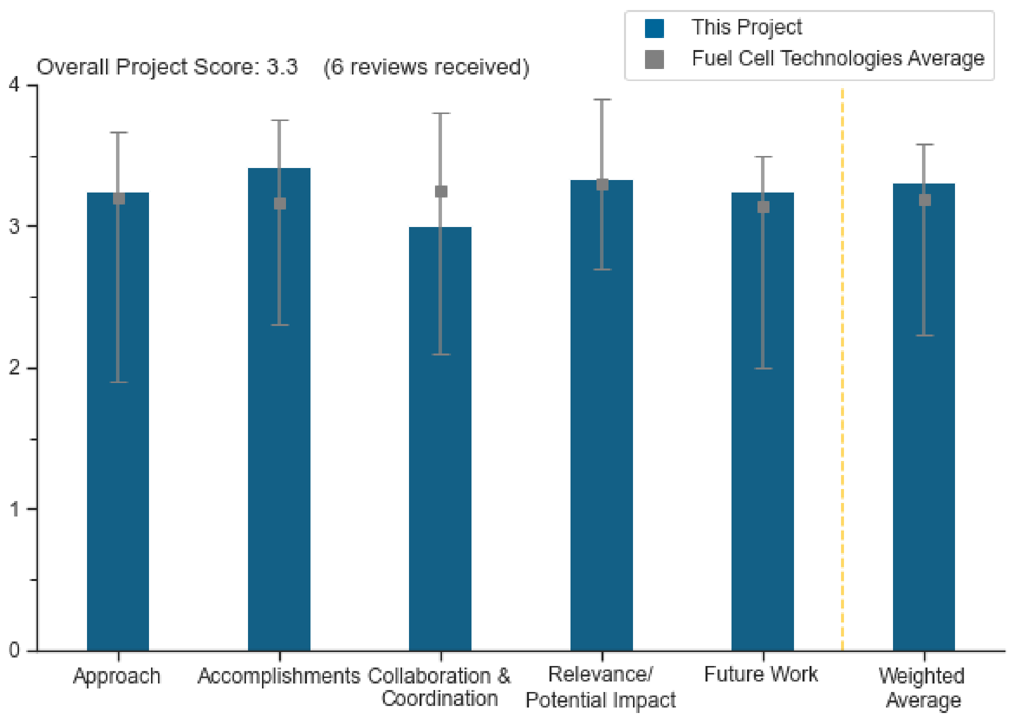
Rod Borup, Los Alamos National Laboratory

DOE Contract #	1.3.0.400
Start and End Dates	10/1/2018
Partners/Collaborators	Oak Ridge National Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Cost: $14/kW$_{net}$ membrane electrode assembly • Cost: Use of low-cost materials and reduced processing costs • Performance: Mitigation of transport losses through improved water management

Project Goal and Brief Summary

The objective of this project is to reduce the cost of gas diffusion layer (GDL) materials and improve GDL performance. To reduce GDL cost, the project will use low-cost fibers, use lower carbonization temperatures to reduce processing costs, and develop low-cost gas phase surface treatments to replace Teflon™ treatments, thereby lowering manufacturing costs. GDL performance will be enhanced through improved water management. The project will develop super-hydrophobicity coatings, which will prevent water flooding and transport losses, and incorporate hydrophilic pathways separate from hydrophobic domains to provide a pathway for water removal.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Gas diffusion media have been overlooked by the research community, yet they are a very crucial part of fuel cell systems and need to be looked at more deeply. This is a good approach to looking at an alternative way to make low-cost gas diffusion media. It has merit. The project is looking at reducing cost and improving performance, i.e., adding value to a component that is already in the market. This is a good, sound strategy.
- The project aims at developing new materials and manufacturing methods based on existing fabrics. This is an innovative approach, and the consortium has shown itself to be capable of investigating this approach to the required degree. The approach to researching the suitability of different fabrics for use as GDLs is screening. This is an adequate approach. The consortium is composed of purely academic entities. It is a pity that it was not possible to have a GDL manufacturer participate, as this would have been of great benefit to the project. It is important to notice, though, that the consortium has made efforts to include GDL suppliers.
- The concept of using paper or cloth as a GDL precursor is a good one—so good that it is surprising that microporous layer (MPL) vendors have not already given it a try. Nonetheless, this is a strong effort for a national laboratory team. The potential for elimination of binders and additional pyrolysis is compelling. It would have been good to see a more metric-driven approach, with a spider diagram comparing natural material MPLs to the state of the art. There were metrics distributed throughout but no big-picture summation metrics. Durability is likely to be important, and accelerated testing is recommended to generate faster results with fewer problems. Carbon, hydrogen, and nitrogen (CHN) analysis, or some other structural assay, may help explain variations in hydrophilicity.
- It is good to see a focus on utilizing raw materials that have lower carbon footprints and make the fuel cell technology more cost-competitive.
- The proposed approach—considering materials and processing concurrently to significantly reduce GDL cost while raising performance—appears relevant. Durability aspects should not be forgotten as potential environmental impacts in the process change.
- The project is interesting in its use of so many different natural fiber types. It is not clear whether there are any concerns about the presence of environmental contaminants (trace pesticides, heavy metals, etc.) in the GDLs or whether there is confidence that the processing steps will eliminate the residual trace elements. There is an elemental composition on slide 36, but it is difficult to read. It is unclear whether the team is looking into possible variation in composition due to raw materials from different locations.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The work is definitely within the scope of DOE's goals for the Hydrogen Program; reducing cost and improving performance of this crucial component in fuel cell systems is critically important. The three-pronged approach of utilizing lower-cost raw materials (fibers), developing hydrophobic surface treatments to replace Teflon, and lowering processing costs is exactly in line with DOE goals. By using cellulosic starting materials and simplifying the production process, the project has reduced costs by over 50%. The team has achieved a high degree of hydrophobicity without agglomeration. This is all very promising, but there is also much more to do, such as looking at the water saturation and looking at overall durability in service.
- The developed process of pyrolysis of cellulosic fibers has proven to be capable of producing materials with, as far as was shown, adequate properties. The process appears to have significant cost-decreasing potential—which is important, as cost is the critical barrier receiving the most attention. For other parameters, such as performance, lifetime, tortuosity, resistivity and conductivity (electric and thermal), and strength, the aim appears to be parity.

- The team has made great progress in identifying top candidate materials and surface treatments. Muslin appears to function poorly on the cathode side without hydrophobic treatment, but with the treatment, muslin is functional. Similar data for Teflonized jute paper would be helpful.
- Very interesting results have been obtained. A large range of raw materials and manufacturing processes led to potential new ways to reduce GDL costs. Among the different characterization tests, more detailed and quantitative mechanical analysis might be carried out to ensure no long-term fatigue issues. Some information on the reproducibility/repeatability of the obtained GDL could be provided. While considering new manufacturing processes in terms of time and energy cost, environmental and safety aspects (the use of silane, for example) should also be considered.
- This project has a very good set of results and a clear presentation. The results of the gas phase treatments look very promising. It is not clear how the cost of chemical vapor deposition treatment with silane precursors compares to the cost of Teflon treatment. There are also questions about slide 18: it is not clear whether the muslin GDL was used at both the anode and the cathode, nor is it clear why the MPL appears to add little to no value at 100% relative humidity (RH).
- The wide range of raw materials that were evaluated showed great diversity in the resulting fibrous structures and properties. Just as discussed for peroxyacetyl nitrate (PAN) materials, more work on looking at the effect of stepwise heat treatment protocols was expected. The hydrophobic post-treatment seems to have the greatest effect on performance, which begs for a closer look at the detailed internal water management.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- The project team is composed of well-recognized experts in GDL, imaging, testing, and synthesis capacities. Contacts with GDL industry suppliers will be useful for investigating the upscaling of the most promising solution(s), as well as with Strategic Analysis, Inc., to evaluate the projected GDL costs and the impact on fuel cell system costs for light-, medium-, and heavy-duty vehicles.
- This is a multi-laboratory project, and that form of collaboration is excellent across national laboratories. It would be great, however, if the team had a commercial/industry partner on board that could provide feedback and testing validation and establish a pathway to commercialization.
- There is no doubt about the collaboration between the partners, though the collaboration with external parties could be stronger. The fact that no GDL manufacturer has joined is out of the hands of the consortium, but others, such as commercial users of GDLs in fuel cells, could have been involved.
- The consortium has a strong knowledge base, and collaboration has proven successful, but some business involvement would make it better.
- More industry collaboration would be useful for this project, especially as this shows some promising cost reduction.
- No collaborations were mentioned.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is of high relevance to achieving the Hydrogen and Fuel Cell Technologies Office cost, performance, and durability targets, in particular with the current trend to produce membrane electrode assemblies (MEAs) from gas diffusion electrodes.
- This is an important component for fuel cell systems. It has the potential to have a big impact, especially if it leads to significant cost reduction and improvement in performance.
- A main focus of the Multi-Year Research, Development, and Demonstration plan is the reduction of costs, which the project tackles. While other aspects, such as lifetime, thermal conductivity, strength, and water

management, are still subject to research, the results are outstanding. However, other GDL-related goals, such as the avoidance of protruding fibers, are not part of the scope.

- This project has very high potential for impact if all metrics can be met. The team should consider a holistic approach to reporting metrics.
- This project's performance could potentially be improved by the use of high-surface-area fibers, beyond the cost and environmental benefits.
- The story is clear, with a promise of cost reduction, but it remains to be seen how many MEA manufacturers will choose a GDL that has a higher risk of quality issues or year-to-year variability. The financial implications of delivering a defective product to customers could far outweigh the short-term benefits.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The remaining activities are related to lifetime assessment, water management, strength, and thermal conductivity. The project should, however, consider including parameters that are critical for the usability of a GDL in a fuel cell in the remaining characterization schedule.
- Understanding durability and water transport through these layers (with MPL and hydrophobicity) is crucial to realizing the potential of these materials.
- The proposed work is well in line with the project targets. Mechanical characterizations and reproducibility testing of the developed GDL may be explicitly added. Durability testing might be investigated for different applications (i.e., light-, medium-, and heavy-duty vehicles).
- The work proposed could well enhance the performance further, implementing combinations of what has worked before. This reviewer questions the potential success using Nafion™ pillars as hydrophilic pillars, while the porous oxidized organic fibers are among the best water-wicking materials (designed by the plant). The expected effect in the fuel cell should be forecasted by comparing two materials from the SGL Carbon (SGL) range, the second of which also exhibits water-wicking fibers (this is commercially available).
- It would be good to see some study of the GDL thickness. It would be helpful to know how the prepared GDLs compare to SGL 29BC. It is not clear whether compressibility of the GDLs can be measured or how thickness changes with compression. It would also be good to know whether there are plans to test at <50% RH, as the difference between prepared and commercial GDLs is greater at lower RH.
- The team is filing patents and moving the technology forward. It is time to bring in some potential industry partners.

Project strengths:

- The ability to convert raw biological fibers into a fully functional component is impressive—and likely also applicable to other electrochemical fields, such as batteries, flow batteries, electrolysis, and Power-2-X stacks.
- The concept is excellent, with strong potential for impact. A good baseline performance has been established, with a range of design choices. There is a good plan to address stated barriers.
- The project appears well-structured, with a very good level of knowledge for investigating this topic. The partners have strong synthesis, diagnostic, and testing capabilities.
- This is an excellent development effort, with great outcomes and promise. It has strong analytical capability and demonstrated accomplishments as a result.
- An innovative route to the production of GDLs for fuel cells has been taken, and promising results have been obtained, so far. The cost reduction has been the key driver behind the efforts.
- Demonstrating viability of natural fibers is very interesting and sounds promising.

Project weaknesses:

- The project needs industrial partnership to drive this forward. The question is who the partner would be. There are not too many players in this field, nor are there players who would invest the money to scale up this process and optimize it for market applications. It would be worth looking at other potential applications beyond fuel cells and hydrogen devices, such as filtration, to see if there is a potential commercial fit in that area.
- The outcome was anticlimactic because—despite all the variation in the input materials, especially compared to the standard SGL materials—the performance in the fuel cell was pretty much similar. It begs the question of how relevant the anode GDL choice is.
- The team could take a more holistic approach to metrics, including structural aspects and durability, to alleviate the concern that there is some reason this has not been done before.
- The project would have benefited from manufacturer and/or commercial user participation. Further, the parameter relevant to usability could have been given a higher priority.
- Understanding practical considerations such as thickness, compressibility, and performance at low RH would make the study more useful for the industry.
- The reproducibility/repeatability of the obtained GDL could be provided.

Recommendations for additions/deletions to project scope:

- The completion of the lifetime assessment is critical for the overall success of the efforts. Furthermore, it is recommended that the project look into the quality/smoothness of the interface toward the catalyst layer, especially if there is no MPL used in the final iteration. This is one of the highest potential risks remaining. The thickness and compression rate under defined forces are critical for usability and commonly measured. Data should be included.
- While considering new ways of manufacturing process in terms of time and energy cost, environmental (including recycling) and safety aspects (for example, the use of silane) should also be considered.
- This project should add a study on GDL compression and measurements below 50% RH.
- The inherent message in the presentation is that there is no performance sacrifice in comparison to standard materials, but it would be helpful to see if the same goes for durability when lifetimes >10,000 hours are expected.
- The team should start seriously thinking out of the box about how this might move forward into the commercial arena and other potential applications. Then, the project should do enough work in characterizing the materials for other applications to be able to draw new players into this field.

Project #FC-320: Electrode Ionomers for High-Temperature Fuel Cells

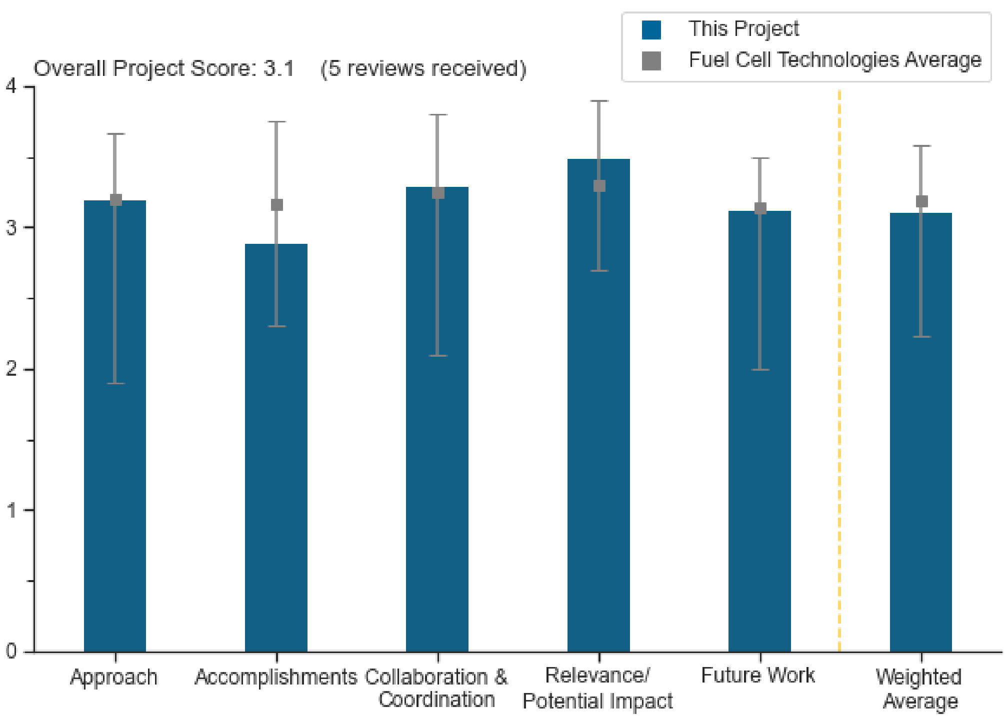
Michael Hibbs, Sandia National Laboratories

DOE Contract #	WBS 1.1.0.804
Start and End Dates	10/1/2018
Partners/Collaborators	Los Alamos National Laboratory
Barriers Addressed	• Cost • Electrode performance • Durability

Project Goal and Brief Summary

Sandia National Laboratories (SNL) seeks to synthesize durable ionomers and demonstrate their use in fuel cells that can operate at temperatures of 200°C–300°C. These ionomers could reduce costs of future fuel cell technologies by enabling operation at high temperatures without humidification and at low-platinum-group-metal (low-PGM) loading. The project team plans to achieve >500 mW/cm^2 peak power density under hydrogen/air conditions, total PGM loading of <0.125 mg PGM/cm^2, and performance decrease of <5% after 1,000 hours of operation at 200°C.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Higher-temperature polymer electrolyte membrane fuel cells (PEMFCs) can be game changers and have large implications for fuel cell system power density, thanks to the potential for decreased thermal management, water management, and increased efficiency. The ion pair approach to high-temperature conductivity in membranes has been one of the most effective approaches for high-temperature polymer electrolyte membranes (HT-PEMs) to date. The use of electron-withdrawing F groups to reduce/eliminate anhydride formation in the phenyl phosphonic acid side chain is a big step forward. Phosphoric acid poisoning of the catalysts can limit catalyst activity. Using a tethered phosphonic acid ionomer may reduce catalyst poisoning compared to an ionomer with phosphoric acid. The project is still using phosphoric-acid-doped membranes. It is not clear if any phosphoric acid is migrating to the catalyst layer during operation and affecting performance.

- The team is well-qualified to perform the work. Investigating different phosphonated ionomer binders over phosphoric acid imbibed polycations is the right approach for reducing kinetic and mass transfer overpotential values in electrode layers. As with most research, new discoveries are made during the project. Here, the team encountered difficulties with anhydride formation with phosphonic acid end groups under dry conditions. This discovery was made after several new ionomer binder chemistries were synthesized and characterized. The anhydride formation precludes their use in fuel cell electrodes, as they do not conduct protons. Borrowing knowledge from poly(tetrafluoro styrene phosphonic acid), it is clear that electron-withdrawing groups in close vicinity to phosphonic acid are needed to increase the functional group's acidity and prevent anhydride formation. The fluorinated styrene moiety has been incorporated into poly(terphenyl) and the SNL polyphenyl backbone to realize new high-temperature phosphonated ionomer materials. There is only one weakness with the approach: the use of ionomers with a lot of phenyl groups that can adsorb to PGM surfaces. Phenyl adsorption can hamper electrode kinetics. Poly(fluorene)-type backbones with phosphonic acid would have been better candidates than the poly(terphenyl).
- The approach to the work appears to be firmly based in rational design of ionomers for the application. More membrane electrode assembly (MEA) diagnostics would benefit the work, as would the discussion of thermal stability and sources of poor performance. Much of this appears to be proprietary.
- Operating at an elevated temperature has many benefits, including easier thermal management and the elimination of humidifiers.
- While the approach in general seems to be supporting higher temperatures for fuel cells, there seems to be some major underlying questions. The chemistry used is very bulky, so it is not clear that it is even possible to achieve theoretical needs for conductivity. Also, it is unclear why the device-level implementations are falling short. Open-circuit voltages (OCVs) are low, while catalyst loadings are very high, suggesting poisoning.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- It is clear that the project team encountered the anhydride formation problem during the synthesis of new ionomer materials. Because of this problem, the researchers had to adjust their synthetic strategy to include fluorinated styrene in their problems. The adjustment of the strategy and pivot speaks to the excellent ability of the team. Overall, the team was able to demonstrate excellent fuel cell power density with TPPA [poly(terphenyl-co-tetrafluoro styrene) phosphonic acid] and PA-DAPP [poly(phenylene) with tetrafluoro styrene phosphonic acid side chains] as the ionomer electrode binders. Peak power density values as high as 1.35 W/cm^2 were realized with H_2/O_2, and values of 700 mW/cm^2 were demonstrated with hydrogen–air. These latter values were with the PA-DAPP ionomer; however, a large PGM loading was used: 1.35 mgPGM/cm^2. The goal was to show >500 mW/cm^2 with hydrogen–air, but with a lower PGM loading (<0.125 mgPGM/cm^2). Low-PGM loading research activities will continue in the L'Innovator Pilot project via the Hydrogen and Fuel Cell Technologies Office (HFTO). Still, the team showed 0.5 W/cm^2 with H_2/O_2, with 0.1 mgPt/cm^2 in the cathode with PWN70 [poly(tetrafluoro styrene phosphonic acid-co-pentafluoro styrene)]. This result demonstrates that low-PGM loadings are possible. From a historical perspective, high-temperature polymer electrolyte membrane fuel cells (HT-PEMFCs) typically require high PGM loadings. The team has exceeded state-of-the-art performance and has shown a pathway to low PGM loadings. The team also showed that the PWN70 ionomer with the ion pair HT-PEM is stable for 550 hours at 160°C and 100 hours at 200°C. (The findings were published in the *Nature Materials* journal in late 2020.) This falls short of the stability goal of 1000 hours at 200°C, but it is progress.

- Some of the project milestones have been met, and good progress toward the remaining milestones has been presented. There has been very good improvement in the maximum power density at 200°C over the course of the project.
- The development of fluor-phenyl phosphonic acid side chains to reduce/eliminate anhydride formation in the phenyl phosphonic acid ionomer is a big step forward. Still, it is far from the target of >500 mW/cm^2 peak power density under hydrogen/air conditions with a total PGM loading of <0.125 $mgPGM/cm^2$, as the performance shown has been with a very high catalyst loading of 1.35 mg/cm^2 platinum, 10 times the target loading.
- The performance gain for the second ionomer discussed appears to be promising. However, limited polymer characterization, no discussion of MEA diagnostic methods, no discussion of platinum content reduction strategies, and hiding durability in the backup slides are all major weaknesses. The project is predicated on higher-efficiency catalyst for lower loadings, but the MEA data being of poorer efficiency, with higher catalyst, requires discussion and justification.
- Materials and testing are taking place, but there is not as systematic of a device for testing, making progress harder to track. While higher-temperature operations are needed, they must also be able to operate at ambient for start-up. There should be testing of start-up and shutdown to confirm if this is possible.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- SNL and Los Alamos National Laboratory (LANL) make a good team. SNL provides expertise in polymer synthesis and characterization, while LANL focuses on fuel cell testing. It is clear the two institutions are sharing materials and results in a timely manner and are moving forward to hit the ambitious project milestones. The project includes industrial partners, such as Advent Technologies.
- This project comprises two national laboratories, where SNL makes the ionomer and LANL tests it in MEAs. This arrangement has appeared to work and has attracted a lab innovator project with Advent to continue. This L'Innovator should focus on the fundamental understanding of MEA performance.
- There is clearly very close collaboration with LANL, which is doing the device construction and testing. Better communication on needs may be helpful.
- There is good collaboration between SNL and LANL.
- The work between LANL and SNL appears to be fairly well-coordinated. Other collaborations, such as with the Fuel Cell Consortium for Performance and Durability (FC-PAD), would be beneficial. FC-PAD labs could perform cell diagnostics and determine voltage loss breakdown, as well as examine durability, phosphoric/phosphonic acid adsorption on catalysts, and effects of decreased catalyst loading. Also of benefit would be collaboration with commercial groups working in the HT-PEM space.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Although HT-PEMFCs have not been a priority for HFTO in the past years, the advent of the ion pair HT-PEMs by LANL has rekindled interest in the technology. In the past, the main problem with HT-PEMFCs has been the loss of phosphoric acid from polybenzimidazole (PBI) at elevated temperatures and humidified conditions and the role of phosphate poisoning in the electrode layers. Because the new ion pair HT-PEM can immobilize the phosphate anions in the membrane matrix via electrostatic interactions, these problems are no longer a serious concern. Furthermore, pairing the ion pair HT-PEM with phosphonated ionomer binders has led to remarkable breakthroughs in peak power density values of HT-PEMFCs that exceed state-of-the-art values (e.g., BASF's Celtec). The HT-PEMFCs with these new materials can operate across a wide temperature range (100°C to 220°C), depending on the application, with low humidity, and can be important for heavy-duty vehicle applications, an important area now for the HFTO. In a very short period of time, the project team has demonstrated HT-PEMFC power density and durability across a wide temperature range, and good performance is starting to be realized with lower

PGM loadings. The high-temperature operation can eliminate the humidifier for the fuel cell stack and reduce radiator size. At elevated temperatures, the fuel cell can run on hydrogen containing CO (i.e., low-cost hydrogen from steam methane reforming). With further maturation of this platform, future priorities should consider potential cycling for drive cycles and start-up/shutdown testing.

- Intermediate-temperature phosphonic acid fuel cells are a potentially high-impact technology that is currently at a low technology readiness level. DOE is well-positioned to support this early work, and ionomer development is a smart area on which to focus.
- Developing lower-cost polymer materials while simplifying the system has excellent potential to advance progress toward DOE research, development, and demonstration goals.
- The approach, if it works, is very much needed. Start-up–shutdown testing is needed to confirm viability, as is the reduction of PGM and the demonstration of needed mechanical properties and electrical conductivity.
- The goal for higher-temperature operation aligns well with the HFTO goals and attempts to improve efficiency and reduce fuel cell balance of plant by operating at higher temperatures. The very high catalyst PGM loadings used decrease the relevance and potential impact. The high loadings can mask durability issues and issues associated with anion adsorption on the catalyst, leading to poisoning and low activity. If poisoning is an issue and these high loadings are required, MEAs of this type will not be economically competitive with traditional low-temperature PEMs, even with the advantages of operating at higher temperature. To be relevant, MEAs with lower PGM loadings need to be demonstrated.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The team has clearly articulated future research directions and has worked on some of them. It is not clear why high ion exchange capacity PA-DAPP is needed. It probably relates to enhanced conductivity in the electrode layers, but it is not clear that greater electrode conductivity is needed. Although not all project milestones were satisfied, many were accomplished, and much progress has been made. The future directions on low PGM loadings and stability with various phosphonic acid ionomers will accelerate HT-PEMFC technology further.
- The plans to work with Advent on future development should be beneficial. The proposed testing with low PGM loadings (or at least normal for low-temperature PEMs) is critical and should be near the highest priority for future work.
- Focusing on durability, platinum loading reduction, and MEA performance are the right places to look for the future.
- Demonstrating long-term durability is a critical next step.
- The PGM loading needs to be reduced, not explored.

Project strengths:

- The major strengths of the project are the availability of three different phosphonic acid ionomers with various backbones, two of which give over 1 W/cm^2 with hydrogen and oxygen. Progress has been made in the project with low PGM loadings, and a peak power density of >0.5 W/cm^2 with hydrogen–air has been demonstrated. The team members' strength is synergistic and contributes to the project goals.
- The project team's approach to HT-PEMs has been one of the few successful approaches in this temperature range.
- The strengths of this project are that it comprises the early leaders and innovators in phosphonic-acid-type intermediate-temperature fuel cell MEAs and that the progress in polymers is promising.
- This is a novel approach to 150°C–250°C fuel cells.
- This is a needed approach, and the project has good device-level testing.

Project weaknesses:

- This project needs more methodical device-level testing of the membrane chemistries to determine whether the ionomers are effective and why OCVs are so low while PGM loading is so high. The principal investigator seems unaware of the device-level testing needs.
- The only weakness was the lack of consideration of phenyl adsorption on PGM catalysts, as the DAPP and TPPA backbones have lots of aryl groups. The poly(fluorene) backbone should be considered.
- MEA diagnostics and durability tests are underdeveloped, and discussion of these activities is not presented sufficiently.
- The use of very high Pt loadings is considered a weakness. The project needs to demonstrate it can get performance with more reasonable Pt content.
- More time would have been needed to complete all project milestones.

Recommendations for additions/deletions to project scope:

- The future work should investigate the potential for replacing the phosphoric acid in the phosphoric-acid-doped quaternary ammonium poly(phenylene) (PA-QAPOH) membrane with the newly developed fluorophenyl phosphonic acid copolymer.
- Understanding sources of kinetic losses would be immensely beneficial to this upstart MEA technology. Discussion of incorporating the ionomers as membrane polymers would be of interest.
- A legend is requested for the comparison plot to commercial PBI on slide 25.
- The project should use start-up/shutdown testing with the use of different catalysts.
- The project funds have been exhausted, and the project is at the end of its timeline, so no recommendations are provided.

Project #FC-323: Durable Fuel Cell Membrane Electrode Assembly through Immobilization of Catalyst Particle and Membrane Chemical Stabilizer

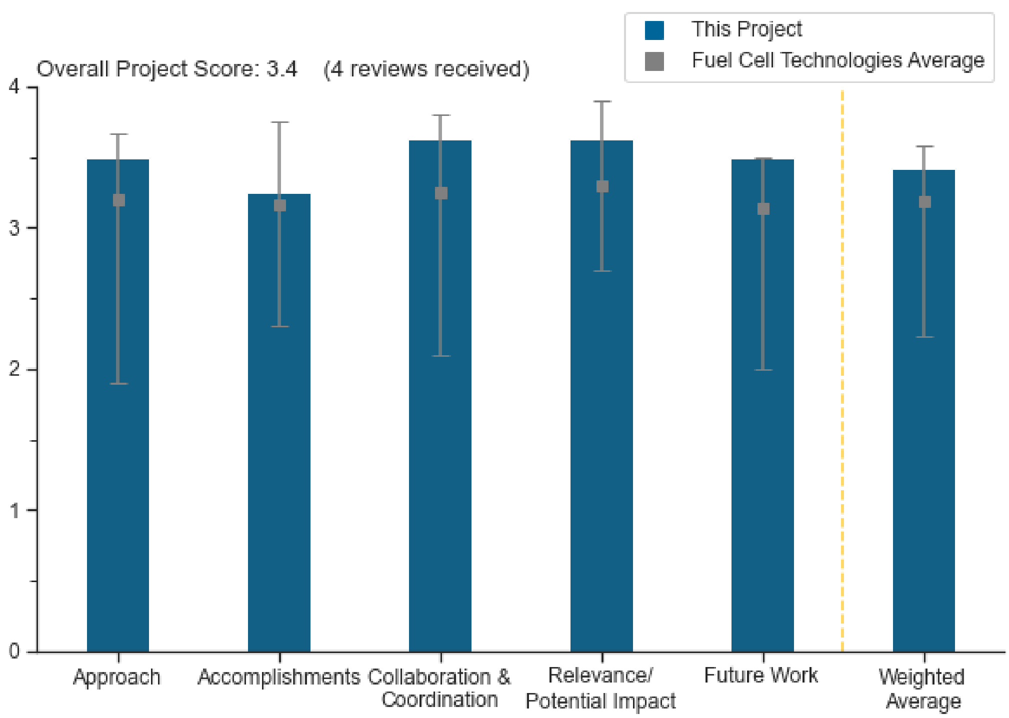
Nagappan Ramaswamy, General Motors LLC

DOE Contract #	DE-EE0008821
Start and End Dates	10/1/2019 to 2/28/2023
Partners/Collaborators	3M Company, Pajarito Powder, LLC, Colorado School of Mines, Cornell University, Million Mile Fuel Cell Truck (M2FCT) Consortium
Barriers Addressed	• Durability: <10% power degradation after 30,000 hours • Cost ≤0.2 $mgPt/cm^2$ cathode Pt metal loading • Efficiency >65% efficiency to decrease fuel cost

Project Goal and Brief Summary

This project aims to develop highly stable catalysts and membrane materials for use in direct hydrogen-fed polymer electrolyte membrane fuel cell (PEMFC) membrane electrode assemblies (MEAs) in medium-duty (MD) and heavy-duty (HD) truck applications. The materials will feature low platinum-group-metal (PGM) loading, fuel efficiency of greater than 65%, and a lifetime of one million miles. If successful, this project will deliver highly durable MEAs for PEMFC applications to enable use in HD trucks. It will also elucidate the fundamental degradation mechanisms of MEAs.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project aims to develop stable catalysts and membrane materials for MD/HD fuel cell trucks with loading, efficiency, and durability targets. The approach for durable catalyst development includes modification of the Pt-C and Pt-ionomer interfaces using polymer additives and graphitized mesoporous carbon. Then the project proposes a stable membrane development using covalently tethered heteropoly acids (HPAs) and dispersed $Ce_{0.85}Zr_{0.15}O_2$ (CZO) additives. These approaches rely on promising paths for improving component durability, with a well-designed path toward the components' integration into a more durable MEA.
- This project is pursuing multiple promising approaches to address two major PEMFC decay mechanisms: catalyst losses and membrane degradation. The concepts are good, and the plans to execute them are well-designed. However, not all major decay mechanisms will be addressed by this project. For example, it is not focused on carbon corrosion. However, the carbons being used here are either standard materials or are the new engineered catalyst support and can be modified to improve stability if needed (e.g., via additional graphitization).
- The goals and approach to achieving the goals are clearly defined. The project seems well-defined and integrates with other efforts being funded by the U.S. Department of Energy.
- This project is focused on critical barriers, but it seems like two completely separate work streams.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- A range of catalysts has been developed, evaluated, and supported by characterization data that will likely help with material design and down-selection for future tasks. The project reports catalyst accelerated stress tests with end-of-life (EOL) versus beginning-of-life (BOL) comparison that shows possible paths for exploration, such as improved durability for the annealed Pt/high-surface-area carbon catalyst.
- Timely progress toward the objectives has been made (despite Covid-19) and has been demonstrated through measurable performance indicators. In terms of measuring catalyst performance, the focus on electrochemical surface area as an indicator of performance is questionable when it does not correlate well with EOL and BOL performance (slides 9 and 12).
- This project is taking on high-risk research, and it is great that DOE is supporting it. These concepts are very difficult to characterize and validate without a large amount of durability data. The project team seems a bit aggressive with its timeline, given the status presented. MEA integration and interpretation of fuel cell results will be difficult without a fundamental understanding of these prototype materials and the critical formulation parameters.
- The progress the team presented is appropriate, relative to the status of the budget (approximately 25% complete). However, there are no results yet that strongly indicate that critical barriers will be overcome. The results to date do show that the team can make some of the proposed new materials, but further work is required to show that these are truly effective.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- There is a strong collaboration team, from the material (catalyst and ionomer) development side to various characterization efforts. The project aims to coordinate a wide range of tasks, from material design to diagnostics, with other entities, which will help with the progress.
- The project has many great team members, and they appear to be working well with each other. There is good evidence of strong collaboration here.

- There is clearly extensive collaboration with industrial and institutional partners and relevant experts in the field.
- The team is ideal for this work, and the project is leveraging expertise exceptionally.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project aims to improve MEA efficiency and durability through ionomer and catalyst development, which supports the Fuel Cell Technologies subprogram goals and objectives for achieving the HD targets.
- Anchoring the catalyst particles is a most critical challenge for HD applications and could simplify system operation.
- Catalyst lifetime and membrane lifetime are critical to enabling success of fuel cells in HD trucking. The membrane work might have a greater impact (this failure mode is more critical). In addition, it is interesting that the proposed catalyst additives have yet to show a level of benefit similar to simply annealing the Pt catalyst, so the potential impact of the catalyst additives portion should be downgraded.
- This project addresses a major challenge for HD vehicles, which is much longer durability than light-duty vehicles. However, it is not clear that the project will contribute directly to the other major HD vehicle goal, which is higher efficiency. The project may do so indirectly by enabling higher operating temperatures with more durable components. However, carbon corrosion may be more of a concern at higher average cell potentials, which does not appear to be addressed here.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- Future work builds upon the current findings in a logical manner and provides a detailed list of challenges and reasonable methods to overcome them. The proposed future work accounts for some of the possible risks, given that the project has multiple approaches. The other assumptions and risks are also listed explicitly.
- Proposed future work is logical, barriers have been considered, and paths to mitigate risk have been suggested. Given that annealed Pt is identified as a promising path on slide 21, this should be addressed in the scope of future work.
- Future plans are clear and are very appropriate.
- It seems like there is much to do before the first go/no-go milestone, but the plan is appropriate.

Project strengths:

- The project explores both ionomer and catalyst development with novel approaches that have potential to improve MEA durability. The extent of collaboration and the detailed tasks covering design, characterization, modeling, and integration are project strengths.
- There are excellent concepts that show promise. There is a great team with the correct skills and capabilities. There is a good plan for future work.
- Clear goals and barriers have been identified. The project has an interesting approach and technology. The analysis is excellent.
- This project has a strong team that is focused on critical technologies for next-generation fuel cells.

Project weaknesses:

- This is not a major weakness, but some additional clarification on the scope would be helpful, as noted in the recommendations section.
- There is no focus on carbon corrosion. It is not clear if General Motors (GM) is really committed to HD vehicle applications since this project is ultimately the same things needed for light-duty vehicles. (Of course, it is not clear when GM may ultimately introduce any commercial fuel cell electric vehicles.)

- Significant work will be required to understand whether the intended mechanism/structure is achieved.
- The project is not structured to follow up on interesting benchmarking results (the annealed Pt).

Recommendations for additions/deletions to project scope:

- Some information on whether approaches are synergistic or complementary in nature would be helpful. For example, it would be helpful to know whether CZO is being added to the electrodes with a Ce-free membrane or to the MEA membrane with some Ce salts or HPA. The selection methods slide could be edited or expanded to demonstrate the integration of these strategies in the future and the decision-making process.
- The team should consider trying to combine multiple approaches at the end of the project, if possible. For example, if both Pt–carbon and Pt–ionomer interface modifications are successful, then the team should see whether they can be combined in the same catalyst layer. It would be useful to know whether the benefits are additive. Additionally, the project should make an ultimate MEA with all of the successful approaches combined and compare the durability results to each of the individual approaches.
- It would be interesting to see more work understanding the benefit of annealed Pt, including the improved oxygen transport mentioned on slide 26.
- This project would benefit from expanded parametric studies.

Project #FC-324: Reversible Fuel Cell Stacks with Integrated Water Management

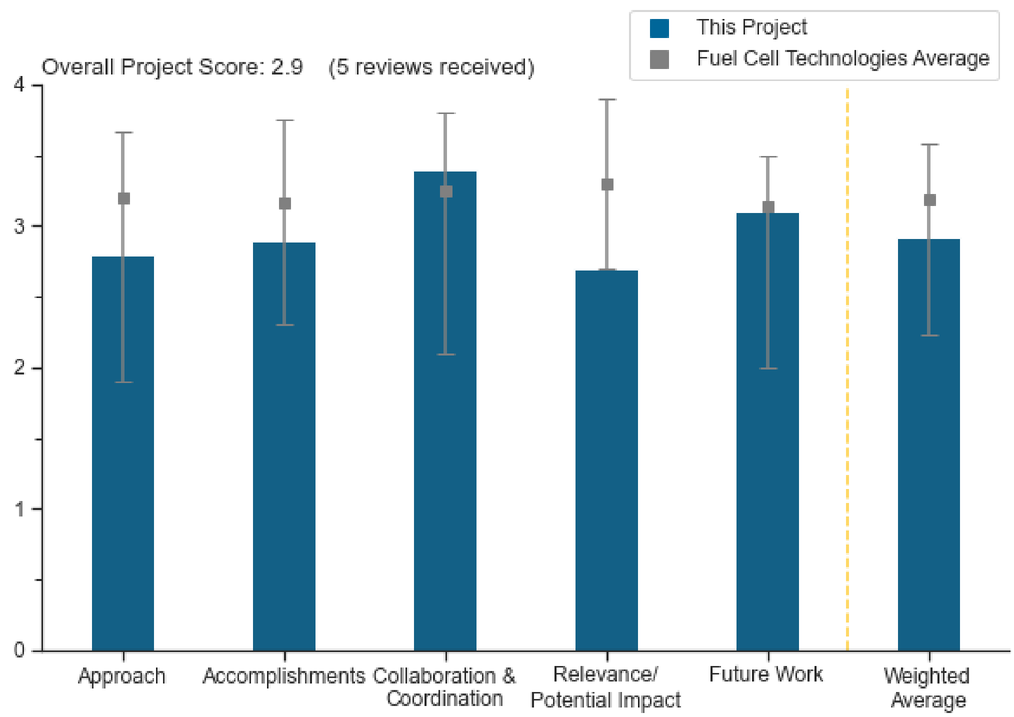
Teddy Wang, Plug Power Inc.

DOE Contract #	DE-EE0008901
Start and End Dates	3/18/2020 to 3/31/2022
Partners/Collaborators	University of Connecticut, Los Alamos National Laboratory
Barriers Addressed	• High capital cost for separate traditional hydrogen production and fuel cell systems • Complicated reversible fuel cell system balance of plant, leading to poor system durability and performance • U.S. Department of Energy reversible fuel cell technical target: 55% voltage round trip efficiency (RTE_V) @ 0.5 A/cm^2 fuel cell and 1 A/cm^2 electrolyzer (2025 target)

Project Goal and Brief Summary

This project aims to develop unitized reversible fuel cell (URFC) stacks and systems by combining Plug Power Inc.'s (Plug Power's) non-flow-through fuel cell design with optimized water management. If successful, this project could dramatically reduce the capital cost of hydrogen fuel cell systems.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **2.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is an outstanding approach starting from a strong platform and addressing key deficiencies—namely, catalytic activity and water management—through materials studies.

- There is a good understanding of the operational targets for both modes and an experimental matrix to support it, but it is not clear whether consistent operation is needed (in a tight window for efficiency) or if it is sufficient to measure a fast I-V curve (current–voltage characteristic curve).
- Slide 4 states that the gas compressor and saturators are no longer necessary with Plug Power's design, which simplifies the system layout. An explanation is not given. Diagnostics are not used to identify sources of performance losses more clearly. A simple approach using air and a 79% helium and 21% oxygen mixture would readily provide an estimate of the mass transfer overpotential associated with oxygen transport in the gas phase (porous transport layer [PTL], microporous layer [MPL], and catalyst layer), which is dependent on the level of liquid water present in pores. More elaborate diagnostics could also be used to gain additional information such as the measurement and separation of mass transfer coefficients into fundamental contributions (molecular diffusion, Knudsen diffusion, and ionomer permeability) and neutron imaging. Results obtained with these diagnostics would accelerate design tasks and help determine whether ultimate targets can be met. The University of Connecticut (UConn) is responsible for electrode characterization (slide 17). However, it is unclear which diagnostics will be used to improve the catalyst layer design. The relevance of these test (PTL/MPL) combinations with or without a hydrophobic treatment) is questionable. The planned Los Alamos National Laboratory (LANL) MPL (slide 27) has a different configuration with a non-uniform in-plane distribution of two different hydrophobicity sites. In contrast, the design depicted in slides 11–14 has a through-plane distribution of two different hydrophobicity sites. Therefore, results are not necessarily applicable to the LANL MPL. This situation raises doubts about a successful integration and application of the results shown on slides 11–14 to the design of LANL MPLs.
- The approach consists of leveraging Plug Power’s static feed fuel cell design and adapting it to electrolyzer/URFC performance. The design appears to be limited in capability relative to a forced feed fuel cell design, but ultimately, the work done in the project will show whether the design is effective enough. Some of the discrete testing should be done under more static conditions to mimic the lack of forced flow. It is unclear what benefits the MPL or amphiphilic coatings will have when capillary forces are required to remove water from fuel cells and switch between modes.
- The combination of different electrochemical devices into a single one would imminently result in underperforming on each side, even with the feasibility of the approach proven. The economic analysis, detailing cost benefits of the approach with sensitivities to underperformance and downtime for switching between two modes, should have been conducted prior to starting the experimental work.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The UConn team has demonstrated significant progress on developing a materials solution and verifying electrochemical feasibility.
- The presentation showed clear results on screening various components with progress in the preferred selection. It is expected that a large set of variations will be tested going forward.
- Good progress can be made across most tasks; milestones are on track. Results so far indicate the high likelihood of meeting targets and DOE targets. Work was delayed due to COVID-19 and company acquisition.
- Progress appears to have been limited because the project was transferred from Giner, Inc., to Plug Power. For example, baseline performance should probably have been established at this point. It is also important to engage project partners, especially LANL, as soon as possible. It is not clear how the pseudo-MPL (Ti sinter) fits into the overall approach in terms of water management. It is unclear how this meshes with the amphiphilic MPLs.
- Materials shown on slides 6 to 8 indicate a platinum-metal-group loading of 1 mg/cm^2 for the cathode. Materials on slides 9 to 14 show a total metal loading of 2.1 mg/cm^2. It is unclear how the target of 1 mg/cm^2 will be met while concurrently increasing the roundtrip electrical efficiency to 55%. On slide 13, the graph containing the 150% fuel cell polarization curves is seemingly missing data (the sinter + felt -

270 + 250 µm case). On slide 23, results were obtained with a 5 cm^2 active area cell rather than the planned 50 cm^2 active area cell (slide 24).

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- The project is structured very well, sharing equally the scope of engagement between industry, university, and national laboratories in the final deliverable.
- There is a large and diverse team of researchers. The project should continue to try to leverage user facilities such as the National Institute of Standards and Technology (via LANL).
- The consortium partners are chosen well, and the takeover by Plug Power does not seems to have affected collaboration.
- There appears to be some good initial coordination, but the contributions from partners could be better emphasized.
- There are indications that coordination could be improved, as the platinum-group-metal loading of the UConn samples does not meet the target (includes only one electrode), and LANL samples have not yet been provided.

Question 4: Relevance/potential impact

This project was rated **2.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The approach of making an operational electrolyzer reversible is a good one because it can take advantage of existing materials properties in the harsher electrolyzer regime. The team must make more progress on water management to realize the largest impact.
- Years of community experience with reversible fuel cells or reversible electrolyzers have always highlighted compromised performances and efficiencies at stack level. The application of this concept is often limited to specific situations.
- The project partially supports the DOE Hydrogen Program and DOE research, development, and demonstration objectives.
- The project is aligned with DOE URFC goals, yet it is unclear what the performance of the stack hardware is, so what its ultimate performance characteristics might be is hard to say.
- Cost and durability aspects will not be addressed. For instance, the added complexity of the cell and stack design with added cell layers (bubble point membrane and water chamber) is expected to increase cost. Therefore, the impact of this project on the DOE Hydrogen Program is limited.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- Considering that only three months of work have been reported, the proposed future work, containing the majority of the proposed project, makes sense.
- Future work is outlined well on the materials development side; however, more design work is desirable on the switching mode and optimization of the non-flow plate to avoid starvations.
- The project should drive more out of the reactive spray deposition technology (RSDT) part of the project, if this is on the critical path for membrane electrode assembly. Test stand upgrades to enable automated testing are great.
- The anticipated step to a larger stack configuration will show how scalable this stack technology is while being subjected to natural flow patterns in the active area.
- The fabrication of the two core components, the catalyst layer and MPL, is tunable with multiple parameters, which reduces risks.

Project strengths:

- This is a good team with a proven track record and good previously demonstrated technology from amphiphilic coating, RSDT, and all that Giner, Inc., and Plug Power have done in this space.
- The concept is interesting; it leverages the UTC Power porous bipolar plate water management concept. The fabrication of the two core components, the catalyst layer and MPL, is tunable with multiple parameters, which reduces risks.
- The project shows there is sufficient experience and expertise on board to further develop the existing reversible fuel cell architecture. There is no shortage of conceivable solutions to evaluate.
- The project starts from an excellent working electrolyzer platform. The proposed materials solutions appear promising.
- The project strength is in partnership and material development on UConn side.

Project weaknesses:

- The project weakness is insufficient design work on compatibility between amphiphilic MPLs and the electrolyzer media. The approach to switching modes between fuel cell and electrolyzer is not sufficiently worked out. The non-flow-through plate could contribute to starvation zones, which is necessary to consider if extended lifetime is planned. Durability considerations are not presented, and shorter stack life may negate the entire purpose of integration into the same hardware.
- The approach justification is insufficient. The absence of cell diagnostics is notable, which will slow technology development. The relevance of several completed tests is debatable. There is a high level of risk in meeting electrical efficiency and platinum-group-metal loading targets concurrently, considering the development plan is unclear. Team coordination could be improved. Cost and durability aspects will not be addressed.
- The development in this project is leaning heavily on practical material selections going in one cell platform (up to now), which is then tested to measure its characteristics. Without fundamental understanding or modeling on what issue we are trying to resolve (first), the project is inherently limited to practical compromises.
- There is much recent literature in this space that is being omitted or presumably not used for comparison. RSDT sprayed in layers not mixed together; this might be a problem functionally.
- There was a limited period of operation in 2020. Significant contributions of partners are yet to be realized.

Recommendations for additions/deletions to project scope:

- The project should conduct economical sensitivity analysis accounting for the stack lifetime in the fuel cell mode, time for switching between the modes, and loss of performance on both modes of operation.
- Operational durability and stability need to be taken into account to justify the underlying goal to make this fuel cell/evaporatively cooled architecture more attractive than two dedicated systems. The overall cost assessment needs to consider the lifetime and over-dimensioning catalyst layers to design robustness against off-spec conditions and dynamic cycling.
- The option 2 bifunctional oxygen electrode appears to be too compact (slide 8) and perhaps should not be used. Regarding slide 15, the use of precious metals is not ideal. Titanium is an earth-abundant element, and therefore, it is preferred in comparison to Ru-based materials.

Project #FC-325: Fiscal Year 2019 Small Business Innovation Research Phase II: Controlled Porosity and Surface Coatings for Advanced Gas Diffusion Layers

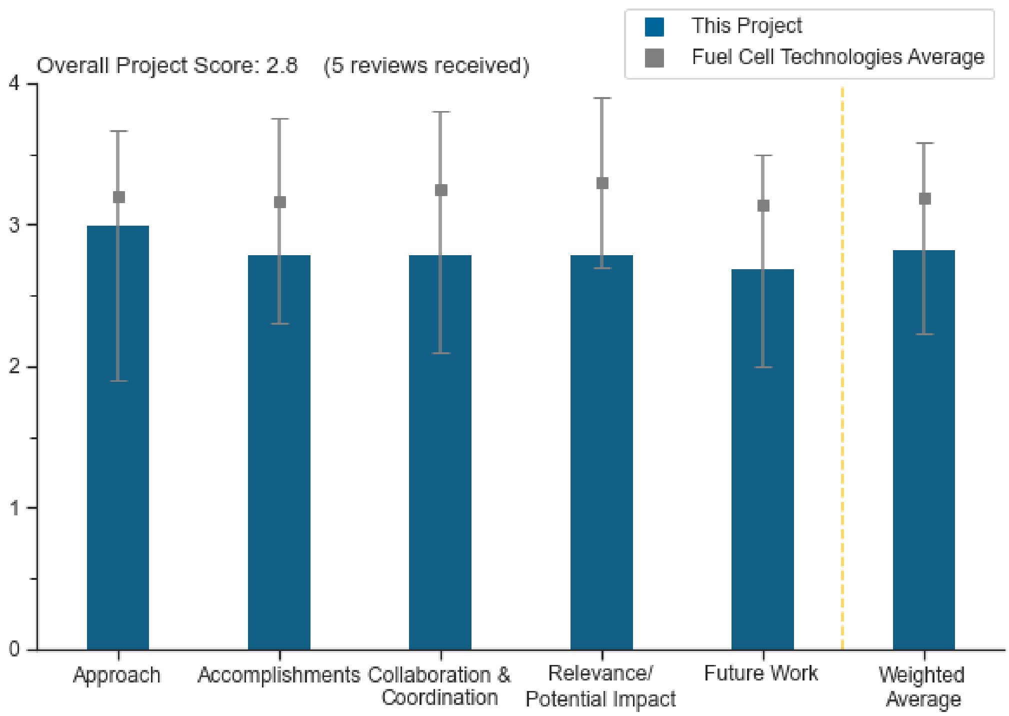
Kristina Bennett, Physical Sciences, Inc.

DOE Contract #	DE-SC0018606
Start and End Dates	5/28/2019 to 5/27/2021
Partners/Collaborators	University of Tennessee, Knoxville, University of Connecticut
Barriers Addressed	• Cost

Project Goal and Brief Summary

This project aims to demonstrate the use of an ice-templating method to tailor the properties of gas diffusion layers (GDLs). This method is scalable and can manufacture GDLs at an estimated 20% lower cost than current methods. If successful, this project will support the adoption of cost-competitive polymer electrolyte membrane fuel cells (PEMFCs) through the production of high-performance GDLs. Physical Sciences, Inc. (PSI) is collaborating with the University of Tennessee, Knoxville (UTK), and the University of Connecticut (UConn) on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project focuses on developing a new approach of ice templating to reduce GDL production costs by 20%. Such a method can also potentially improve performance and durability by tailoring transport properties and using electrochemically stable materials, respectively.

- This is a very interesting approach to fabricating a GDL structure. Overall, the elimination of high-energy heat treatment processing steps and a relatively simple process flow makes this an interesting GDL development process.
- Ice templating should result in a significant reduction in process complexity, leading to cost savings. The challenge will be to demonstrate equivalent performance with ice-templated GDLs across all performance metrics.
- The ice templating method is a seemingly novel technique to make GDLs. The enhanced durability of the GDLs is seemingly due to the electrochemically stable materials; however, no information was given about the materials. It is unclear whether these are standard peroxyacetyl nitrate fibers, carbon, Teflon™, etc. In the cost analysis, an identical raw material cost is used; thus, it appears the materials must be the same; thus, no enhanced durability should be expected. As the material cost is the same, the advantage of this technique would seem to be a reduced cost and an ability to tune the GDL porosity, yet the project does not provide any characterization detail related to the difference in porosity or the desired porosity.
- The idea to use ice as a template is novel and practically explored in reference to a commercial material, but true benefit was not evaluated in a cutting-edge window of operation.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Overall, good progress was made on this project, with the production of a GDL candidate material that was comparable to a commercial reference. The voltage and current density decay look promising, although the overall performance appears to be much lower than would be expected, as most commercial GDLs operate around 0.7 V at 1 A/cm^2 under hot, wet conditions. It is also unclear from this effort how much material was made and how much variation in typical GDL properties (thickness, basis weight, compressibility, etc.) was seen from batch to batch. Regardless of the drawbacks, the success of making a GDL material with this methodology is impressive.
- The project has demonstrated GDLs with potentially 20% lower cost and identical durability. The project is unclear as to whether the performance of the GDL is identical to commercial GDLs; it is clear only that the cell voltage differential, during a durability test, is identical to that of commercial GDLs over 200 hours and 360 hours. A key to GDL performance is the ability to operate at a range of conditions (e.g., temperature and relative humidity [RH]). The project did not present the operating conditions used, nor did it show a range of operating conditions, so the overall operating ability of these GDLs is unclear.
- A cost reduction of 20% was demonstrated by modeling, with the main savings from reduced energy consumption, less labor, and less equipment and maintenance. The project demonstrated performance and durability competitive with a commercial product (SGL 39AA). However, reported durability and performance were quite far from DOE 2020 targets.
- The presentation showed clear outcomes from the experimental matrix and could show a higher performance in the graphs presented.
- Additional performance metrics, such as resistance, porosity, and hydrophobicity, would provide more confidence of success.

Question 3: Collaboration and coordination

This project was rated **2.8** for its engagement with and coordination of project partners and interaction with other entities.

- The collaboration on this project appears to be very good, with each partner having a key role to play in either the generation or the evaluation of the GDL material.
- PSI, UTK, and UConn have good testing capabilities for this project to be successful.
- The project has good partners that could be better integrated. Additional data from UTK could be reported. Stack testing in slide 9 may be from UConn, but if so, it should be attributed to the collaborator.

- PSI collaborates with UTK on GDL performance characterization and with UConn on PEMFC testing. It is unclear how effectively the results from collaborators might have contributed to improvement of GDL production at PSI because very limited data are reported.
- The wish was expressed to work with a GDL manufacturer and reduce the energy spent on drying and firing the GDL processed in the regular manner, but the presentation left the impression that such potential customers were not contacted in prior discussions sufficiently to understand the relevance of this issue.

Question 4: Relevance/potential impact

This project was rated **2.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Lower-cost materials with expanded durability fit into Program goals and are needed for both light-duty and heavy-duty vehicles.
- This is an interesting project, and the initial success is interesting to see. It is difficult to judge the overall impact without more data on piece-to-piece and lot-to-lot variability. The initial cell performance is also somewhat underwhelming, but it will be interesting to see how the cell performs in stack testing. The results achieved so far are interesting, but the potential impact of this project is relatively low right now—but could change as the process is refined and performance improves.
- The impact of a functional, low-cost GDL could be significant. The impact could be better demonstrated here. The membrane electrode assembly (MEA) data shown are not compelling. It is unclear whether the comparison MEA is state of the art, but if it is, it is best to show absolute polarization rather than relative polarization. It is best to compare MEAs under the same conditions. On slide 9, the PSI GDL at 0.6 A/cm^2 is compared to SGL Carbon at 0.7 A/cm^2.
- In the current project period, the goal has been set to reduce production cost by 20%, while demonstrating the same level of performance and durability as commercial products. The project could have a bigger impact if effort were dedicated more to performance and durability improvement instead, considering the GDL is not a top cost contributor to fuel cell stacks, but performance and durability improvements can lead to overall stack cost reduction.
- The functionality of the resulting GDL was not sufficient to evaluate this in the higher fuel cell performance window expected by DOE. It is possible that the party executing the comparison testing had insufficient testing resources.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- The proposed future work covers the main concerns associated with the material by continuing to evaluate the performance over longer periods of time, looking at stack testing, and examining the viability of scale-up, which should include challenges related to piece-to-piece and lot-to-lot variability.
- The future work seems reasonable, but the information from the project could be expanded by additional reporting, testing, and characterization.
- The proposed future work should consider including more GDL material property characterization and make an effort to address the big performance gap toward DOE 2020 targets.
- There is limited scope in the project to explore further benefits of using ice particles to template the porosity. The work is independent of the slow production conditions. Making enough material will show process stability and reproducibility.
- The pathway to 10 m^2 is not clear. There should be some effort to identify roadblocks for these materials and mitigation strategies. Process throughput should be considered. For example, the team should consider how hold time to control porosity effects square meters per day.

Project strengths:

- This is an interesting project with a very novel approach to manufacturing a GDL material. There has been some significant success in making a material that performs relatively well compared to a commercially available GDL in one set of conditions.
- The project has a strong starting point with a low-cost process. Good progress has been demonstrated toward scaled-up manufacturing, and project partners are in a position to contribute significant performance metrics.
- This project has a novel design of the ice-templating process that can reduce the cost of production and potentially improve durability and performance.
- A clear effort was made to assemble process instruments to fabricate the targeted structures.
- The project is showing a reduction in cost and equivalent durability.

Project weaknesses:

- The overall weakness in this project is the generally lower-than-expected performance when compared to single-cell testing that has been seen elsewhere (e.g., ~0.7 V at 1 A/cm^2). This may be due to the size of the active area in the cell or poor MEA components. Further data looking at both within-part and part-to-part variability would also be helpful to understanding the manufacturing process. The issues related to scalability will be addressed in the proposed future work and may improve upon this current weakness.
- The project could use more characterization related to the GDL properties and material properties. More information about the overall performance over a range of conditions would be good. Since the strength of the ice templating technique is the ability to control the manufacturing, the team should demonstrate a range of GDL properties and porosity.
- The weakness is the lack of material characterization that is critical to validating the proposed control of GDL physical properties and to helping corelate to MEA performance and durability results. This also makes it difficult to assess how the team can propose effective countermeasures to narrow the gaps between current status and DOE 2020 targets.
- The performance metrics are underreported, external collaborators seem under-engaged, and comparison to commercial GDLs is not compelling. The project must be able to assess the state of the art.
- Without the application of a microporous layer on the GDL, this component is not complete and is unable to demonstrate its true potential.

Recommendations for additions/deletions to project scope:

- The project should expand its characterization and information related to the GDLs and materials. This should include a discussion about porosity, tailoring the porosity, what the technique can do, and what porosity is wanted. Other information should include the material hydrophobicity as a function of operating time. Testing should include showing direct beginning-of-life performance and voltage–current–resistance performance comparisons to commercial materials over a range of temperatures and RH.
- The capability to template a structure, rather than presenting only a reduction in drying costs, seems more attractive from a business point of view. The project is asked to verify the commercial interest in the presented "Unique Selling Points" slide.
- It would be great if the project team could consider adding or enhancing the following studies into the scope:
    - Measure and compare the new GDLs' physical properties (such as electrical resistivity, thermal conductivity, hydrophobicity, porosity, density, and compressibility) to those of commercial products.
    - Include gas diffusion analysis in the fuel cell performance testing to compare with commercial products.
    - Demonstrate how the new process may control key parameters, such as pore structure, that can lead to the change of gas permeability and MEA performance improvement.

- The proposed future work accounts for most of the concerns, although adding in variability analysis of critical GDL values (thickness, basis weight, etc.) would be beneficial for this project.
- The project might consider the effect of adding a microporous layer for water management.

Project #FC-326: Durable Membrane Electrode Assemblies for Heavy-Duty Fuel Cell Electric Trucks

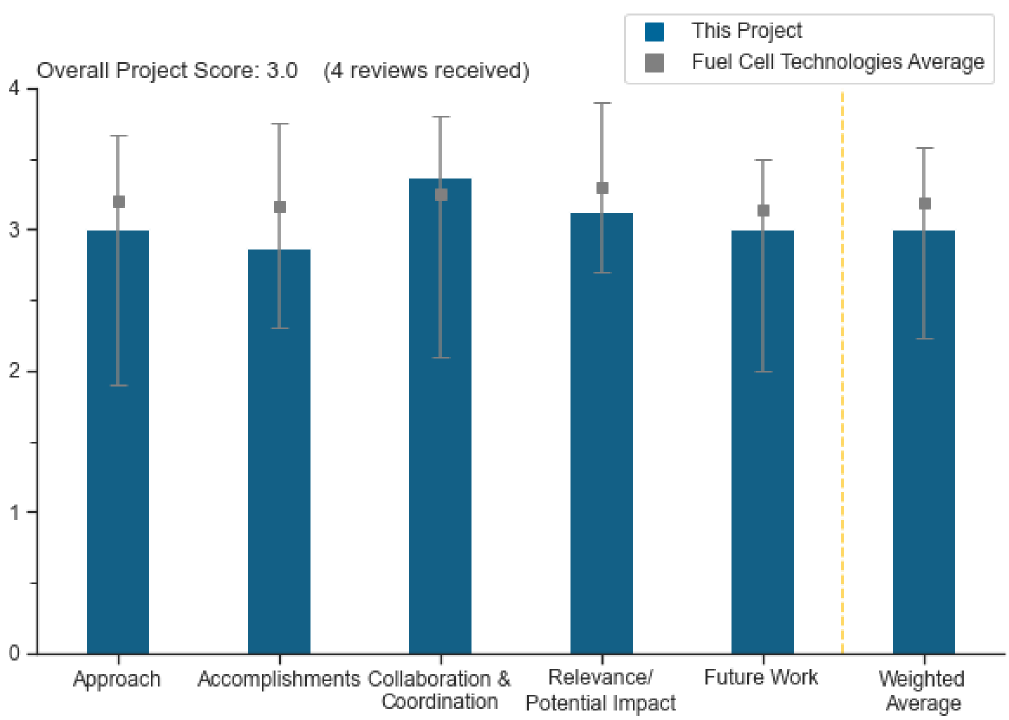
Vivek Murthi, Nikola Motor Company

DOE Contract #	DE-EE0008820
Start and End Dates	Q3 2020 to Q3 2023
Partners/Collaborators	Georgia Institute of Technology, Northeastern University, Carnegie Mellon University, Los Alamos National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory
Barriers Addressed	• Durability: Improve stability of membrane electrode assemblies for operating conditions relevant to heavy-duty trucks • Performance: Increase catalyst while reducing ionomer poisoning effects to achieve high power density and higher efficiency • Cost: Enable reduction in platinum-group-metal catalyst loading and improve ionomer utilization

Project Goal and Brief Summary

This project will fabricate, characterize, and evaluate a membrane electrode assembly (MEA) with a novel catalyst layer incorporating a "nanocapsule" electrode structure that separates ionomer and platinum to maximize activity while allowing ionic transport. If successful, this project will allow for better use of highly active and/or highly durable catalysts and the bridging of the activity gap between rotating disk electrodes and MEAs.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project is focused on all key improvements sought for heavy-duty (HD) vehicle applications, namely, improved durability, efficiency (performance), and cost. This project is trying some promising concepts, including a highly innovative catalyst layer design. This is an area where more work is justified, since the polymer electrolyte membrane fuel cell community is still essentially using a 30+-year-old catalyst layer architecture that was first developed by Los Alamos National Laboratory circa 1990. However, new catalyst layer architectures are very risky, the failure of 3M's nanostructured thin film (NSTF) being a good example.
- The project approach of developing and optimizing nanocapsule-based electrodes appears to have many significant challenges. While conceptually the approach of minimizing ionomer contact with Pt to minimize activation losses is appropriate, the structure itself may have significant challenges. One concern is associated with having sufficient ionic conductivity within the nanocapsule with reduced or no ionomer within the nanocapsule; maintaining sufficient ionic conductivity at low relative humidity (RH) is a challenge with more traditional electrode structures, and it would appear that the nanocapsule approach may have even more challenges. A second concern is associated with oxygen and water mass transport through the ionomer film around the nanocapsule. A third concern is flooding within the pore structure within the nanocapsule, especially with the ion beam assisted deposition (IBAD)-type catalysts (the pore walls within the nanopores will be lined with Pt, which is very hydrophilic). A final concern is the stability of the nanocapsules in the event of carbon corrosion. It appears (from the reviewer-only section) that the team has considered many of these concerns with modeling, but having more experimental feasibility data would be very useful.
- The concept is a novel approach that is feasible, but it is far from certain that it will work. A number of parameters must be optimized to result in the overall improvement expected. Even if ideal structures can be created, the modeling does not appear sufficient to prove the approach will work. Creating the ideal structures will also be difficult. There are a large number of variables to work with and so many levers to push, but there may be too many. Some early success on achieving an indication that the approach is working will be required before descending into numerous parameter studies. The reviewer-only slides provide a bit more explanation of the model data and parameter sensitivities. Some good physical characterization techniques are shown, but revealing the ionomer in the structure may be difficult. It is unclear how long the HD drive cycle test will be operated. RH sensitivities may be important but were not discussed (the design may suffer from flooding in ionomer-rich regions and drying in ionomer-poor regions).
- It does not seem that the key milestones (slide 7) lead to the go/no-go decisions (slide 8).

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made satisfactory progress, considering the early phase of the project and challenges associated with the pandemic. Initial modeling results appear to show that the nanocapsule approach could provide a large benefit at high humidity conditions but needs to be validated experimentally.
- It is very early in the project in terms of money spent to see much progress.
- It is early in this project, but the reported results are sparse for six months of work. It seems like this group may have missed the first milestones.
- Not much has actually been done yet. This is understandable, though.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- The team is good and has the appropriate skills and capabilities required. There is not much evidence of real collaboration yet, but that is probably because not much has been completed yet. Fabricating and testing MEAs with these new materials will require collaboration.
- An excellent team has been gathered.
- Collaboration appears to be good based on initial results in the early phases of the project.
- Research organizations and project workflow are appropriate.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is well-aligned with addressing the key barriers of performance and activity, but there does not appear to be an overt effort toward improving durability other than the stated intention of using catalysts with good durability (e.g., ordered PtCo).
- The project is well-aligned with DOE's objectives and has much promise. Whether it will actually be successful, though, is still to be determined.
- If the approach works, the project may have high impact. There is concern about eventual manufacturability of the designs, but nevertheless, significant learning might be accomplished.
- This work is likely to encounter the same barriers as previous nanostructured catalyst concepts. Water management, catalyst utilization, and sheet resistance are critical issues. It is unclear how these are being addressed differently from issues with 3M's NSTF catalyst layers.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The questions posed on slide 13 seem like an appropriate roadmap for this work. In addition, MEA fabrication studies are going to be important. Catalyst layer thickness, coating method, ionomer distribution, porosity, and other parameters will need to be studied to meet performance and durability project goals.
- The proposed future work of experimental development and testing physical electrodes using the nanocapsule approach is appropriate.
- The plan is okay but presents a significant number of questions to answer. It is not clear if all can be addressed.
- The proposed future plans seem fine, but the details are sparse. The timeline is vague, except for the annual milestones listed on slide 8. These milestones are not very challenging, although these modest performance goals are probably appropriate for a brand new architecture.

Project strengths:

- The project is focused on the development of an innovative catalyst layer architecture. This is the kind of high-risk, high-reward work that DOE should invest in more frequently. The concept is good, and it builds on one of the truly valuable things that was demonstrated by NSTF, namely, that one does not need any ionomer for proton transport over very short distances. The team has the skills required to execute the plan. The new principal investigator (PI) has good communication skills.
- The project aims to use a unique approach for developing a new engineered electrode structure with the potential to significantly improve activity by reducing sulfonate poisoning. The team comprises a set of highly capable researchers, with an appropriate balance of synthesis, modeling, and characterization.

- The project has a strong team, excellent candidate materials (catalyst), and a novel approach, with preliminary indications of possible significant improvements.
- It is too early to tell, but the subcontractors have a strong record of success on other projects.

Project weaknesses:

- This is a high-risk project, and DOE therefore needs to track it carefully to determine whether continued work is justified. However, it is certainly worthwhile to devote three years to it. It is not clear why the project PI is changing. The new PI has minimal project leadership experience.
- The project seems off-balance. Much of the characterization for modeling and fundamental understanding is fantastic, but to meet the go/no-go decision points, the project should consider more process optimization and development studies. It was not clear in the question-and-answer session if the prime organization had a strong background in prior NSFT work. Understanding the successes and challenges documented by these researchers will certainly benefit this project.
- The project does not appear to have any experimental validation that the nanocapsule approach will increase activity, a core tenet of the approach.
- There are too many parameters to consider, and the level of modeling is not clear.

Recommendations for additions/deletions to project scope:

- DOE should continue to fund projects that explore innovative catalyst layers, such as this one and Vanderbilt University's fiber-based layers. As long as these projects continue to make good technical progress, they should continue to be funded. However, DOE also needs to be diligent about looking for possible fatal flaws in these new architectures to avoid repeating the NSTF experience. In that case, the new architecture was not operationally robust (i.e., it could perform well under only a very narrow range of conditions). The innovative catalyst layer being proposed here has some similarities to NSTF, namely, minimal or no ionomer in some parts. Therefore, the project should be asked to demonstrate operational robustness near the end of the project (i.e., measure performance curves under various RH, temperature, and pressure values and compare to conventional MEAs).
- It is recommended that additional criteria around the first budget period go/no-go decision point be considered beyond the current hydrogen–air kinetic performance at 0.8 V. Some aspect of hydrogen–air-rated power performance and durability should be included in the event that some of the concerns around the nanocapsule approach are larger than anticipated.
- The project should understand feasibility of manufacturing. A 50 cm^2 MEA may be sufficient to prove this concept. The value of a full-size MEA test is not clear.
- This project should consider more process optimization and development studies related to MEA integration.

Project #FC-327: Durable High-Power-Density Fuel Cell Cathodes for Heavy-Duty Vehicles

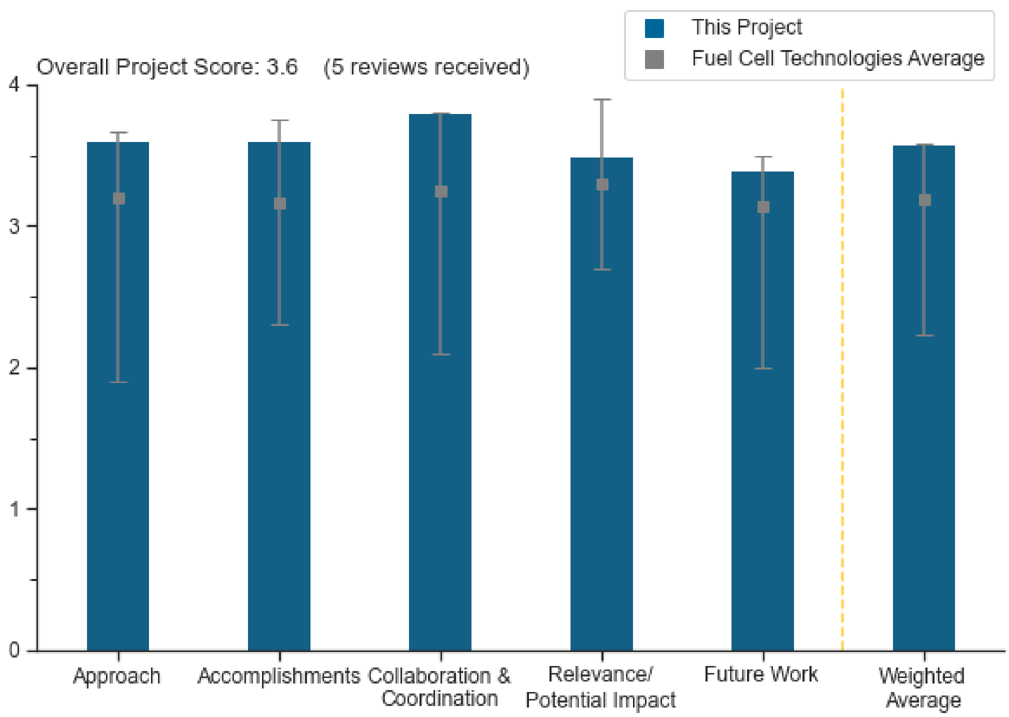
Shawn Litster, Carnegie Mellon University

DOE Contract #	DE-EE0008822
Start and End Dates	10/1/2019 to 1/31/2023
Partners/Collaborators	The Chemours Company, Ballard Power Systems, Inc., Million Mile Fuel Cell Truck (M2FCT) Consortium
Barriers Addressed	• Cost • Performance • Durability

Project Goal and Brief Summary

This project aims to (1) synthesize and implement a custom-designed ionomer that permits enhanced oxygen transport to the platinum surface for improved performance and durability, (2) demonstrate that the ionomer will reduce oxygen transport resistance in a membrane electrode assembly (MEA), and (3) optimize the design of the ionomer for commercialization. If successful, the project will facilitate low platinum loadings in an advanced MEA cathode catalyst layer for heavy-duty vehicles.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Incorporating a high-oxygen-solubility and -transport polymer instead of the traditional ionomers in the cathode catalyst layer is a new novel approach that could significantly improve the performance of the catalyst layers.
- Addressing the long-standing challenge of oxygen transport to the platinum surface has the potential to improve performance and durability for all polymer electrolyte membrane fuel cells (PEMFCs). Shorter side chain perfluorosulfonic acid (PFSA) chemistry is a good choice to implement this concept.
- The project is well-formulated and focuses on the use of high oxygen permeability ionomers (HOPIs) to improve the long-term performance of heavy-duty (HD) fuel cells. The team lays out the rationale well based on the importance of local transport resistance and the loss of electrochemical surface area (ECSA). The primary unknowns of the approach are how central catalyst degradation will be in HD systems and how chemically robust the HOPIs are in use.
- The goals, as well as the progression of work to reach those goals, are well-defined, with reasonable steps and achievable milestones.
- It is unclear whether HOPIs are needed or helpful at 0.2 $mgPt/cm^2$. A significant impact would be expected at lower loadings (<0.1 $mgPt/cm^2$). Modeling at lower loadings should also be considered. The project should focus on high-surface-area-carbon-type (HSC-type) supports, as these work the best at a low loading.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project met all Year 1 go/no-go milestones. The project had outstanding progress with polymer synthesis and modeling, as well as electrode fabrication and fuel cell characterization. Impressive voltage gains in fuel cell tests at high current density were accomplished. The project achieved a large reduction in the MEA performance degradation rate in accelerated stress test (AST) cycles.
- The progress to date has demonstrated significant success. The developed ionomer yields significant performance enhancements, and the team has provided insight into the source of the performance enhancements. The developed ionomer also yields a greater degree of MEA performance retention following an AST protocol.
- The results are quite good at such an early stage of the project. The team is obviously leveraging previous work by The Chemours Company (Chemours) in developing HOPIs. The fuel cell results clearly show the ability of HOPIs to improve both specific activity and mass transport losses, although the specific activity improvements seem to be dependent on the use of non-porous carbons. The modeling also shows good initial results.
- Although the modeling work and the ex situ characterization of the new HOPI polymer confirm that it should improve the performance of the cathode catalyst layer, the proof at the end of the day for the high-roughness-factor MEAs was just not there. Ballard tests show only minute improvements over the D2020 baseline when the roughness factor is >100. This begs the question of whether some other factor is dominating the performance of the catalyst layer, such as the catalyst layer resistance being higher for the HOPI, or the optimal ionomer-to-catalyst ratio being different for the HOPI, as compared to D2020, possibly because the density of D2020 is higher. The excellent team approach and well-guided optimization of the materials and structure should lead to further improvements.
- Good progress has been made for meeting go/no-go milestone 1. Perhaps a loading study could replicate the roughness factor vs. performance trend observed in the degradation studies.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- This project has a great team. Original equipment manufacturers, suppliers, and a well-established university comprise a recipe for fundamental understanding while constraining cost and manufacturability. The principal investigator (PI) has a strong record of collaborative work with successful outcomes.
- This project has excellent teaming and coordinated work. This approach of modeling, ex situ material characterization, and good fuel cell testing work will properly guide the team to further optimize the formulation so that the full benefits of the HOPI can be realized.
- The team, including M2FCT laboratories, is strong, and all team members seem to have a clear role in the project. Almost all are at the very leading edge of what they are doing within the project, with Ballard having a great fit and Chemours bringing unique specific materials and capabilities to the project. The PI is at the top level of researchers at a similar stage of their careers. The modeling effort seems to have all the appropriate skills, but there is less background strength in this area compared to the rest of this extremely strong team.
- The team and the degree of collaboration are good and complementary to the work.
- This is an outstanding team with outstanding collaboration.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This work demonstrates the significant impact of ionomer chemistry on MEA performance. This work is critical for HD PEMFCs, as it will help to remove some of the performance burden from the catalyst.
- Since HD applications typically use higher Pt loadings, degradation studies are critical. For this application, the implementation of HOPI will be highly dependent on cost. Perhaps the investigators can discuss cost impacts in future disclosures.
- Increasing fuel cell performance and durability are key to lifecycle cost reduction.
- It looks as if more work will result in further improvements of the approach.
- Pursuing HOPIs as a pathway to achieve improved durability is interesting. It is essentially trying to take a catalyst degradation and addressing it through improving transport processes. The threefold improvement in oxygen permeability is meaningful, but it is not clear how well it will be maintained over time or whether there are other degradation phenomena that may be worse in HOPI than in other PFSAs. The HOPI approach also requires that Pt ECSA loss be treated as a significant degradation concern because it cannot be addressed either by novel catalysis approaches or by systems controls. This is a worthwhile project, but it is not enough by itself to fully cover durability concerns.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- This project has an outstanding plan to build on the results to date to address the remaining challenges.
- The proposed future work is good.
- The topics for future work all make sense and should lead to advances. The work needs clearer priorities of focus, as the list seems more like a laundry list that is not as focused on key issues as would be preferred. Additional studies investigating the HOPI membrane for bulk properties such as water uptake, permeability, conductivity, and durability to radical attack would be good inclusions.
- Future work should be focused on demonstrating a performance improvement in line with what the modeling predicts. A fundamental study of the catalyst layer structures needs to be done so that the high-roughness-factor catalyst layers show a similar level of performance improvement over D2020, as compared to the sub-optimal low-roughness factors.

- The project has a good plan. The team should consider adding cost and HSC support studies.

Project strengths:

- This is a great team that shows strong progress toward fundamental understanding and development of HOPIs. HOPIs are critical technology for next-generation fuel cells, and the team seems to have a well-developed approach.
- The project has well-defined goals and a logical approach. It is an accomplished and well-integrated team that has demonstrated significant performance enhancements with synthesized HOPIs and provided detailed insight into the source of performance enhancement for the HOPIs.
- This project has an outstanding concept, plan, and execution by a well-equipped team. The fabrication processes are scalable to enable faster rollout of the technology once its development is successfully completed.
- This is a novel approach that should give significant catalyst performance gains. The project has an excellent team, and each member's strength is well-utilized.
- Overall, this is a great team and a solid topic with good initial results.

Project weaknesses:

- The HOPI ionomer chemistry adds additional ether linkages in the passive repeating unit of the polymer. Ether linkages have been identified as a weak point in other PFSA ionomers. As this project is targeted for HD PEMFCs, the effort should be focused on fully characterizing the stability of this ionomer against chemical/electrochemical degradation.
- The project's weakness is the difficulty in performing all the needed catalyst layer optimizations to properly demonstrate the improvement in the catalyst layer performance using a HOPI.
- The HOPI will likely benefit light-duty applications in the near term. Constraining development to HD targets does not seem like a logical first step.
- There is uncertainty regarding the criticality of Pt ECSA loss in HD applications and uncertainty regarding chemical stability issues of HOPIs.

Recommendations for additions/deletions to project scope:

- Modeling indicates a lower degree of sulfonate-specific adsorption. This could be supported by direct measurements of sulfonate coverage through techniques such as Co displacement. AST results indicate no significant ECSA retention over D2020, yet there is a marked decrease in MEA performance loss for the HOPI. This is an interesting result, but it appears that why this is the case is not fully understood. It would be beneficial to perform dedicated diagnostics testing to determine exactly what is going on, as it could inform future ionomer design. Kinetic enhancement is attributed to increased oxygen concentration at the catalyst surface. While the researchers provide a simple correlation between oxygen solubility and diffusivity in the HOPI, they could provide direct evidence by looking at the MEA performance as a function of oxygen partial pressure in the cathode. This would prove that it is the high oxygen solubility/concentration in the ionomer that is the source of the performance enhancement. This is important, as it will guide further development of this ionomer, as well as others.
- The inclusion of membrane studies on free-standing films of HOPIs would provide valuable insight into some of the key concerns that may arise from their use in HD fuel cells.
- The project should estimate the cost increase relative to D2020, as well as consider HSC support studies and a loading study to compare with the roughness factor vs. performance trend observed in the degradation studies.

Project #FC-328: Fiscal Year 2019 Small Business Innovation Research Phase II: Novel Fluorinated Ionomer for Polymer Electrolyte Membrane Fuel Cells

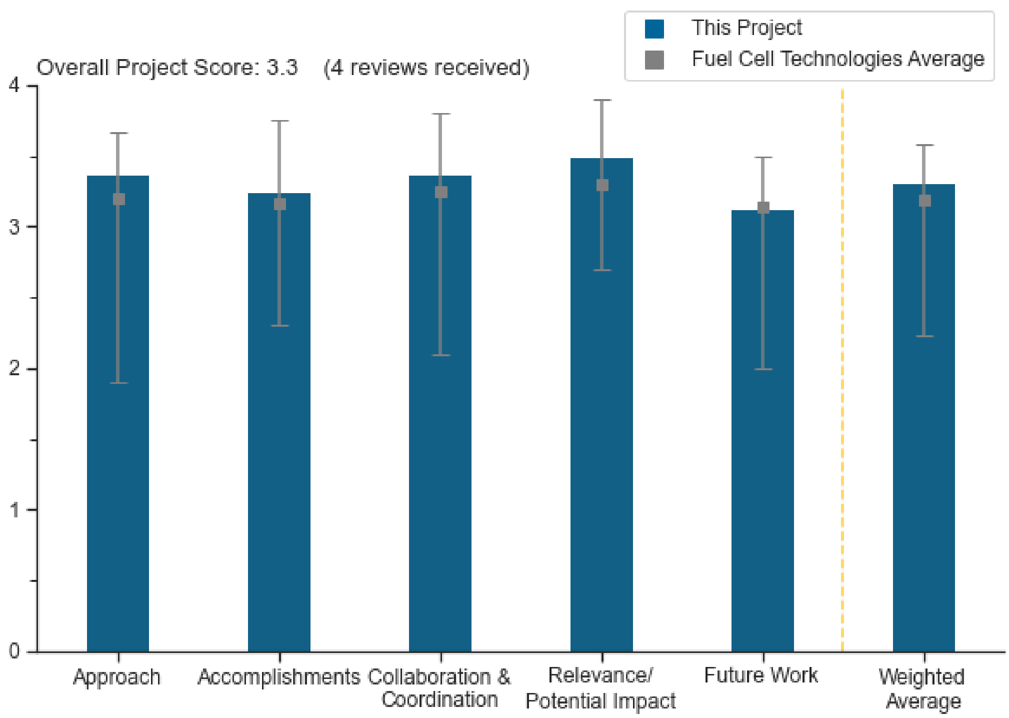
Hui Xu, Giner, Inc.

DOE Contract #	DE-SC0018597
Start and End Dates	5/28/2019 to 5/27/2021
Partners/Collaborators	Compact Membrane Systems, University of Connecticut, University of California
Barriers Addressed	• Polymer electrolyte membrane fuel cell transport loss at low Pt loadings and high power densities

Project Goal and Brief Summary

This project aims to develop a high-oxygen-permeability ionomer that will reduce local oxygen transport loss in polymer electrolyte membrane (PEM) fuel cell cathodes by engineering the polymer backbone to contain molecules with more open space available for transport. If successful, the project will introduce alternative ionomer materials that enable higher power densities compared to state-of-the-art ionomers.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This team is investigating perfluorosulfonic acid (PFSA) materials that have substituted tetrafluoroethylene (TFE) with perfluoro-2,2-dimethyl-1,3-dioxole (PDD) for improving oxygen permeability in the cathode layer. The PDD reduces the crystallinity in the material, leading to enhanced oxygen permeability. This is a good strategy for reducing mass transfer resistances and for extending the current density at low cell voltages. The incorporation of non-crystalline fluoroether over TFE into PFSA was demonstrated by Modestino, Weber, and Kusoglu in the *Journal of the American Chemical Society* (2020); however, the fuel cell results and ionomers are much better in this presentation.

- The team has demonstrated the ability to introduce the PDD monomer into the copolymer at different compositions. The PDD is attributed to the increasing free volume and correlates well with the presented oxygen permeability data. The microscopy and other analyses are good tools to help develop the material and processing understanding.
- The copolymerization of the PDD monomer to increase oxygen permeability in ionomers is an interesting idea, as it could improve both PEM fuel cell and electrolysis performance.
- The work is very relevant to the U.S. Department of Energy's focus on improving performance and durability of PEM fuel cell membrane electrode assemblies (MEAs). However, with the recent focus on heavy-duty (HD) applications and the long life requirements for this application, any new material that is being developed should be compared with the best-in-class, state-of-the-art ionomers, rather than just Nafion™-based material. It would be good to see performance and durability comparisons with other PFSA-based materials.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team demonstrated several different ionomer variants of PDD PFSA in which the perfluoro(sulfonyl vinyl ether) (PFSVE) or perfluoro(sulfonyl ethyl propyl vinyl ether (PSEPVE) and termonomer were varied. The termonomer is confidential information to Giner, Inc. The oxygen gas permeability improved by a factor of 10 for one variant versus Nafion, but this version did not conduct protons well. The best ionomer variant (PDD4) satisfied proton conductivity requirements at 50%, 70%, and 90% relative humidity (RH) (20 to 90 mS/cm), while showing a threefold to fourfold improvement in oxygen gas permeability over Nafion. PDD4 gave a 150 mV gain at 2.5 A/cm^2 when benchmarked against Nafion. Finally, when electrochemically cycled for HD applications (94°C, 65% RH, 250 kPa), PDD4 also had less fluoride emission rate degradation than Nafion. Overall, the project team has made excellent progress toward the project goals. The researchers have also repeated the synthesis of PDD4 (labeled PDD9).
- The project appears to meet several DOE 2020 targets. The presenter states that other targets may be achieved using W.L. Gore PEMs, but no specifics were provided to support the projection.
- Good catalyst accelerated stress test (AST) durability is shown. However, the ionomer's durability should also be based on other HD operating conditions, such as higher temperature, low-humidity conditions, and durability tests that are similar to membrane AST protocol to assess the open circuit durability tolerance of the ionomer.
- This idea is interesting, but unfortunately, the performance is not great. For example, in slide 7, the authors boast three times or ten times higher oxygen permeation at room temperature, but when the temperature is raised to 60°C, the oxygen permeation drops significantly. The high fractional-free volume of the PDD seems to collapse at a slightly higher temperature. It would be interesting to know what the permeation of oxygen was during fuel cell testing at 80°C. Also, the incorporation of PDD has its tradeoff effect in lower conductivity. PDD7, which had the ten-times-better oxygen permeation, had the worst conductivity. Fuel cell performance was also not very exciting; while there was some improvement over Nafion at high current densities, at the low current densities, there was no improvement. It would have been interesting if the higher concentration of oxygen had led to lower overpotential losses at high voltage, but that was not the case. The authors show some durability improvement over Nafion, but that difference is fairly small—not enough to suggest that this material is better than the state of the art.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- The project includes collaborations with Compact Membrane Systems (CMS), the University of California, Irvine, General Motors (GM), and the University of Connecticut. CMS has contributed with the assistance of PFSA synthesis using PDD. The other collaborators determined the local oxygen mass transfer resistance and ionomer surface coverage for the various new PDD ionomers, in addition to looking at changes in the cathode structure post-mortem cycling (e.g., via transmission electron microscopy [TEM] and nano computed tomography [nano-CT]). These measurements can help optimize the next version of the PDD variant for fuel cell applications.
- The team has successfully collaborated to prepare and evaluate these new ionomers for the cathode with improved oxygen permeation and coauthored a journal publication that has been submitted. Future plans include collaborations with the Fuel Cell Consortium for Performance and Durability (FC-PAD) and original equipment manufacturers (OEMs) toward material validation, which may (ideally) have begun now.
- GM has provided flowfields to test oxygen transport. It would be good to see some MEA testing by industry leaders such as W.L. Gore and The Chemours Company as well.
- The collaborations are sufficient.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project team has hit most of the 2020 Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRD&D Plan) catalyst and HD MEA targets with the new materials. This includes activity and MEA performance requirements at high cell voltages. The durability at high cell voltages was retained. Performance and performance durability at lower cell voltages, where reaction kinetics is more controlling, was not satisfied, but the attained results were close to hitting the targets.
- Considering the relevance and potential impact of the project concept, an investigation to scale up the ionomer polymerization is critical to the success of this approach.
- This is an important area for fuel cell performance. It would have been good to provide the oxygen permeability values from slide 7 at 80°C, as fuel cell tests were performed at 80°C.
- The idea was sound, but unfortunately, the resultant materials did not have high enough oxygen permeation (especially at higher temperatures of 60°C). Moreover, the incorporation of PDD had a large effect on lowering the proton conductivity. The results of both of these issues led to subpar fuel cell performance at fully humidified conditions. It seems likely that at lower RH and higher temperatures, the performance of these materials falls behind the current state of the art.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- Future activities focus on material scale-up and providing samples to fuel manufacturer partners. Other activities include adopting a better membrane with free radical scavengers, in addition to testing ionomer durability with a more rigorous stress test (e.g., hydrogen peroxide vapor cell testing). The team is putting together a *Nature Energy* paper based upon the results.
- The presenter stated that there are plans to scale the synthesis of ionomer batches from the current 200 ml to kilogram scale. There were comments related to slight variations between batches (actual percentage of PDD in the product), so it will be important to determine acceptable compositional tolerances and maintain desired performance. No cost analysis projections for the ionomers were noted.
- This project has a good approach to test the MEAs at other locations, including FC-PAD. However, the testing at 50–100 cm^2 is not sufficient. A larger testing platform (200–300 cm^2) should be planned. Most

performance and durability losses due to current distribution and mass transfer losses are more apparent at that scale.
- This project looks to be spent out, and although future work is planned, there is no budget to do the work. The project appears to be done, with a closeout date of May 27, 2021.

Project strengths:

- The new PFSA ionomer binders for the cathode featuring PDD have improved oxygen permeability, while having adequate proton conductivity. Unlike the 2020 report by Modestino and co-workers, this work optimized the PDD binders to ensure cathode kinetics, while also promoting gas mass transfer. The team satisfied several quarterly project goals and has achieved most of the 2020 requirements for the MYRD&D Plan. In addition to the excellent project progress, the team has engaged in good science to understand how these ionomers interact with electrocatalysts and how they degrade differently from Nafion.
- The project objective and approach are clear and appear fairly controlled. The collective team has the skills and resources to achieve the project goals. While these ionomer materials will likely be limited to PFSAs, this approach may be applicable to ionomers for alternative membrane systems.
- The project was based on an interesting concept and, in principle, should result in ionomers with better properties than the current state of the art.
- This project had a good approach to solve for oxygen transport issues in the ionomer and testing the catalyst AST. However, an AST similar to the open circuit test is critical for assessing the ionomer durability under start-up/shutdown conditions. This is good collaborative work to synthesize novel composite ionomers.

Project weaknesses:

- There are no major project weaknesses noted for this project. The presenter stated that some automation within the synthesis may improve composition reproducibility. In general, achieving tight composition control in free radical reactions is challenging.
- Subscale-size MEAs do not shed light on the overall mass transfer and current distribution issues in real-world HD applications. A larger MEA (200 cm^2) should be tested under similar test conditions. Ionomer thickness in the catalyst layer, and its effects on overall performance and durability, is necessary to arrive at an optimal catalyst layer ionomer content, as well as to understand cost and durability tradeoffs.
- Unfortunately, the actual materials did not meet expectations and did not meet DOE Hydrogen and Fuel Cell Technologies Office milestones.
- No major weaknesses were identified with this project.

Recommendations for additions/deletions to project scope:

- This project has ended, but any future funding to this technical approach to improve oxygen transport using PDD-based ionomers should include a scalability study, both for manufacturing ionomers and for testing larger-platform MEAs.
- The collaborations with FC-PAD and OEMs will be important, but delays due to COVID-19 are understood to be a hindrance.
- The project seems to have wrapped up, so there are no recommendations.

Project #FC-330: High-Efficiency Reversible Solid Oxide System

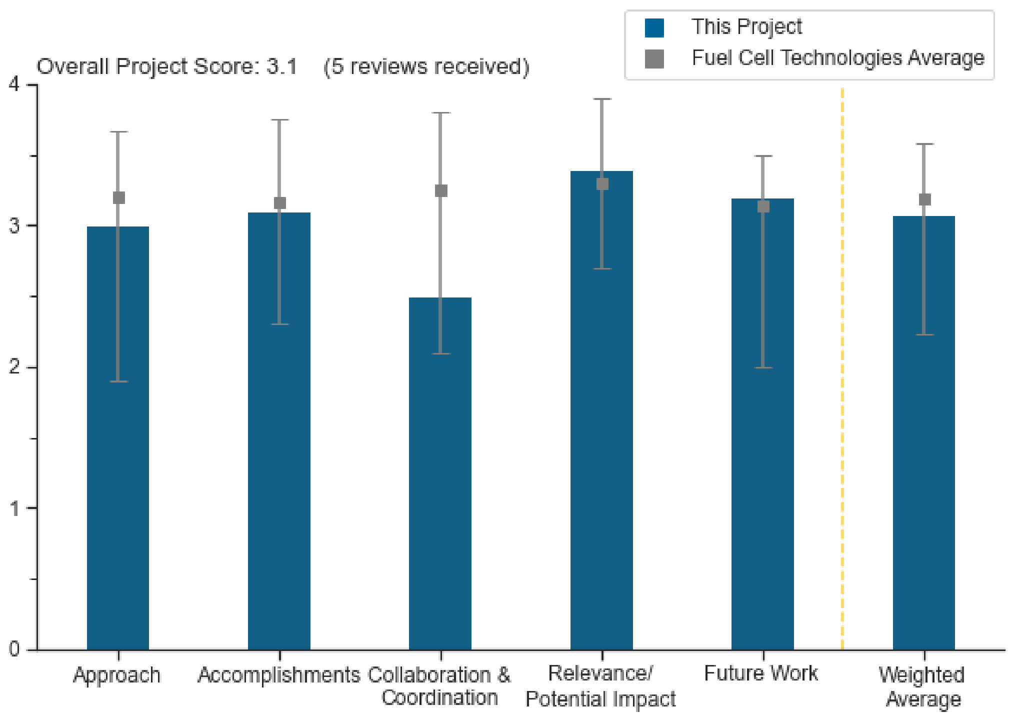
Hossein Ghezel-Ayagh, FuelCell Energy, Inc.

DOE Contract #	DE-EE0008847
Start and End Dates	10/1/2019 to 5/31/2022
Partners/Collaborators	Versa Power Systems
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Renewable electricity generation Integration

Project Goal and Brief Summary

FuelCell Energy, Inc. (FuelCell Energy) will demonstrate a unitized reversible solid oxide fuel cell (RSOFC)-based system, rated at 3 kWe fuel cell power output and 15 kWe electrolyzer power input. The RSOFC system will integrate a novel hot water thermal energy storage system to demonstrate up to 60% system round-trip efficiency (RTE) in testing, with a path to ≥70% RTE. Technoeconomic analysis will validate the projected system costs, which are expected to be at \$1,000/kW and \$100/kWh. The team will complete a system design and define the required operating conditions for the unitized RSOFC stack, including preferred pressurized operation to achieve the targeted RTE performance. Stack testing will validate the technical approach and operating conditions and will demonstrate less than 5%/1,000 cycles RTE degradation over 100 cycles between fuel cell and electrolysis operating modes.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project objectives and critical barriers have been clearly identified, and tasks are well-designed, feasible, and integrated with other relevant efforts.
- FuelCell Energy is a U.S. leader in solid oxide electrolyzer cells (SOECs) and solid oxide fuel cells (SOFCs). The approach to performing the work is consistent, logical, and aimed at accomplishing the U.S. Department of Energy (DOE) Hydrogen Program goals and milestones. However, FuelCell Energy needs to report the thermal situation of the SOEC, that is, whether it is thermal-neutral. More details need to be given on the thermal storage device and its economic and operational significance.
- The goal of this project is to develop a system for grid-scale storage. The principal investigator shows a depiction of a 1 MW system, which would be the appropriate scale, but the plan for a full-size stack is approximately 10 kW. This means there would be approximately 100 stacks in a 1 MW system (e.g., the process diagram shown in slide 14 with 100 stack modules), which is not viable. Plumbing is required, and half of this plumbing is transporting hydrogen. If DOE sees a need for a small-scale system (e.g., for residential applications), then this approach would be acceptable. However, this technology is not viable for megawatt scale unless the stacks are on the order of 100 kW, which does not seem to be possible for this developer.
- The approach was not clearly described. The objective stated, "Develop storage system design and identify operating conditions that maximize the potential of the RSOFC stack and materials technology in meeting RTE performance and degradation goals; Demonstrate 0.5%/100 cycles RTE degradation," but how exactly RTE could be improved or determined was not explained. It was unclear whether the measured RTE was >70%, how the operating conditions (partial pressure of water [pH_2O], how the voltage–current density curve [V-I], and utilization) would be changed to improve RTE, whether only a pressure effect on RTE would be tested, and what would happen if the pressure does not have a significant effect on RTE.
- It is not clear how the team plans to verify that the energy cost of <$100/kWh is achievable. It would be helpful to clarify how the verification is done—whether only through technoeconomic analysis (TEA), perhaps based on the operating strategy already demonstrated, or through a targeted experiment to verify or prove the technical feasibility.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made significant progress, as measured against well-defined performance indicators, and attained accomplishments above the project milestones toward addressing critical barriers to achieving DOE goals.
- An RTE of 75%–80% was achieved; however, the conditions were not mentioned. The stack operating temperature and the gas composition for SOFCs and SOECs should be included. Slide 9 gives 100% H_2 for SOFCs and 22% H_2 for SOECs, but it is unlikely that the gas was completely changed on every cycle. The chosen current densities were low at 0.2–0.35 A/cm^2. These results are quite a bit lower than typically reported by FuelCell Energy; no reason was given. It was also unclear what was causing the main losses on cyclability.
- The results are impressive for this point in the project, with <10% of funding spent; however, the durability results are not adequate. A major issue with solid oxide cells is thermal cycles, and it does not appear that any complete start-and-stop cycles (which will occur in the real world) have been done. Even if the plan is to keep the system hot at all times, it will still need to be put into a standby mode (unless the cells will be kept filled with hydrogen), and the system will be shut down for maintenance. Durability results need to include these stressors, not just continuous cycles.
- There has been interesting and important progress in RTE. The major concern with the project is the acute underspending.

- The project needs to clarify whether there are delays for some of the milestones (milestones 3 to 6 and milestone 9), as appears to be the case on slide 6.

Question 3: Collaboration and coordination

This project was rated **2.5** for its engagement with and coordination of project partners and interaction with other entities.

- A list of potential industry committee members has been identified, and an advisory board is being formed. It is expected that the advisory board will provide valuable guidance for product definition and specifications and oversee the development of the proposed high-efficiency RSOFC system.
- An advisory board is being formed to provide guidance for product definition and specifications and to oversee the development of the energy storage RSOFC systems. Otherwise, there is no apparent technical collaboration.
- Having an advisory board is a good way to identify a demonstration site and receive user feedback; however, having eight very different organizations might be too complicated, as it would be difficult to coordinate, actually collaborate, and discuss the issues. It is suggested that the group be reduced to around three members.
- It is not clear whether the industry committee members (slide 16) have already been engaged and, if so, how. Also, it is not clear how the committee will help with defining the system operating conditions, given the specificity of the system design. Finally, it is not clear what the involvement of Versa Power Systems (VPS) is within the project.
- Only one official collaborator is mentioned—VPS—and VPS's role in this project is never made clear. The researchers claim they are going to form an advisory board, but it is not clear why this has not already been done if the project started in 2019 (as stated on slide 2). The team could definitely use some guidance on storage requirements on the grid.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project will significantly contribute to the Fuel Cell Technologies subprogram by addressing the barriers of cost and performance and demonstrating RSOFC technology.
- Projects focused on the development of RSOFC systems achieving RTE, cost, efficiency, thermal integration, and operability are key projects for the Fuel Cell Technologies subprogram of the Hydrogen and Fuel Cell Technologies Office.
- The project is well-aligned with the general Hydrogen Program goals.
- There is a question of how easy it would be to translate the data obtained from a 3 kW demo to a 250 kW unit, which would be 80 times larger, and whether there would be additional losses and penalties expected in that scale-up.
- It is unlikely that this project will have any real-world impact, even if it is successful from a technology perspective as it is currently set up. Nonetheless, this project could contribute to the advancement of RSOFCs, which might be useful if the team can find an application that wants a relatively small-scale storage system with ultra-long duration (e.g., >12 hours, which is the point at which the capital expenditures on a dollar-per-kilowatt-hour-stored basis might be somewhat reasonable).

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- The project has effectively identified the remaining challenges and planned its future in a logical manner by incorporating appropriate decision points and considering barriers to its goals.
- The proposed work is appropriate. Much work remains to come up with an optimized storage system, such as a completing an RSOFC system analysis, completing a process flow diagram, developing steady-state

CHEMCAD models for electrolysis and fuel cell modes, developing a dynamic model for a thermal storage system, running simulations to optimize system configuration and equipment sizes, performing TEA, conducting an RSOFC product configuration, developing stack and system costs at high-volume production, and considering operating and maintenance costs.

- It appears that future tasks are mainly system modeling and TEA. No details on the validation were given. The stack test task is very vague, and no details were provided on how the degradation will be reduced. It was unclear if it is all in operating conditions for parameters such as pressure.
- The Remaining Challenges and Barriers on slide 17 appear to indicate that the current project approach is not viable because improvements in both cyclability and durability are needed (i.e., the successfully completed GN1 milestone is an inadequate assessment of what is actually needed); the system-level RTE is still a challenge, even though the cell RTE is good (this will always be the case in a high-temperature system); the TEA has not been done; and the results could be either poor (and realistic) or decent (with bad assumptions), since it is quite obvious that a 1 MW size system will simply be prohibitively complex.

Project strengths:

- The project has made significant progress successfully building and testing a 50-cell SOEC stack operating up to 410 charge–discharge cycles for >2000 hours, exceeding both RTE and degradation targets.
- This is an important effort to demonstrate a potentially high RTE of SOFCs and SOECs. The calculated data are less optimistic at <45%. Good experimental data are needed.
- This is a well-qualified team. The RTE work is excellent.
- This project is focused on challenging technology that requires substantial improvements.

Project weaknesses:

- The tasks description is very vague throughout. The project needs a clear path on how the losses on cycling and degradation will be addressed and what causes them.
- It is unclear how the project will contribute to identifying limitations related to the materials and cell design used for RSOFCs.
- This project's weakness is underspending. It has a well-qualified team that is drastically underspent.
- The overall system and the viability to meet the DOE objectives is not well-thought-out.
- The team is weak in its collaboration at this juncture.

Recommendations for additions/deletions to project scope:

- The project has proceeded as planned, and there is no need to change the project scope.
- The project should identify possible reasons for the degradation and how it could be reduced or eliminated.
- The team should review the schedule, timeline, and budget for the project and determine whether the work can be completed in a timely manner.
- DOE should consider stopping this project, unless the Department is interested in ultra-long-duration storage for small-scale applications. This project is highly unlikely to address grid-scale needs or the ramping up of intermittent renewables in a significant manner.

Project #FC-331: A Novel Stack Approach to Enable High Round-Trip Efficiencies in Unitized Polymer Electrolyte Membrane Regenerative Fuel Cells

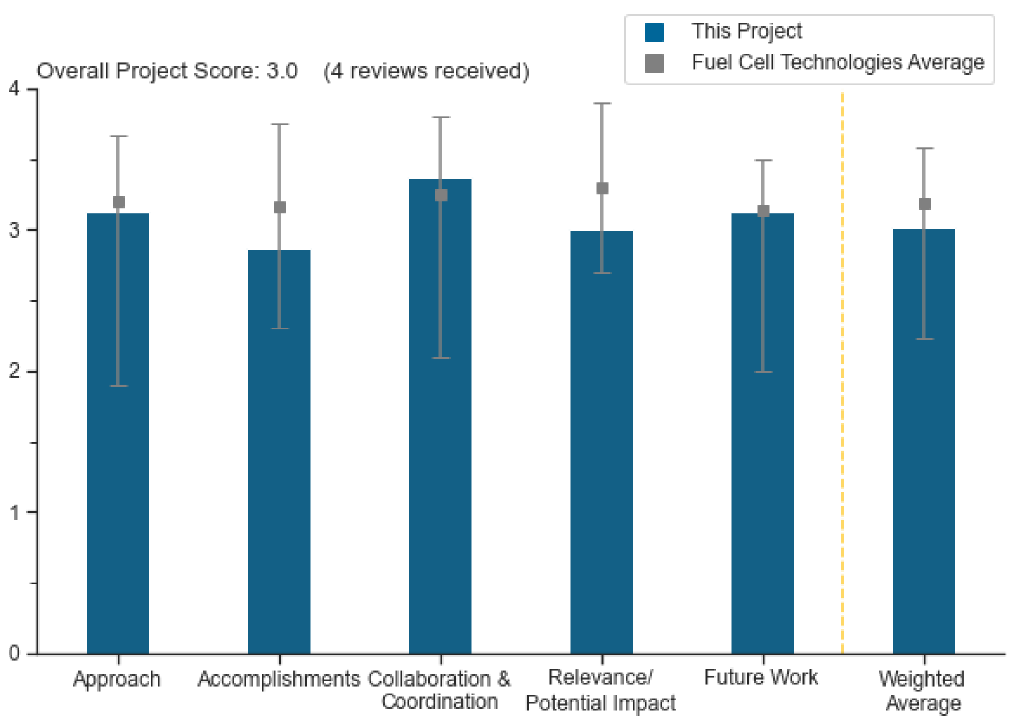
Katherine Ayers, Nel Hydrogen

DOE Contract #	DE-EE0008848
Start and End Dates	5/1/2020 to 12/31/2023
Partners/Collaborators	Electric Power Research Institute, Southern Company, Lawrence Berkeley National Laboratory, Gaia Energy Research Institute
Barriers Addressed	• No regenerative fuel-cell-specific barriers • Optimization between fuel cell and electrolyzer barriers • Fuel cells (durability, cost, performance) • Hydrogen production (capital cost, system efficiency, and electricity cost)

Project Goal and Brief Summary

The overall project goal is to demonstrate a unitized reversible fuel cell (URFC) system based on polymer electrolyte membrane technology that can achieve 50% round trip efficiency (RTE) and reliable performance under relevant duty cycles, with projected costs below $1750/kW. An early focus of this project is to develop a low pressure electrolyzer membrane electrode assembly and stack design which much more closely resembles the fuel cell construction (e.g., thinner membrane), providing a pathway to higher RTEs for URFCs.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project has a well-balanced and well-thought-out approach. Having a trade-off study to vary the extent of stack pressurization vs. mechanical pressurization is a good idea. The idea of a series of tutorial presentations to the power industry is appropriate for improved outreach and has some merit. The key approach to improved systems appears to be a thinner membrane (balanced with an optimized operating pressure) and proper water management.
- This is an experienced team with a significant amount of technology background, integrated with potential end users and those experienced in cost analysis. The approach appears to be sound.
- It is hard for a project to do a great job in addressing U.S. Department of Energy (DOE) objectives, if DOE has not established clear targets. If there are no regenerative fuel-cell-specific barriers, as stated on slide 3, then the principal investigator (PI) should provide some and show how this approach addresses them. There certainly are challenges, which can be more specific than the simple qualitative ones listed on slide 3.
- It is difficult to identify the innovation in this project. The project focuses on stack optimization, system integration, system testing, modeling, and outreach. There is not much focus on scientific development or materials/components development. It seems to be more of a demonstration project than a research and development (R&D) project.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Not much work has been done yet because of COVID-19 delays, so most of the work is still future work; however, significant work has been done on down-selection of catalysts and membranes and on modeling and model validation.
- The project is still in the early phases and was delayed by COVID-19 and so simply is not at a point where the team has many technical results to report. What the researchers have so far is good and as expected.
- The team has done a good job at demonstrating electrolyzer performance during the first five quarters, but there is little evidence that much has been done on demonstrating fuel cell performance.
- Little progress is shown on the stack design, although it is listed as a primary accomplishment. The cell optimization graphs show good progress and substantial polarization improvements with thinner membranes and high platinum loadings. The meanings of the open symbols on slide 11 are not defined. Analysis of four different membranes is very good. More description/assessment should be paid to durability. The slight changes in voltage during the short-term-durability testing are not clearly significant, yet durability should be a main factor in cell design selection.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration with the Electric Power Research Institute (EPRI), Southern Company, and Lawrence Berkeley National Laboratory (LBNL) grants significant benefits to the project. Gaia Energy Research Institute is qualified to conduct the pressure trade-off study and is very well-suited to conducting the outreach presentations.
- The team is well-composed, and the outreach activities are valuable.
- The project includes some relevant and capable team members, namely LBNL and Gaia Energy Research Institute; however, it is not clear how much these two members have contributed lately. The work with EPRI to educate electric utilities is commendable, as teaching utilities is a major challenge for many reasons.
- Nel Hydrogen's established collaboration with LBNL is a big part of this project. Given that there is a separate project led by LBNL with Nel Hydrogen as a team member, some discussion about how the work

scope is divided between the projects should be included. Two partners are included whose roles seem to relate mainly to outreach and promotion of URFCs. Those partners' contribution to R&D in the project is not clear.

Question 4: Relevance/potential impact

This project was rated **3.0** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- A low-temperature URFC is a viable pathway to using hydrogen for grid-scale energy storage, especially ultra-long duration. Nel Hydrogen has demonstrated the ability to build megawatt-scale electrolyzers, and the approach is credible.
- This project ties into the overall goals of the Hydrogen and Fuel Cells Technologies Office around long-duration storage using hydrogen. It a serious question whether it makes sense to make a URFC, as this team is trying to do, versus two separate systems. The ultimate relevance of this approach should be clearer by the end of the project.
- The relevance and potential impact are significant if the project can meet or beat the targets. There are concerns that the cost goal of $1750/kW is too high for economical implementation.
- The project focuses on screening materials and optimizing stack performance. The project is unlikely to achieve more than incremental improvements in URFC technology. There is not much new science or R&D that could have a substantial impact. The project is about a novel stack approach, but the novelty is not clear.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The future work focuses on analysis, screening, demonstration, and outreach. This work fits within the modest goals of the project but does not seem likely to result in innovation.
- The future work is as expected and is in accordance with the project plan.
- The plan looks good, except there should be more durability testing during this project. It is understood that the primary focus is meeting performance targets, but 100-hour or 200-hour durability tests are anemic. If longer tests are seen as impractical here, then the team should do some accelerated stress tests (ASTs). LBNL has already identified some key durability challenges, such as extreme potential cycles that result in catalyst dissolution and losses.
- The slide for future work does not hold much information, but the slide for key milestones furnishes the needed information.

Project strengths:

- Nel Hydrogen and the PI are very well-qualified to conduct this project. There is a high probability of project success. Collaboration with EPRI, Southern Company, and LBNL brings substantial support and capability to the project.
- The project has a good approach to the development of a viable URFC. There is a great team with the right skills and capabilities.
- Nel Hydrogen is a key developer of electrolyzer and URFC technology and brings substantial background in this area.

Project weaknesses:

- The project is focused on incremental progress through optimization of URFC stacks. There is not much innovation in the approach, nor is there a key idea or hypothesis driving the work. The project would fit better in a demonstration program than in an R&D program.
- There is no explanation of how a thinner membrane can be appropriately supported under the delta pressures contemplated. There is insufficient durability testing and discussion of durability aspects. There is

no discussion of the cost target's being adequate for the overall URFC mission. There is no cost breakdown of the stack or discussion of how the URFC stack differs from dedicated fuel cell or electrolyzer stacks.

- There is not enough emphasis on fuel cell performance to date or enough focus on durability issues.

Recommendations for additions/deletions to project scope:

- More engagement with LBNL should be shown; perhaps it is occurring, but it is not clear. For example, the researchers could explain whether they considered using the Constant Gas vs. Constant Electrode configuration and, if so, share which one was selected and why. Additionally, LBNL could create some key ASTs for URFCs and perform some of these. At least one utility that is actually a leader in grid-scale storage should be added to the team. Working with Southern Company, who is actually doing almost nothing in electrical energy storage, is not ideal (it seems Southern Company is not doing anything new but rather is waiting for the ultimate solution). Even if this works, Southern Company will insist that a gigawatt-hour--scale system is needed to start, which is not viable. The team should find at least one more utility partner.
- The project would be improved with more durability testing early on and confirmation that macro goals are achieved if project cost ($1750/kW) and round-trip efficiency (50%) goals are achieved.
- The focus on outreach and the webcasts to electric utilities belong more in an education or technology acceleration project than in a R&D project.

Project #FC-333: Advanced Membranes for Heavy-Duty Fuel Cell Trucks

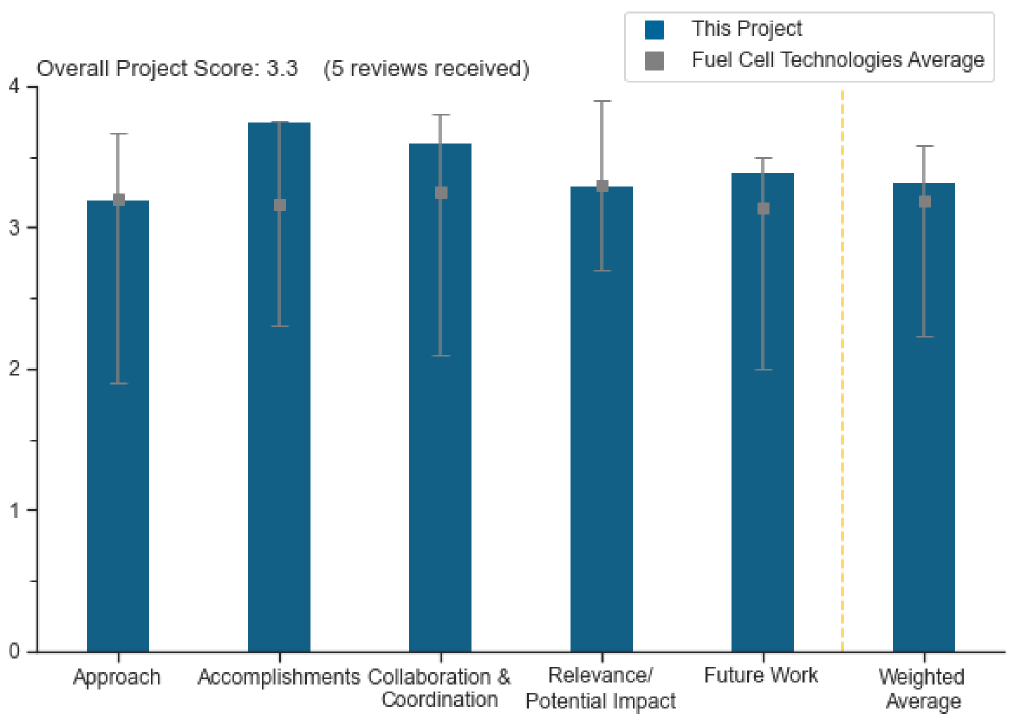
Vivek Murthi, Nikola Motor Company

DOE Contract #	DE-EE0009243
Start and End Dates	Q3 2021 to Q3 2024
Partners/Collaborators	The Chemours Company, Million Mile Fuel Cell Truck (M2FCT) Consortium
Barriers Addressed	• Durability • Performance • Cost

Project Goal and Brief Summary

This project aims to develop membranes with optimized architectures that incorporate thermally stable ionomer chemistries and immobilized radial scavengers. If successful, the project will improve the lifetime efficiencies of membrane electrode assemblies (MEAs) in heavy-duty fuel cell vehicles, reduce the lifetime operational expenses of heavy-duty (HD) fuel cell systems, and improve their commercial viability relative to diesel energy sources. Nikola Motor Company is collaborating with The Chemours (Chemours) Company and the Million Mile Fuel Cell Truck (M2FCT) Consortium on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Note: This is a new project in 2021. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project has not started; it is anticipated for the third quarter (Q3) of 2021. The project looks at property–function relationships for MEA development for HD truck application. There is new polymer development with various equivalent weights. Radical scavengers in general are an interesting approach to improving fuel cell service life and efficiency. This project looks at radical scavengers with reduced mobility by a factor of two as an alternative approach to cerium systems. The presenter stated that the team could selectively control the area and local concentration of the radical scavengers. It will be interesting to understand more about how this is practically achieved in mass-produced membranes. An organized work plan for the team was presented. It appears to have identified possible challenges and provided initial approaches to mitigate them. Gaining insight into factors that govern dissolution and migration of scavengers, as well as radical scavenger efficacy, would benefit the field. The association of the cerium cation approach was mentioned.
- The project aims to improve the MEA's lifetime and efficiency by incorporating thermally stable ionomer chemistries and immobilized radical scavengers for higher-temperature membranes. This is a feasible approach for realizing this goal, and the approach addresses the challenges and discusses how to overcome them. The project also includes an effort to synthesize new monomers/ionomers.
- The proposed approach to ionomer synthesis, radical scavenger doping, and performance/diagnostic testing is adequate and well-defined. Tailoring analysis to HD drive cycles will do a better job of highlighting early limitations of the developed materials, helping the project to make the needed adjustments.
- Increasing the life and reducing the lifecycle cost of MEAs for fuel cell trucks is critical.
- The approach attempts to modify the polymer chain to increase the stability and also immobilize the ceria radical scavenger. The project identified targets for reduced ceria mobility to one-half of what is the current state of the art. It is not clear that is enough to reach U.S. Department of Energy targets for HD application. Other targets for resistance and hydrogen crossover mechanical and chemical accelerated stress tests (ASTs) are already achieved (aside from a slight improvement targeted for AST) with the state-of-the-art membrane NC-700, so based on the project targets slide, it looks like the project is targeting only a small improvement.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project is just starting, and no DOE funds have been spent so far. Thus, the progress cannot be evaluated fully.
- The project just started, so it is difficult to make a quantitative analysis of accomplishments.
- The project has not started, so no accomplishments/progress were presented.
- This is not applicable, as the project has not yet started.
- The project is expected to start in Q3 2021.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- There is an excellent team, with an original equipment manufacturer leading the project for measuring lifetime under realistic driving conditions; there is an excellent membrane industrial team member.
- This is a very good team that combines synthesis, characterization, and evaluation expertise. Interaction with M2FCT is planned.

- There are many collaborations, from ionomer suppliers to membrane characterization. A wide range of research activities, from synthesis and cell testing to characterization, will improve the project's likelihood of achieving its objectives.
- A membrane manufacturer is on the team, as well as an academic partner for membrane characterization and AST development.
- The team has been assembled, and the proposed flow of work sets it up for success.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Membrane durability, particularly membrane durability at elevated temperatures, is critical for HD applications. The integration of drive-cycle analysis, organic and inorganic membrane chemistry modifiers for radical scavenging, and detailed analytics position this project to make a significant impact. This work is needed as part of the push to advanced HD polymer electrolyte membrane fuel cells.
- Success in completing this project will be very important to increasing the service life of fuel cells and achieving DOE goals.
- The project goals to improve MEA efficiency and durability through ionomer chemistry and optimization of the radical scavengers and the MEA architecture are in line with DOE Hydrogen Program objectives.
- Developing MEAs that meet the extended lifetimes for fuel cell trucks and expand the operating envelope is on the critical path toward DOE's objectives.
- It is uncertain how much impact this project can make; the team has not yet developed an AST procedure, let alone the target. The go/no-go for Q6 looks like all points already achieved with the NC700, the current state-of-the-art membrane.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- Focusing on synthesizing the novel ionomer while in parallel improving membrane reinforcement, ionomer polymerization/dispersion, and refining membrane ASTs is an excellent plan.
- The future work, which is essentially the whole project, is well-defined and has a good chance of accomplishing the proposed goals.
- The proposal includes a plan with tasks involving membrane design and optimization and cell testing with ASTs. Two approaches for immobilization have been proposed, metal-doped ceria and a polymeric route, along with the development of a new ionomer that can help mitigate certain risks associated with the proposed strategies.
- Proposed future work is good; it just needs some work on defining the goals and targets. If the premise is that Ce migration has a strong impact on membrane lifetime (which makes sense), then if the project strongly immobilizes Ce, lifetime (or lifetime AST) should increase dramatically.
- Since the project has not started, the project is considered as future work. The polymer synthesis and structure–property relationship studies are always valuable to the community if the data are shared and published. Only one go/no-go milestone (Q6) was presented.

Project strengths:

- There are well-defined methods to diagnose and characterize the scavenger migration rate and efficacy. They will likely provide useful insights for understanding this phenomenon and for developing immobilization strategies. The team and the collaborations, with well-defined tasks and responsibilities, will likely support the approach and realize the goals.
- There is a good team and good potential to make a fundamental improvement in membrane durability.
- The combined approach of a possible new membrane with Chemours and a possible systematic introduction at the monomer level of tethered radical scavengers is a significant strength.

- The project addresses critical needs for HD fuel cell vehicles in a logical manner with a very good team.
- Risks are mitigated by using both inorganic and organic radical scavengers. Detailed analysis of Ce mobility/transport is included. Detailed drive cycle analysis will help guide other materials development projects. The project has monomer-directed inclusion of radical scavengers.

Project weaknesses:

- No weaknesses were noted in the stated project objectives and approach to addressing the specific goals. The use of perfluorosulfonic-acid-type membranes will continue to limit practical cell operating temperatures. The presenter mentioned the possibility of reducing the radiator size with higher-temperature operations, but it is believed that 80°C–95°C may not be significant enough to warrant that general statement.
- The task lists have too many parameters to choose and optimize from new monomers to membrane parameters and scavenger strategies. It is not clear how they will be prioritized and narrowed down with a clear path forward (work plan).
- Targets and goals should be better defined.

Recommendations for additions/deletions to project scope:

- It is unclear how the team plans to control and optimize local variation with novel monomers or other strategies (slide 15). It is not entirely clear whether the synthesis effort for new monomers is part of the strategy for immobilizing the radicals or whether it will be a separate effort to develop membranes for improved durability. This should be clarified: whether the focus is the optimization of radical scavengers or whether the other membrane properties will also be optimized for HD fuel cell trucks.
- The project should define appropriate targets and ASTs early in the project.
- The project should determine whether scavengers can be regenerated.

Project #FC-334: Extending Perfluorosulfonic Acid Membrane Durability through Enhanced Ionomer Backbone Stability

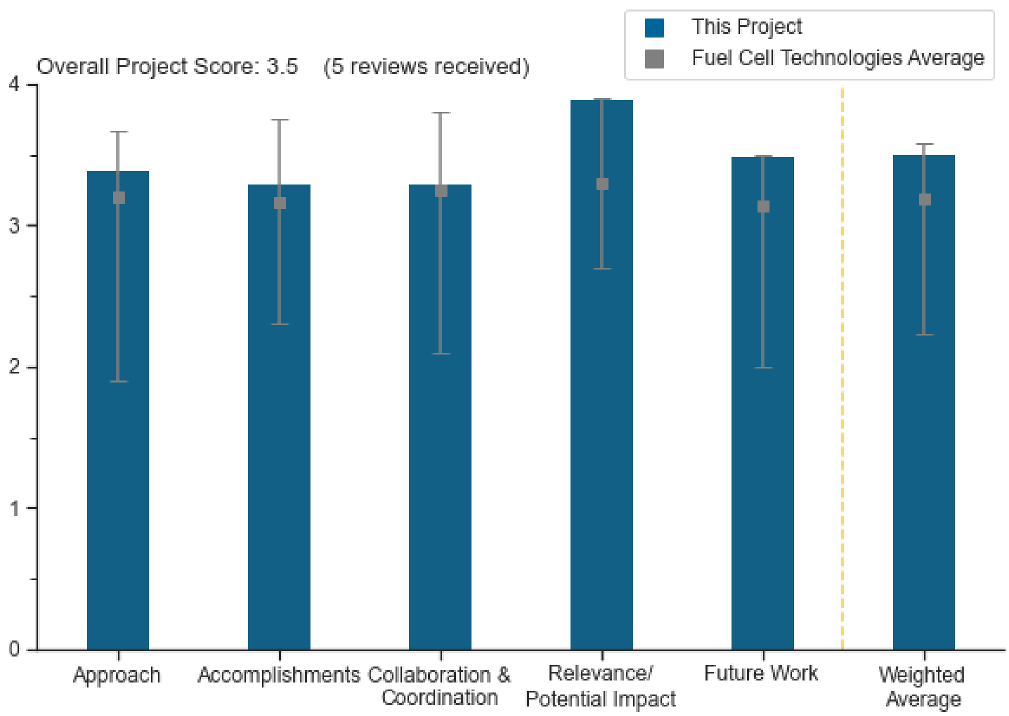
Michael Yandrasits, 3M Company

DOE Contract #	DE-EE0009244
Start and End Dates	1/1/2021 to 12/31/2023
Partners/Collaborators	National Renewable Energy Laboratory, General Motors
Barriers Addressed	• Durability • Performance • Cost

Project Goal and Brief Summary

This project aims to increase membrane lifetimes by improving the inherent chemical stability of perfluorinated membrane ionomers. If successful, the project will increase fuel cell lifetimes and allow fuel cells to meet the U.S. Department of Energy's 2030 heavy-duty transportation target of 25,000 hours of operation.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Note: This is a new project in 2021. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project approach is excellent. The team first identifies the chemically weak linkage of perfluorosulfonic acid (PFSA) using density functional theory (DFT) calculations and tries to improve the stability by synthesizing novel ionomers. Also, the project approach contains a small molecule study that can verify the DFT results.

- The team has done an excellent job in identifying the critical barriers, setting the project objectives, and developing a very logical approach.
- The team's approach is to get a fundamental understanding of the energy state of degradation initiation atoms and, hence, design a "new" perfluorinated ionomer with a side chain architecture immune to radical scavenging and stable under oxidative attacks under dry fuel cell operational conditions to achieve the desired high-performing/low-degrading membrane. This is the correct approach of balancing the structure–property relationship of new ionomeric membranes. The team's objective of understanding the effect of manipulating C-F and C-O groups to enhance side chain stability is the correct approach. Before spending the resources on synthesizing new ionomer, it is better to conduct the modeling of the proposed side chain structure and understand the oxidative activation barriers of oxidation-susceptive bonds. This will help the team in focusing on an ionomer structure that has a high chance of meeting U.S. Department of Energy's chemical durability targets.
- This is a very interesting approach to improving the durability of PFSA-type materials by replacing various weak links (tertiary fluorine and ether linkage) with perfluoromethyl groups. The fact that this project is looking to stabilize PFSA is great, but the changes will not affect the acid-containing unit, so it is possible to expect higher durability and loss in conductivity. Moreover, fluorochemistry manipulation is not trivial, but the folks at 3M Company (3M) are experts in this area, which gives this project a higher probability of success.
- The project has very detailed and clear tasks. A clear effect of changing the structure on chemical durability would be expected, but it is only about the durability regardless of performance, i.e., ionic conductivity. As mentioned in the slide, the end group working on ionic conducting is out of scope. There should be additional research for the performance improvement.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project started in January 2021. In six months, the team has accomplished DFT calculation of reaction barrier modeling, DFT solvation, and protonation modeling, as well as establishing the synthetic pathway of a monomer precursor with isopropenyl ether functionality. The team has also established the baseline of 3M standard ionomer degradation under open-circuit voltage (OCV) conditions. Six months into the project, the team has made significant progress into its effort of developing oxidatively stable ionomers for fuel cell use.
- There is not much experimental progress with this project, as the project started on January 1, 2021. The National Renewable Energy Laboratory (NREL) DFT modeling study has made some progress. DFT reaction barrier modeling shows that H radicals attach on ionomer C-F bonds. The 3M ionomer has more stability than a long side chain ionomer. The proposed ionomer that replaces C-F with CF3 in the PFSA backbone may further increase the stability. DFT calculation also shows that introducing CF3 in the polymer backbone would have no impact on the protonation state, which is intuitive. Monomer synthesis seems to be challenging. 3M has started the monomer synthesis. Other accomplishments, such as OCV studies, degradation mechanism studies, and combined chemical–mechanical tests, were presented. Those are relevant to the project, but it is believed that the works were done by other resources. It is acceptable since the project started late.
- The DFT modeling task has progressed well. Good progress has also been made in the effort to establish some baseline performance for the current 3M ionomers. The team seems to have yield issues for the monomer synthesis, but the milestones are not due yet.
- Fluorochemistry is not easy, and monomers are being synthesized, but the optimization will take time, and it should not be expected that optimization occurs in a few months.
- Considering the initial state of the project, the plan and initial study are very logical, with a clear target.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The team constitutes two industry representatives (3M and General Motors [GM]) and one national laboratory (NREL) as partners. The work has been distributed well amongst them based on their core expertise. The six-month progress reported by the team on DFT modeling (NREL), monomer synthesis (3M), and establishing the OCV baseline degradation condition and conducting different accelerated stress test/highly accelerated stress test (HAST) protocols (3M, GM) clearly shows a good collaborative relationship between these three partners. In the past, the prime, 3M, has worked with NREL and GM on several DOE-funded projects, and the three organizations have demonstrated good working relationships. Therefore, it can be expected that the team will demonstrate a similar collaborative environment in this project.
- The team is strong, and the team members have the right expertise for the project. NREL demonstrated modeling work for the project, and GM likely provided valuable durability data using the company's HAST protocol.
- There is a good team of a national laboratory (for modeling), material synthesis, and original equipment manufacturers (OEMs).
- All partners need to be engaged and are very engaged.
- It is still in the initial state, so it is not expected that there is deep collaboration.

Question 4: Relevance/potential impact

This project was rated **3.9** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is relevant to three out of seven DOE targets established for Class 8 long-haul tractor-trailers. The success of this project will make a significant impact in bringing the fuel cell technology a step closer to commercialization. This project directly addresses the fuel cell system lifetime and consequently addresses system cost and peak efficiency targets. The chemical durability (OCV) target of DOE is >500 hours. The OCV durability target of this project is three times higher (>1500 hours) than DOE's target. In support of the chemical durability of the membrane, over and above DOE's chemical durability target, the team has put in place separate accelerated durability targets, OCV fluoride release rates, and a combined "chemical–mechanical" accelerated durability target of >1,750 hours. These two additional targets will reinforce chemical durability properties of new membrane material and are expected to help push up the DOE chemical durability target.
- This approach to improving the durability of PFSA, while still maintaining its high proton conductivity, is very interesting. If this project is successful in developing the next-generation PFSA, 3M can then readily scale the chemistry, and GM would be a perfect end user. If everything plays out as hoped, this could be a potential game changer.
- Developing chemically stable polymer electrolyte membranes (PEMs) is one of the most urgent challenges for automotive fuel cell applications. The approach to modify the chemical structure of PFSA will have a tremendous impact, if successful, and overall, it is a better approach to enhance chemical stability than using a radical scavenger. The downside of this approach is synthetic uncertainty and cost. Nevertheless, this type of effort should be supported by the U.S. government.
- Developing stable ionomers that are free from those known vulnerable groups is critical to reaching the really long lifetimes required by trucks.
- Using a very popular and fundamental material will have a big impact on other research, once there is a meaningful result.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The future work cited on slide 18 is aligned with the development course of the project. Proposed DFT simulation study of category 1 and category 2 structural linkages on slide 11 is a good way of sorting out the weakest link responsible for degradation initiation under low-relative-humidity (low-RH) fuel cell operational conditions. The team has identified the future work correctly, including the work on (i) degradation studies, (ii) DFT modeling, (iii) monomer synthesis and (iv) durability validation needed for identifying the weakest link of the perfluorinated ionomer and, hence, developing a robust side chain linkage for an oxidatively stable ionomer. There is no obvious gap in the proposed work in terms of executing the proposed project.
- The future work is well-organized, including degradation studies, DFT modeling, monomer synthesis, and durability validation. The project needs to focus more on monomer synthesis and polymerization.
- The proposed future work is reasonable and planned out well.
- It is in the initial state. It is expected that there will be a significant development.
- The approaches for the future are very logical.

Project strengths:

- The strength of the project is 3M's expertise in PFSA membrane design. Variations of the chemical structure for current PFSA PEMs can provide valuable information, and the tasks should be done. 3M has done much work in this area, and the studies contributed much to advanced PEM design. The project team is strong and complementary. The project's principal investigator understands the PFSA chemistry well, and the tasks can be accomplished efficiently. GM's involvement in this project is also advantageous.
- Overall, the project is a very well-thought-out project, focusing on identifying the weakest link in perfluorinated ionomer chains and, hence, developing a tailor-made side chain structure that will be stable under low-RH fuel cell operational conditions and, hence, helping DOE to achieve its desired fuel cell membrane target for Class 8 long-haul tractor–trailers. The project partnered with respective technical experts from reputable organizations, well known for their fuel cell expertise. The technical approach and future work proposed by the team are systematic and logical.
- There are many strengths of this project, which has PFSA manufacturing experts who are partnered with a large OEM at GM working to improve PFSA durability. It will be exciting to see what results they can demonstrate next year.
- This project is based on very fundamental materials, and the target is very clear. If there is a good result, then there will be a big impact on future research and development.
- The project team is very strong. The plans of the project, current and future, have been well-thought-out and are well-executed.

Project weaknesses:

- There are none. The project is wished luck, as it is not easy to work with fluorinated polymers.
- There are no particular project weaknesses, other than the fact that this is high-risk and high-reward type of project.
- The team should have a strategy to determine the possibility of synthesizing DFT simulation-predicted side chain structures. The team also needs to have a strategy to rate and compare DFT simulation-predicted stable side chain structures on the scale of OCV oxidative stability and synthesizability of those side chain structures.
- The reservation for this project is how the chemistry manipulation will affect the final cost of the new PFSA. These new monomers will have different reaction steps, product yields, and reactivity ratios, which makes cost very concerning. Also, even small changes in the polymer structure are sure to affect the mechanical properties and hydration characteristics.

- Research using a very fundamental material has two different views. Many similar chemical structures studied in past decades have not shown better properties. If the results show similar or even worse properties, then there would be no impact on future development.

Recommendations for additions/deletions to project scope:

- More work is suggested on monomer or model polymer synthesis before extensive degradation studies and modeling. Novel PFSA development is limited mostly by polymer synthesis.
- To improve ionic conductivity, there should be additional research on the end groups.

Project #FC-335: Additive Functionalized Polymers for Extended Heavy-Duty Polymer Electrolyte Membrane Lifetimes

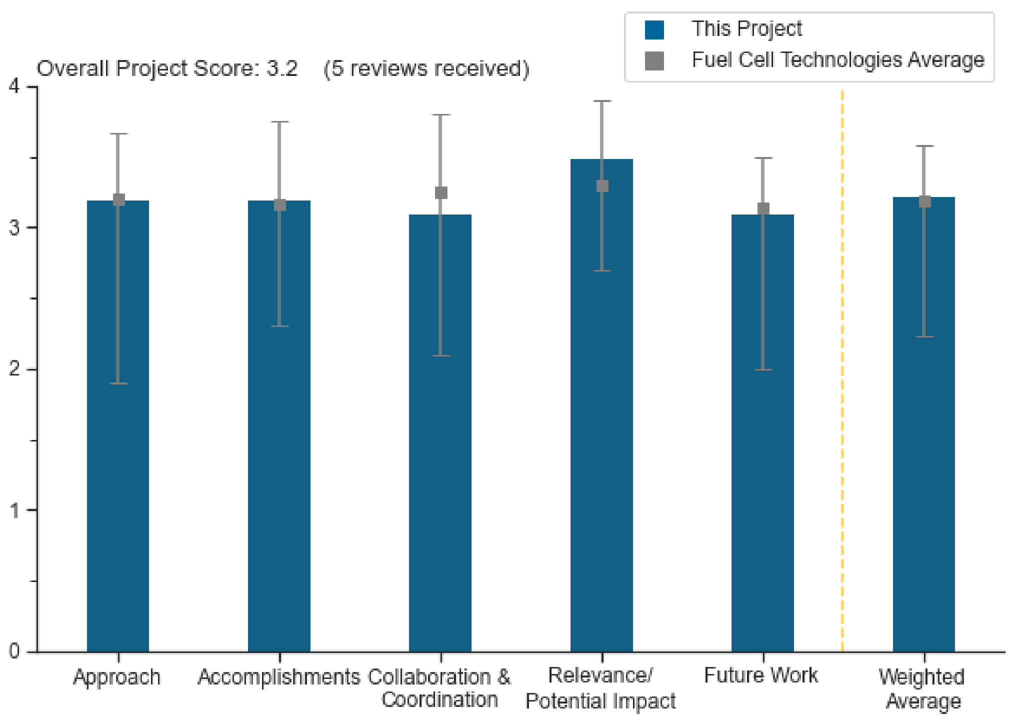
Tom Corrigan, The Lubrizol Corporation

DOE Contract #	DE-EE0009245
Start and End Dates	Q2 2021 to Q3 2023
Partners/Collaborators	National Renewable Energy Laboratory
Barriers Addressed	• Chemical durability of polymer electrolyte membranes • Shortcomings of current radical scavengers • Fuel cell stack lifetime

Project Goal and Brief Summary

The Lubrizol Corporation (Lubrizol) will work with the National Renewable Energy Laboratory (NREL) to develop membranes with enhanced chemical durability, with the goal of improving the lifetimes of polymer electrolyte membrane (PEM) fuel cells for heavy-duty vehicles (HDVs). The research team will identify novel additives to mitigate chemical degradation and find strategies to immobilize these additives, thereby addressing radical scavenger shortcomings. The improved membrane durability could enable PEM fuel cell HDV lifetimes that achieve the U.S. Department of Energy (DOE) target of 25,000 hours (one million miles for long-haul trucks).

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Note: This is a new project in 2021. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The development of membranes with enhanced chemical durability for HDVs is important to achieving DOE's and original equipment manufacturers' (OEMs') goals. Lubrizol is a leading manufacturer of additives for various industries, including radical scavengers. The project wants to demonstrate better scavenging performance than that achieved with cerium, including no migration. The physical blending and covalent attachment are approaches for application of scavengers. The team will use open-circuit voltage accelerated testing to qualify the material. The Year 1 go/no-go milestone to demonstrate chemical stability is comparable with or better than Ce-doped perfluorosulfonic acid (PFSA), with three times greater stability in hydrocarbon PEMs.
- The project goals are to improve durability by overcoming the shortcomings of the current radical scavengers by using two covalent functionalization strategies to immobilize the scavengers. The strategies are explained clearly with specific deliverables.
- This project has a good plan for screening, incorporating, and characterizing membranes with the novel additives. An understanding of the underlying mechanisms of the additives was not discussed.
- The project's approach is good; however, there is some doubt about the point of using an additive to improve the durability of a hydrocarbon membrane that will not be stable enough itself.
- The approach is centered on two methodologies to incorporate additives into the membrane to mitigate chemical degradation. A significant amount of information is left out, most likely for proprietary reasons, making it challenging to judge the potential effectiveness of the proposed strategy.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project is new, with a start date of April 1, 2021. The project has explored two membrane impregnation procedures: swollen membrane and solution casting. The team has demonstrated the preparation of impregnated PFSA membranes via solution casting, with good homogeneity for initial results, and presented initial conductivity data for impregnated PFSA membranes. The preliminary in-plane conductivity shows some effect on conductivity for some additives, but there are no comments on the reason. The preliminary qualitative Fenton test performed shows promising results.
- The team has made excellent progress, given that the project only just started. The team has already demonstrated some durability improvements over non-Ce-doped control samples, which demonstrates that the approach is working. Goals should be set higher than the go/no-go of only equal durability to state-of-the-art PFSA materials. In fact, the team should use a Chemours NC700 as the benchmark, or at least a Nafion™ XL membrane, to determine whether improvement over the state of the art is made.
- The membranes incorporating non-covalent additives have been fabricated using two strategies. The project identified the pros and cons for each strategy and membrane. Casting and fabrication conditions have been optimized to cast membranes that are intact. The bar plot in slide 9 zooms into a narrow range of values and could be misleading since the actual reduction achieved would be less than it appears.
- A number of control samples and samples with additives have already been prepared. The Fenton test results and membrane conductivity may be within the error margin of the measurement.
- The project just started, but it has demonstrated two methods for additive incorporation, and early testing indicates that chemical stability improved with the additive.

Question 3: Collaboration and coordination

This project was rated **3.1** for its engagement with and coordination of project partners and interaction with other entities.

- The project listed NREL (Million Mile Fuel Cell Truck [M2FCT]) for various types of evaluation and cell testing. Such testing will help with the project's progress and membrane assessment in the cell.

- NREL is a good partner that can verify the accelerated stress test improvements by comparing results to the laboratory's own baseline.
- NREL has very good expertise in membrane electrode assembly fabrication and characterization.
- NREL is the only partner mentioned. The general work plan with NREL was presented.
- The team is sufficient to complete the proposed work.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The approach has excellent potential to improve the state of the art if the project can demonstrate the immobilization of the additive and demonstrate that the additive will not leach out or get destroyed during operation.
- If Lubrizol can identify a low-cost additive membrane system that can be solution-cast and demonstrate between radical scavenging behavior, without the migration observed with Ce, it would have great impact on the DOE goals for fuel cell electric vehicles (FCEVs).
- The goal to improve the durability by altering the radical scavengers or their attachment to the membrane for immobilization is in line with the Fuel Cell Technologies subprogram goals and supports the need for durable PEMs for HDVs.
- The work is very relevant to the HDV funding opportunity announcement. If successful, the project could have a significant impact on membrane longevity.
- The extending membrane lifetime is a critical need for heavy-duty FCEVs.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The listed activities are all relevant and important for the realization of the project goals. The crossover and stability, in addition to the relative humidity conductivity, are all important properties.
- The proposed work is good, and the project should continue to benchmark its own additive-prepared membranes to control membranes even without Ce+ additive. This will demonstrate that the project's approach is working. However, the team should also use commercially available membranes with Ce+ additive in the tests to determine the target over and above the state of the art. There should be an improvement in durability over existing Ce+-based membranes.
- Considering that this is a new project, the presented work plan details are very good for achieving goals with the collaboration with NREL.
- The project just started, but the proposed future work appears adequate at this point.
- Potentially only one additive will be evaluated.

Project strengths:

- Radical scavenging is important for cell durability. Lubrizol has a catalog of additives and experience in radical scavenging in general. The collaboration with NREL should allow for the identification of at least one candidate additive that will be effective for scavenging but not hinder or deteriorate other membrane properties (i.e., conductivity, mechanical). Details and progress on the covalent additive systems are happily anticipated.
- The combination of casting strategies as part of the impregnation and fabrication could be effective and useful for improving membrane properties. The membrane preparation and processing are explained in detail.
- This project's strengths are the use of multiple additive incorporation strategies and the focus on unique additives beyond cerium.

- Studying the effect of additive concentration is a good plan.
- An immobilized additive has potential for large improvements in lifetime.

Project weaknesses:

- There are no significant weakness noted for the project objective. It would be good to collaborate with OEMs sooner rather than later. There is no mention of consideration as to whether the impregnated additives, if liquid or low-melting, will plasticize the membrane, thereby depressing the glass transition of the polymer, which may limit cell operation temperature. This would not be an issue with covalently bonded additives.
- The effectiveness of the proposed immobilization strategies is yet to be proven since the current progress is based on a limited dataset with Fenton tests only.
- While the project has two methods of incorporating additives, to mitigate the risk of any of those additives not working, it would be helpful to have an additional approach to improving membrane durability.
- At this stage, with limited information, it is difficult to assess the risk of the novel additives.
- The project's goals and targets are not set high enough.

Recommendations for additions/deletions to project scope:

- The project reports and compares fluoride (F^-) release rates, which are helpful for evaluating the effectiveness of the additives, but the changes in F emission are different from what was reported in the literature. The procedure and values should be checked against the previously reported data. The project could benefit from some additional membrane characterization efforts, including temperature-dependent properties, maybe with dimethylacetamide (DMA), and some additional transport properties. It would be helpful to know the percentage of loading of the additives relative to SO_3 groups.
- As with similar projects, it is important to determine whether the additive is regenerable to have a long-term impact on membrane lifetime.
- It is suggested that the project use nuclear magnetic resonance analysis to assess chemical degradation of membranes and additive incorporated membranes.
- Multiple samples of each process/composition should be prepared and characterized to ensure repeatable results.
- The project should raise the bar for the performance targets.

Project #FC-336: A Systematic Approach to Developing Durable Conductive Membranes for Operation at 120°C

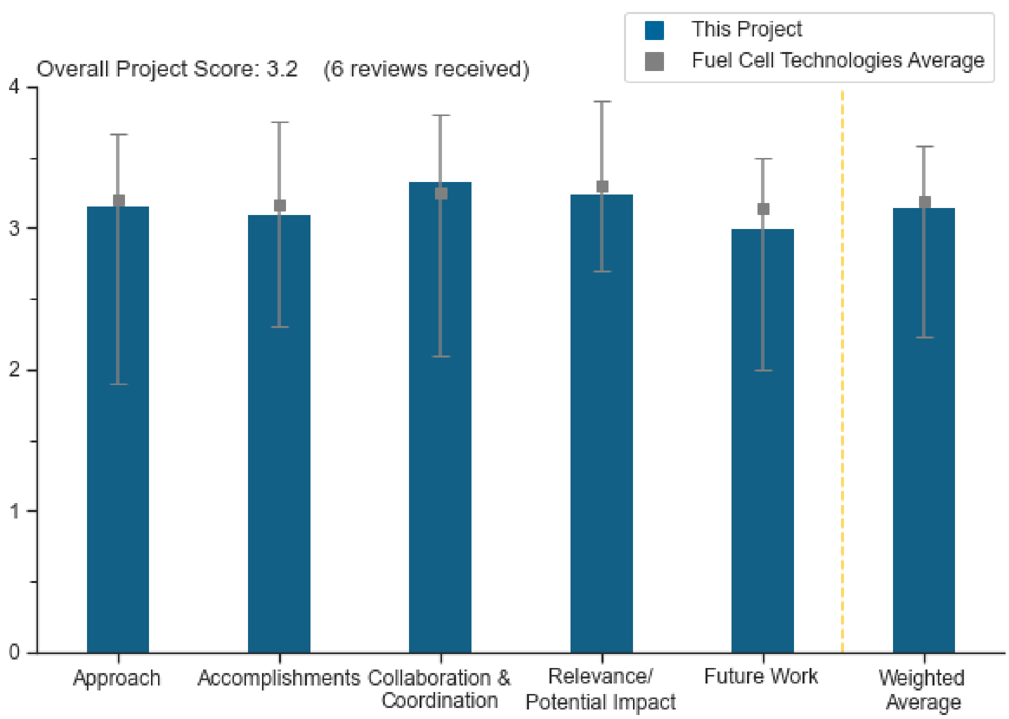
Tom Zawodzinski, University of Tennessee, Knoxville

DOE Contract #	DE-EE0009246
Start and End Dates	10/1/2020 to 3/31/2021
Partners/Collaborators	Oak Ridge National Laboratory, Akron Polymer Systems
Barriers Addressed	• Low area-specific resistance • Low oxygen, hydrogen crossover • 25,000-hour lifetime

Project Goal and Brief Summary

This project aims to develop membranes with sufficient performance and lifetime to meet the requirements of long-term applications of polymer electrolyte membrane fuel cells (PEMFCs) for heavy-duty (HD) vehicles. The research team will use background measurements and literature evaluation to inform paths forward for membrane development to meet cell resistance requirements over ranges of temperature and relative humidity (RH) that reflect operating conditions in HD vehicles. Researchers will then identify and prepare new membrane materials with side chain and polymer chemistry tailored to achieve acceptable conductivity and resistance, with low water uptake and swelling. The University of Tennessee, Knoxville (UTK) is collaborating with Oak Ridge National Laboratory (ORNL) and Akron Polymer Systems (APS) on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Note: This is a new project in 2021. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The team's approach of "mining for protons" is a good way to bring the results from past work together and gather more information on the mode of water transport per mole of sulfonic acid group. This will help the researchers to design their proposed multi-acid exchange site ionomer, as shown in slides 11 and 12. The team's approach of manipulating composite structure to balance proton conductivity and water transport is a good way to determine the balance needed for the 120°C functional fuel cell membrane. Overall, the approach is adequate and aligned with the proposed goal of the project to develop a low-RH membrane.
- The project approach is clearly defined as obtaining acceptable conductivity with minimal water and obtaining high durability. For the acceptable conductivity with minimal water, the team plans to work on preparing composite structures and high ion-exchange capacity (IEC). For durability, the team plans to minimize dimensional changes over RH/temperature, gas crossover. Those approaches that the team is pursuing are not new but seem worth trying further with this project. The team understands the issues with sulfonated polymers for high-temperature (HT) and low-RH fuel cell operations. The technical approach is technically sound.
- The project aims to address membrane performance with a focus on the role of water, specifically retention of water and proton conduction of different ionomer types, structures, and composites at elevated temperatures. Another important aspect of determining a path toward low gas crossover is described but is not part of the Year 1 go/no-go milestones. Both published data and ex situ material properties will be collected through data mining and direct measurements, respectively, to discern potential modeling or predictive parameters leading to enhanced proton conductivity and increased lifetimes at hot and dry conditions relevant to heavy vehicle PEMFC applications. An interesting approach to increasing the acid content of the perfluorinated sulfonic acid (PFSA) using multifunctional phenyl groups, based on previous UTK work, will help probe IEC–structure relationships. The reason to use bis(trifluoromethylsulfonyl)imide (TFSI) as an analogous acidic group was less clear. The gas phase acidity of perfluorinated bis(sulfonyl)imides has been shown to be stronger than that of PFSA for small molecules; however, the added mass (i.e., lower IEC per gram) and the mixed phenyl-trifluoromethyl imide in the hydrocarbon (HC) systems may be less acidic. The bis(sulfonyl)imide structures also lead to the potential for increased gas crossover, and impact to bulk structure may confound performance results; that said, measurements of all proposed material properties on these systems may give direction as to which functional groups to focus on for HT applications.
- The approach of the project is rather unique in that the team does not have its own particular polymer to promote. Instead, the project is using a set of guiding principles to look at all possibilities and try to arrive at a polymer that is good. There is an intrinsic risk to this approach.
- Tom Zawodzinski has made a tremendous impact in PEMFCs over several decades, and it will be interesting to see the progress that his team makes in the next year. However, the team has already seen the use of HC polymer in PEMFCs and additives, as well. The team should, as planned, "mine" the literature to further develop concepts that have shown promise; however, while high IEC, additives, and sulfonamides have shown promise, they have also proven to have issues. High IEC materials have high water content and typically quickly degrade mechanically and/or chemically (radical attack). Additives, although not described in detail, will result in brittle membranes at high contents, and the additives can migrate or degrade. Finally, sulfonamides have higher acidity than sulfonic acids, but the impact in fuel cell performance is small, as was discovered by 3M Company. It will be interesting to see the progress of this project.
- To obtain higher proton conductivity at 120°C, the overall approach looks very reasonable and promising. However, there is no clear approach on how to get high durability. There would likely be a trade-off between high conductivity and high durability, especially at high temperatures, such as above 100°C. The reviewer is a little worried that the current membrane material would have a limitation on durability at high temperatures, even though there would be a significant modification from the current material.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team has acquired PFSA resins with a large range of equivalent weights, from which two bis(sulfonyl)imide derivatives have been prepared. Additionally, precursor HC polymers (e.g., PPO-Br) have been acquired, and APS polymers have been prepared for membrane property testing. As this project has just begun, the collection of a suite of materials, clear plans of polymer functionalization and fabrication, and the acquisition of material characterization equipment to date are appropriate. The team has made progress since the slides were submitted, as described during the presentation. The details about the data mining team's progress were lacking, but certain literature information the team will collect was discussed.
- The project started in April 2021, and the subcontractor agreement was completed in May 2021. This gave the team very little time to report any measurable progress for the 2021 DOE Hydrogen Program Annual Merit Review (AMR). Within this short time, the team has conducted "mining for protons"; prepared and tested the membrane materials; and deployed and used new test beds for automated testing over a full range of RH and temperature. Overall, the progress is significant within this short period of time.
- It seems that the project just received its funding not long ago. Its milestones have been pushed back, likely due to the delay of funding. The team has made some progress on the data mining part of the project. Materials have been acquired, and things are beginning to move.
- This project has just started, so it's hard to tell about the results, but there's been very good preparation on background research on how to get high conductivity.
- There wasn't much done in terms of accomplishment, but that is not the fault of the principal investigator (PI), as the funds arrived in mid-March. It seems the time was spent planning future synthesis and partnering with a toll manufacturer.
- The actual start date for the project is March 15, 2021. Because of the late start date, there are limited accomplishments. The chemical structures of the planned polymers were shown, but no supporting spectroscopic data were provided.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The team is a well-balanced research team composed of an academic institute, a national laboratory, and a polymer company. The team is well-posed and has the necessary expertise to conduct the proposed development work. The role of each partner is well-defined, and the tasks are assigned appropriately and are aligned with the partners' core expertise. The PI is a well-known researcher in the fuel cell area and is engaged with both UTK and ORNL. His link with both entities will help the progress of the project due to effective communication between both entities. The team is tightly engaged.
- UTK has clearly established the roles of all partners in the project plan. APS is providing scalable HC polymers, and UTK will handle some polymer modification synthesis, detailed material testing, and, eventually, data mining. Engagement with ORNL for side chain modification was apparent, and the presenter described having an industrial partner with precision coating capability, Kodak, for when scaled-up coatings are needed. The project is in its early stages, so defining the roles of the team partners and establishing partnerships to generate high-quality materials for characterization were critical.
- The team is composed of a university (the prime), a national laboratory, and an industry partner. All three institutions are involved with polymer synthesis and characterizations. Collaboration with Kodak for a large-scale film preparation looks like a good plan. It is possible that institutions for fuel cell testing can be included. The validation of membrane performance in membrane electrode assemblies (MEAs) by fuel cell or automotive companies may be desirable.
- The partnership is fairly small right now, but it makes sense. Initially, ORNL and APS were focusing on making small batches of materials and looking at blending additives. If ORNL comes across a material that

is interesting, it can hand it off to APS to scale. Eventually, another partner will have to be added, such as Los Alamos National Laboratory or General Motors, to run third-party fuel cell testing.

- The project has just started. There seems to be a very good collaboration to get the plan going.
- All partners seem to be engaged.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is relevant to the multi-year research, development, and demonstration plan (MYRD&D plan) and DOE's targets for long-range trucks. The success of this project will make a significant impact in the progress of fuel cells to large-vehicle use. This project addresses DOE goals by providing paths to (i) lower greenhouse gas emissions, (ii) create good-paying jobs in the U.S., (iii) build clean energy infrastructure, and (iv) support environmental justice.
- The project supports the Million Mile Fuel Cell Truck (M2FCT) consortium goals, which include material (component-level) targets that are relevant to long-haul trucking (e.g., a wide range of operating humidity and temperature with minimized gas crossover). This project supports high-level goals of DOE, including advancing competitive materials for the market, with a focus on durable PEMFC MEA components, and an emphasis on HD efforts that include enhancing efficiency and durability, which should also benefit medium-duty and stationary applications. Moving toward zero emissions and clean energy infrastructure are outcomes that could be accelerated by the anticipated results of this project. A partial focus on HC membranes targets costs associated with PEMFC components and new strategies to probe structure–performance relationships. These hit directly on the Hydrogen and Fuel Cell Technologies Office's research, development, and demonstration (RD&D) strategies involving innovative membranes and ionomers to achieve lower costs, higher durability, and improved power density.
- Developing polymer electrolyte membranes (PEMs) for HT and low-RH operations is critical for HD fuel cell applications. The project goal is well-aligned with MYRD&D plan goals.
- Once there is a higher-performance and higher-durability membrane for 120°C operation, there will be a great variety of applications in the HD truck industry because heat rejection is one of the biggest challenges.
- The PI is experienced in the type of work proposed, so it is expected that the work will stay focused on the relevant goals.
- It is too early to predict the potential impact of this project since it is still getting off the ground. The PI has a plan, and he does have ideas of improving membrane performance to meet DOE targets. There are not many details of what the PI has planned, but that is understandable, as the field is very competitive and they must be careful not to disclose information at this stage of development.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The project's planned approach is logical, including wide-net literature mining and data generation to complement sparse published data at low RH and high temperatures. The emphasis on formulating and scaling materials to explore avenues (i.e., cross-linking, reinforcements) for swelling control in a chosen system to enhance durability is appropriate. However, it was not clear whether only materials meeting the Year 1 go/no-go would be moved forward in the scaling effort. Synthetic strategies aimed at both HC block copolymer and PFSA polymer modifications, such as the "Ball o' Sulfonates" approach to study structure–performance relationships, could provide important insight into management of water in membrane materials.
- The future work cited on slide 16 is aligned with the development course of the project. Since the project just started and very little progress has been made, it is difficult to comment on the future work and judge the relevance and alignment of the future work to the project goal. Maybe in the next AMR, there will be enough information to judge the relevance of the future work.

- It is a good approach to obtaining high conductivity, but it is still unclear how to get higher durability at 120°C.
- The proposed work is relevant. Once more progress is made, it will be easier to determine whether the future plans are logical.
- The future works are described in general terms. It seems there are no specific structures to get to the performance and durability targets, for example, approaches to making composite membranes that include cross-linking, reinforcing, and fillers. There needs to be more specific methodology for cross-linking and similar types of inclusions. The future work looks more like basic research rather than PEM development for HD fuel cells.
- The material that was presented in the slides was not particularly exciting since what was shown has already been looked at in some shape or form in the past. However, the PI is not showing his cards yet. It will be interesting to see the progress that is made from now until next year's review since that will be a better indicator of the project's direction and will give the reviewers a better idea of the materials–performance synergy that is being made.

Project strengths:

- There is significant potential for the project to generate very useful parameters for determining how a membrane material will perform at low RH and high temperatures, as well as structures that provide consistent performance over the RH range at a given temperature. The team has experience determining critical parameters for predicting performance, such as water and proton mobilities, as well as composite materials that flatten the conductivity curve over an 80% RH range. Collaboration with an HC team that has scaled materials is helpful for determining feasibility of material sets and producing relevant quantities of polymers for this project.
- The personnel in this team and their technical expertise is the strength of the project. The PI and ORNL have immense knowledge and resources to explore the proposed objectives of the project. ORNL has world-class analytical techniques for fuel cell components, especially in the MEA space. The project is expected to get the best possible support needed for its progress.
- The strength of this project is that Tom Zawodzinski is leading it. With his leadership, at the very least, we will gain better fundamental understanding in the area of PFSA/HC/additives and its impact on water diffusion, proton conduction, gas permeation, degradation, and fuel cell performance.
- The project PI is a well-known expert on PEMs and has worked for a long time to develop PEMs for HT and low-RH fuel cell operation. The proposed HC membranes can be tailored easily to accomplish the project approaches. Once desirable materials are prepared, the scale-up of those materials may not be challenging compared to that of PFSAs.
- The target is very clear, and the high performance and durability are very important for the next-generation fuel cell system. This project has a good plan for how to reach the target, and there will be a good chance of solving current practical issues.
- The team is strong, and the approach is unique. The potential is large.

Project weaknesses:

- The project is new, and not enough progress has been made to understand the weaknesses. Overall, the proposed steps of the project seem to be logical, and it is too early to point out any weaknesses of the project.
- The weakness is that the materials that are discussed are materials that have been already evaluated; however, it seems likely that the PI is holding some ideas back to protect them.
- The project is intrinsically a high-risk one, as it does not have a "promising" material with which to begin. However, this has been the uniqueness of the project.
- This project needs more engagement with fuel cell testing. It needs a solid plan with M2FCT and other coordination for the purpose. Fundamental understanding is important, but it should not be the main part of the project. Currently, the project looks like low-technology-readiness-level research. The project should not pursue large-scale production until the materials show high performance in an MEA under HT and low-

RH conditions. The area-specific resistance (ASR) milestone is 0.02 ohm cm^2. However, the project is pursuing acceptable conductivity at high temperatures and low RH. Therefore, the milestone and project target are not aligned. If the team is indeed looking for an HT membrane with such low ASR, this is a very challenging project, and no clear pathway was provided.

- The materials set includes materials known to the investigators as ones that likely will not meet durability requirements (e.g., styrenic materials). Prioritizing HC-based materials with structures that have proven adequate chemical stability is more appropriate when determining parameters for increased performance and water management relative to PFSAs. It is unclear what materials set the investigators will move forward with if, for instance, only high-IEC PFSA materials meet the Year 1 go/no-go targets.
- There is no clear approach on how to get high durability.

Recommendations for additions/deletions to project scope:

- The team should consider going through the work of Professor Alan Hay from McGill University on the dendrimer-based ionomeric polymer. Some of his work has been published in *Macromolecules* 41, 2 (2008): 281–284. The proposed project on preparing densely sulfonate-packed structures (e.g., Ball o' Sulfonates) has some similarity to Professor Hay's work.
- To get the high durability at 120°C, it is necessary to develop a different structure of the polymer, or modification from the current material could be an option. The team is asked to make it clear how to approach that issue.
- The project has an is appropriate scope: to determine the most important material parameters for effective water usage with minimal dimensional changes that first meet DOE performance targets by the Year 1 go/no-go point (material milestones). Milestones include publishing findings from data mining and choosing or developing a relevant durability test with which to test the team's materials solutions. No additions or deletions to the project scope are recommended at this time.
- No particular tasks need to be deleted, but the team may consider narrowing down the composite membrane approach. It is essential for fuel cell testing (single-cell level) to evaluate the membrane performance and durability. Most other MEA component development includes fuel cell testing or demonstration to verify that the proposed approaches are valid.

Project #FC-337: Cummins Polymer Electrolyte Membrane Fuel Cell System for Heavy-Duty Applications

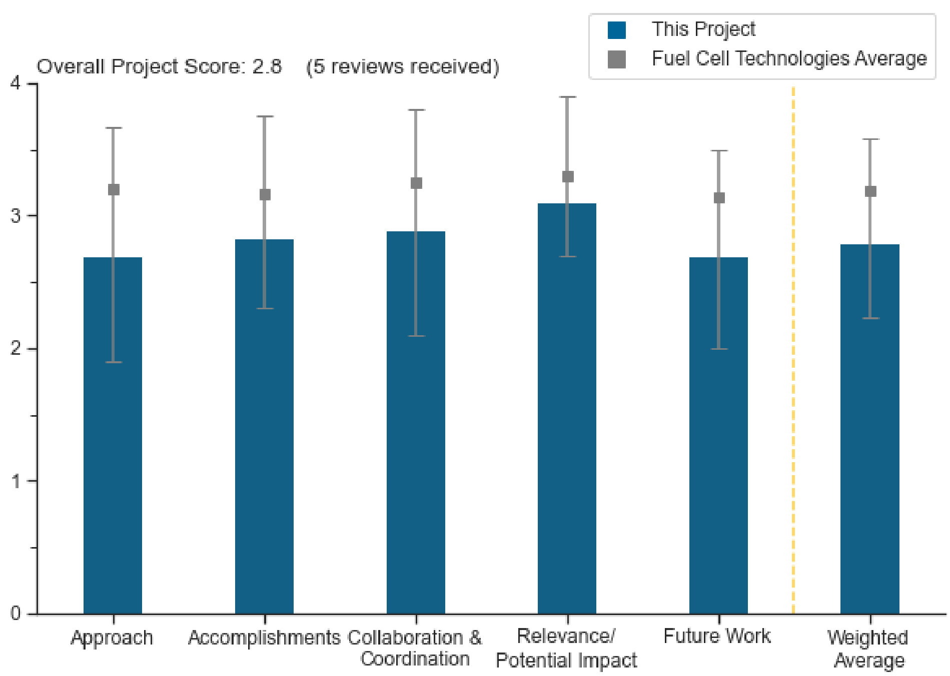
Darren Hickey, Cummins Inc.

DOE Contract #	DE-EE0009247
Start and End Dates	8/1/2021–7/31/2024
Partners/Collaborators	Cummins Hydrogenics, Argonne National Laboratory, W.L. Gore & Associates, Inc., Dana Incorporated, Cummins Turbo Technologies
Barriers Addressed	• Operation ≥100°C • 68% peak efficiency • 25,000-hour life • $80/kW system cost in mass manufacture

Project Goal and Brief Summary

The objective of this project is to develop and demonstrate a new standardized, modular, and scalable 100 kW polymer electrolyte membrane fuel cell (PEMFC) stack that meets performance, efficiency, durability, and affordability requirements for heavy-duty (HD) applications. Membrane electrode assembly (MEA) and bipolar plate (BPP) development efforts will be undertaken and demonstrated in progressively larger stacks. The stack will be designed to run at higher pressure and tolerate high temperatures (≥100°C) during peak power excursions. A key metric is the system cost of $80/kW at 100,000 units per year volume. To achieve this objective. a study on advanced manufacturing methods to reduce production costs will be undertaken. This project is a collaboration between Cummins Inc.; its Fuel Cells and Hydrogen Technologies division (FCHT, comprised in part by Cummins' acquisition of Hydrogenics); Cummins Turbo Technologies (CTT); Argonne National Laboratory (ANL); W.L. Gore & Associates, Inc. (W.L. Gore); and Dana Incorporated (Dana).

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Note: This is a new project in 2021. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

This project was rated **2.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach as cited on slides 6–7 of the presentation is a well-thought-out approach for developing a high-pressure PEMFC stack and system for HD applications with high efficiency. The team's top-to-bottom task flow is well-connected and logical and is owned by partners with the appropriate expertise needed to address the criticality of individual tasks. One thing is not clear from slide 6, and that is why the team is selecting the W.L. Gore membrane to make a MEA with >100°C operational capability. The operational temperature has impacts on the membrane dryness and, hence, the performance. Presumably, the team looked into this matter before selecting the W.L. Gore membrane. Another point to be noticed is that the team wants Dana to develop the manufacturing process of graphite BPPs (slide 11). This could become a bottleneck of the project. It is to be hoped that Dana already has a manufacturing plan to provide an adequate amount of graphite BPP for this project.
- The high-temperature membrane is an interesting and potentially exciting portion of this project; more details will be helpful. A more in-depth discussion about the time at high temperatures (e.g., 1% of 25,000 hours at >100°C) will be very valuable.
- The market/industry-requirements-led approach is effective, and the focus on high-temperature capability, combined with a simultaneous focus on system components (e.g., the air compressor), is good and is needed for successful HD applications. However, the focus on membrane capability at high temperature may not be sufficient, as catalyst failure modes are also accelerated at high temperature; this may be the limiting factor in achieving the lifetime requirement.
- The project properly notes the importance of higher maximum operating temperature to meet Class 8 long-haul HD requirements. However, it is unclear how durability will be achieved while simultaneously increasing maximum temperature. The approach to do so is not described. Similarly, how to achieve higher efficiency, other than the reduction in electrode activation at higher temperature, is not described. Further, this implies operating at elevated temperature not just during extreme events but all the time (to realize efficiency and fuel economy increases). There was no description of the approach to doing so while not compromising electrode and membrane life. It would be good to demonstrate that graphite plates can be cost-competitive and meet the necessary power density for the chosen application.
- No technical approach was addressed, even though reviewers asked about one. The project set a goal to achieve 25,000 hours of life and to be able to operate at temperature of 100ºC or more. Usually, higher temperatures accelerate catalyst degradation, so the goal is very challenging. It is very important to address how to technically achieve it. Achieving 68% of peak efficiency is also challenging. The cell voltage should be very high. This also accelerates catalyst degradation.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project did not start until April 12, 2021. Therefore, the team did not have much time before the DOE Hydrogen Program Annual Merit Review to progress through the planned work. However, CTT has received external funding and is working with FCHT to define the specifications of the e-turbo. CTT has started working on material selection, turbine wheel design, and e-turbo concept design, which will be used in designing the e-turbo for this project.
- The project has not yet been started, but progress is being made on overcoming the hurdles to start the project.
- This project has not started yet; there are no accomplishments. This should not be rated yet.
- The project is just commencing, so it is impossible to rate, so it was given a middle grade, which should be ignored.
- This is a new project.

Question 3: Collaboration and coordination

This project was rated **2.9** for its engagement with and coordination of project partners and interaction with other entities.

- The list of collaborators looks to be excellent and includes Cummins, FCHT (Hydrogenics), ANL, W.L. Gore, Dana, and CTT. It is reasonably clear what each of the collaborators will provide to this project, although it is unclear whether W.L. Gore will provide just the membrane or the full MEA; it seems as though Hydrogenics will do the full MEA using the W.L. Gore membrane. The project should discuss whether and how the national laboratories' Million Mile Fuel Cell Truck (M2FCT) can provide assistance to this project and should leverage the characterization abilities of M2FCT, especially related to durability.
- The team is composed of institutions with appropriate resources and expertise. The project's partners and their roles in this project are shown in slide 11. There is no mention of the feedback process from the team to W.L. Gore and Dana. Preferably, no membrane and graphite BPP development work will be done at W.L. Gore and Dana. The team will just be buying their commercial membrane and BPP, and the researchers will develop/optimize their own MEA and stack at FCHT.
- ANL, W.L. Gore, and Dana are capable partners for modeling, membranes, and BPPs, respectively. However, it is not clear who will lead electrode development, a key element, given the plan to run at elevated temperature and cell voltage to meet the thermal and efficiency targets.
- It is difficult to judge the level and effectiveness of collaboration on a project that has not yet started, but the plans and connections to industrial, government, and commercial partners are there.
- Catalysts could be one of the key enablers, but it is unclear who within the collaboration roster is supposed to develop these. This funding opportunity announcement was the development of the domestically manufactured stack. It is not clear these partners can meet this requirement.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is relevant to DOE Class 8 HD targets. Success of this project will make a significant impact in proving the MEA/stack and balance-of-plant design parameters for commercial trucks, bringing fuel cell truck technology close to commercialization. This project plans to address all four critical barriers of DOE Class 8 HD targets, i.e., operation ≥100°C, 68% peak efficiency, 25,000-hour life, and $80/kW system cost in mass manufacture. It would have been nice if the team had disclosed an estimated cost of high-temperature MEAs and graphite BPPs. Both high-temperature membranes and graphite BPPs are expensive. Although the team claims it will meet $80/kW system cost in mass manufacture, it would be nice to know the present cost of membranes and BPPs and what commercial volume has been considered for mass manufacture cost modeling.
- The project clearly aligns with the high-level DOE research, development, and demonstration objectives (durability, efficiency, cost, and higher-temperature operation).
- Industry-led definition of requirements and evaluation of fuel cell technology are critical to advancing DOE Hydrogen Program (Program) goals and objectives.
- A domestically supplied and manufactured stack fits directly into the Program and applies to the emphasis on HD trucks.
- High-temperature operation is a goal, but it is very difficult to achieve the lifetime with this condition. The project needs to qualitatively show how much benefit can be obtained if this goal is achieved.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- The proposed work for this project, on slide 13, is logical. The team has thought through all necessary elements of the project and has spelled out the future work appropriately. The team should consider cost analysis as a part of a go/no-go decision in fiscal year (FY) 2022 during short stack testing. Assembly of the short test stack should give the team an understanding of the potential cost of a 100 kW commercially viable stack. Given the cost of the stack components, cost analysis and potential stack cost information will be crucial to ensuring the viability of meeting DOE's cost target during the development phase of the project.

- The catalyst is an important enabler for high-temperature operation and long lifetime, but no task was defined for the catalyst.
- Without a clear approach, it is difficult to comment on the future work. The basic steps are there but lacking in detail, with no mitigation pathways cited.
- As the project has not started yet, it is premature to comment on whether the outlined work builds on past work and will overcome barriers. In general, the plan and decision points make sense.
- The project has not yet started, but the project plan seems solid at this stage.

Project strengths:

- This is a well-crafted project with capable partners with necessary expertise for executing this project. The team's decision to use a commercial membrane and BPP to assemble a 100 kW stack and focus on stack manufacture/optimization is the correct course of action for this project. By involving ANL for high-temperature MEA/stack system development, the team has made a good choice. The decision to have the go/no-go decision in FY 2022 after short stack testing is the correct decision. The short stack testing should give the team ample information to understand the viability of meeting DOE Class 8 HD targets for a 100 kW stack.
- The project collaborators look to be in place for a successful project. The project plan looks to be in place to cover the needed portions to make a stack that can meet DOE HD targets.
- The strength of this project lies in combining industry-led requirements evaluation (real-world requirements and use case) with the technological advancements needed at both the fuel cell and system levels.
- The strengths are a group of capable partners (ANL, W.L. Gore, and Dana).
- It is hard to see any project strengths.

Project weaknesses:

- The project has not started yet, and not much information is available to understand the weaknesses. Overall, proposed steps of the project seem to be logical, and it is too early to point out any weakness of the project.
- Hydrogenics is in Canada, and a barrier was mentioned about that and legal agreements. Clearly, as Hydrogenics is making the MEA from the W.L. Gore membrane, this is a critical issue that has to be solved. The project seems to lack any fundamental aspect related to understanding performance and material degradation. The team should work with the national laboratory M2FCT consortium to fill that gap. The DOE targets are being based on end-of-life targets; the researchers discussed little to no information about how they will meet the durability target of 25,000 hours, which is especially critical with the discussed use of high operating temperatures.
- This project may be overlooking some of the high-temperature failure modes, which might prevent the project from meeting its lifetime objectives.
- The project needs to quantitatively clarify the benefit of this challenging goal (high-temperature operation and long lifetime). Also, the project needs to show the technical approach and identify what the enabler to achieve the goal is. The peak efficiency goal needs a clear technical approach to achieve it. The principal investigator's answers to reviewers' questions were not enough.
- A weakness is the lack of a clear approach to achieve the aggressive requirements that often have non-complementary traditional solutions (high temperature and high cell voltage to meet heat rejection and efficiency versus low temperature and low cell voltage generally used to achieve durability).

Recommendations for additions/deletions to project scope:

- The team should consider adding stack cost analysis as a part of the short stack development work and report to DOE during the go/no-go decision.
- Expanding the collaboration to M2FCT to understand MEA performance and durability should have a positive impact on the project.
- The project will demonstrate a full stack plus turbo-compressor. However, to assess durability, it is recommended that a complete system, including humidification, be designed and tested, as these play integral roles in demonstrating system durability.
- It might be beneficial to add a collaboration with some of the catalyst durability projects or groups to ensure success.
- It is highly recommended that the project re-define the goal and address the technical approach.

Project #FC-338: Domestically Manufactured Fuel Cells for Heavy-Duty Applications

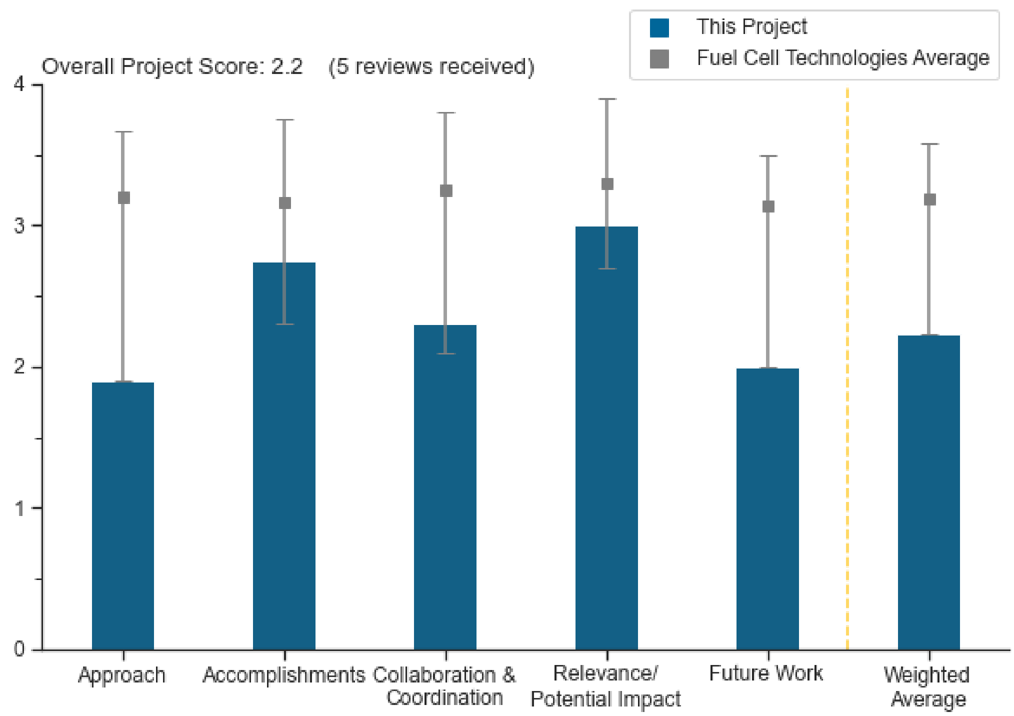
John Lawler, Plug Power Inc.

DOE Contract #	DE-EE0009248
Start and End Dates	5/1/2021 to 5/1/2024
Partners/Collaborators	Argonne National Laboratory
Barriers Addressed	• Durability (25,000-hour life) • Cost ($80/kW) • Performance (limited platinum group metal loading 0.2–0.3 mg PGM/cm^2)

Project Goal and Brief Summary

Plug Power Inc. (Plug Power) is working with Argonne National Laboratory (ANL) to develop a heavy-duty (HD) fuel cell stack that is a suitable drop-in replacement for diesel engine applications. If successful, this project will enable high-volume production of bipolar plates (BPPs) and 100 kW modular stack systems to create a reliable and efficient stack with improved durability, cost-effectiveness, and performance.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Note: This is a new project in 2021. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

This project was rated **1.9** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach of this project is to develop new plate and seal designs for a 5 kW short stack and the U.S. Department of Energy's (DOE's) target 100 kW stack for testing. This stack is a single-power unit intended for use in multi-stack systems with a single balance of plant (BOP). The team is also taking an approach to determine the appropriate seal testing method for a commercial production environment. The material choice for sealing elements and BPPs is appropriate for large-scale manufacturing.
- The approach is logical. Starting with a 5 kW substack for an eventual 100 kW stack is reasonable. The 100 kW stack may still be considered small for a Class 8 truck application but is large enough to be representative. Because of proprietary information issues (and as Plug Power is not under contract yet), there is a lack of detail regarding specifics of the design approach, particularly for the BPP and coating. This is both understandable and frustrating.
- The presentation focuses on two aspects: leak testing and design for manufacture automation. While these are important and possibly overlooked aspects, details of the team's approach to meeting the most difficult and high-level targets (cost, durability, and high-temperature operation) are lacking.
- This pre-start project presentation lacks detail. No information is provided related to the type of materials used. Future presentations should include details related to the membrane electrode assembly (MEA), membrane, catalyst, gas diffusion layer (GDL), BPP material/coating, and/or the expected operating conditions. At present, it is impossible to know whether this design will meet DOE targets or be suitable for HD applications.
- The presentation and the slides do not provide enough information to be able to discern the approach or approaches that will be used to meet the performance targets and metrics. The presentation lacks information about the MEA, membrane, or catalyst improvements that will be investigated to provide the durability needed for the HD application. While BPPs and seals were discussed briefly, information on BPP or coating material strategies and seal materials or strategies was also lacking. Some of the information appears to suggest that by optimizing BPP materials and operating conditions, durability and performance targets can be met with current MEA designs, but that is considered highly unlikely. The principal investigator (PI) appeared to be unaware of previous DOE work looking at seal materials and the accumulated materials compatibility database that contains information on seal materials.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project started on May 1, 2021. Therefore, the team did not have much time to work on the project and report notable progress in the June 2021 DOE Hydrogen Program Annual Merit Review (AMR). The team has completed the workplan for the 5 kW stack demonstration. The workplan is sound and covers necessary elements of redesigning the stack based on the new BPP design.
- This project has not started; thus, there are no accomplishments or progress. The score is irrelevant because it is too early to evaluate the project when no funding has been spent.
- The project is just commencing, and rating it is impossible, so it received a middle grade. This section should be ignored.
- The project has not yet officially started, so there are no accomplishments yet.
- The project has not started.

Question 3: Collaboration and coordination

This project was rated **2.3** for its engagement with and coordination of project partners and interaction with other entities.

- The team constitutes two partners: Plug Power (prime contractor) and ANL (subcontractor). Plug Power is constructing a test bench capable of running the accelerated stress tests proposed by the Million Mile Fuel

Cell Truck (M2FCT) consortium at the 100 kW system power level to generate performance data for modeling the HD fuel cell stack at ANL. The collaboration meets the project objective. Both Plug Power and ANL have the required resources and expertise needed for conducting the tasks proposed in the project.

- Collaboration with ANL for system modeling is prudent and appropriate. There is substantial experience in the community and among vendors regarding design and fabrication of metal plate and MEA systems. Plug Power's desire to create its own proprietary system is understandable; however, additional collaboration with vendors or consultants that have that development experience already would offer substantial risk reduction benefits. The technology transfer associated with the alliances with Renault Group and SK Group appears to be significant to the project, and future presentations should mention any overlap and collaborative efforts where relevant.
- The only collaboration listed is with ANL, on a limited work scope. Most of that modeling is not even related to the actual stack manufacturing, which is the title of the project. The team comments that the project will follow M2FCT-developed accelerated stress tests.
- This project has not yet started. It appears that Plug Power is collaborating with ANL, but it is not clear whether that is through M2FCT or separate from that. Collaboration with the M2FCT consortium would be beneficial.
- No collaborations are listed.

Question 4: Relevance/potential impact

This project was rated **3.0** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The team's goal is to develop and demonstrate a 100 kW fuel cell stack with domestically sourced components, which will serve as a single-power unit intended for use in multi-stack systems with a single BOP and which has potential to meet the 2030 system targets for HD fuel cells. This project will focus on key technical barriers, such as durability, cost, and performance, that are key to meeting DOE's 2030 interim goal of 25,000 hours of stack/system life for the Class 8 tractor–trailer application. Instead of researching many fuel cell components, the team has taken on the task of using existing material and BOP systems and maximizing the stack performance through BPP flow field and sealing optimization to reduce leakage-related performance loss. The project has direct relevance to DOE's developmental goal, and the project's success will make significant impact in driving the progress of hydrogen fuel cell applications in larger vehicles. The team is also concentrating on a closely coupled stack design and manufacturing system that has the potential to meet production volumes for Class 8 trucks and marine and rail markets.
- The project tracks the Hydrogen and Fuel Cell Technologies Office (HFTO) targets and planning near-verbatim. Thus, the project is well-aligned regarding relevance.
- It appears that the overall goals align with high-level DOE targets and goals, though the lack of information provided makes it difficult to discern whether lower-level targets and goals at the component level are aligned. The project plans to integrate BPP design and manufacturing and move Plug Power's sourcing of BPPs from outside the United States to the facility inside the United States, which aligns with the goals to strengthen the U.S. supply chain.
- A U.S. manufactured fuel cell stack for HD applications aligns with the DOE Hydrogen Program. Not enough information was provided to understand whether the project will be able to meet DOE targets.
- The project listed the primary DOE research, development, and demonstration objectives as stated project targets, but little can be gleaned without any detail or approach to how to achieve these targets (and only some comments on sealing, automation, and optimizing operating conditions, followed by BPP design, to align with these). The project needs to detail the approach and priorities.

Question 5: Proposed future work

This project was rated **2.0** for effective and logical planning.

- The project has not started yet. The team is in final contract negotiations with DOE. The team's immediate goal after the start of the project is to begin developing a 5 kW short stack.

- Since the project has not yet started, everything is considered future work. The slide on future work refers only to developing the 5 kW substack. Additional information should have been described.
- Only plans for the first budget period are described. The plans that were presented left several points unclear: why the flow analysis is delayed until after the 5 kW stack testing, whether there will be initial computational fluid dynamics/finite element analysis modeling and design, and what the target operating conditions are. The presentation is lacking in any other details on the proposed and future work.
- This project has not started yet, so the information is all about future work. The presentation discussed only BPPs (but did not give any information), gave a list of possible gasket materials, and discussed leak testing. Essentially no information is provided about the MEA, which is the critical component in determining whether the project can meet DOE targets.
- The project provided insufficient detail to allow reviewers to determine what the proposed future work is and how it addresses the barriers.

Project strengths:

- The team's knowledge and experience is the strength of the project. Both Plug Power and ANL have performed hydrogen fuel cell research and development for decades, and combined, they have experience to drive such a project to develop understanding in BOP and system levels, which is necessary for developing HD fuel cells for larger vehicles.
- Plug Power has substantial internal capability and is well-suited to developing a U.S. domestic product. Teaming with ANL is a good alliance. The selection of 5 kW and 100 kW demonstration power levels is appropriate.
- Plug Power is a leading manufacturer of MEAs and fuel cells for industrial applications. The proposed work to bring BPP manufacturing in-house could be beneficial to U.S. manufacturing and the fuel cell supply chain.
- Plug Power has a history of focusing on what is needed to enter the market with a saleable product.
- Plug Power has commercially sold fuel cells for applications such as forklifts. That work may translate to making HD fuel cell stacks, but as to whether it actually will, the team did not present enough information to enable that determination.

Project weaknesses:

- The team is working on domestic fuel cell manufacturing. It is not clear whence the MEA will be sourced; the reviewer's understanding is that W.L. Gore's commercial MEAs are manufactured outside the United States. The team did not provide the MEA sourcing information.
- The selection of metal plates with coatings for a 25,000-hour lifetime is not well-supported or -explained. The selection of 0.769 V/cell at end of life, even though specified by DOE, is an aggressive value that may not be consistent with cell degradation and a 25,000-hour lifetime.
- There are no listed collaborations and no details of plans. Having neither gives little confidence that the aggressive targets can be met successfully, and there is no method to gauge whether the project has potential even to advance from the state of the art.
- Details regarding Plug Power's proposed work and approach to improving durability and addressing performance were lacking. It was not possible to determine what the approach is or how the team proposes to address the challenges associated with fuel cells for HD trucking.
- The project did not provide information to clarify what the researchers are going to develop during the project. There was a total lack of information presented in the AMR. It is basically impossible to know the weaknesses of this project because the presentation did not give any information.

Recommendations for additions/deletions to project scope:

- The end-of-life cell voltage is unreasonably high for this project and should be reconsidered. Consideration should be given to the metal plate/coating and MEA experience of the past from other groups. Perhaps this is being done, but as presented, it seems a Plug Power development is in isolation. The involvement and technology transfer to and from partners Renault Group and SK Group should be more clearly defined.

- Plug Power is being funded by the federal government for this project. Part of being funded by the federal government is being reviewed at the AMR. Projects are supposed to be additive to the HFTO portfolio, and this project is currently not. Plug Power presented no information that would help any other project, whether government, academic, or industrial. This project needs to provide a minimum amount of information so that it can be reviewed to enable understanding of whether it can meet future DOE targets.
- The PI needs to provide more information about the approach. The project is receiving public money, and the PI needs to provide more information so we know the researchers are using it wisely and that their plans address the relevant barriers.
- The team should clearly delineate an approach and plan to meet the high-level targets set forth in the DOE Hydrogen Program.

Project #FC-339: M2FCT: Million Mile Fuel Cell Truck Consortium

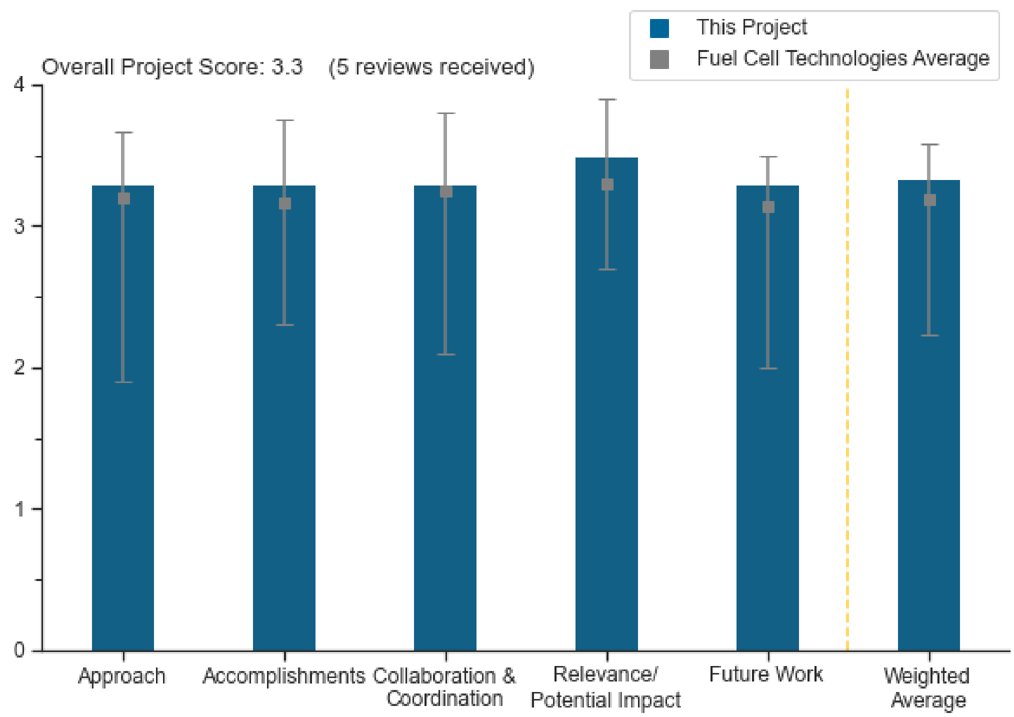
Rod Borup and Adam Weber, M2FCT

DOE Contract #	WBS 1.5.0.402
Start and End Dates	10/1/2020 to 9/30/2025
Partners/Collaborators	Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Argonne National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Brookhaven National Laboratory
Barriers Addressed	• Durability: 30,000-hour lifetime • 72% peak efficiency • $60/kW fuel cell system cost

Project Goal and Brief Summary

The project team is working to construct fuel cells that provide 2.5 kW of power per gram of platinum group metal (PGM) after a 25,000-hour-equivalent accelerated durability test. The purpose is to create durable and efficient fuel cell designs suitable for adoption by the heavy-duty vehicle (HDV) market.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Note: This is a new project in 2021. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The proposed approach is to combine different activities toward common objectives, including materials development, component integration, component/cell durability, and system analysis. The proposed workflows for each segment appear relevant for achieving the project targets. The organization of the project should ensure good communication between the different members. The “team-of-teams” approach is composed of well-recognized experts in the field and, as it has already demonstrated its relevance in several U.S. Department of Energy-funded projects, appears to be the most effective way to work on these important challenges. Because most of these national laboratories are/were also participating in complementary projects such as the Fuel Cell Consortium for Performance and Durability (FC-PAD) and the Electrocatalysis Consortium (ElectroCat), this consortium’s approach will facilitate the capitalization and valorization of the results in profit of this new project. Even if many stack components are mentioned, it is clear that membrane electrode assemblies (MEAs) will be at the heart of the activities. The approach of developing an MEA and then validating it in industrial stacks is interesting if there are regular loops during the project. Concurrently developing MEAs and bipolar plates, however, usually leads to the best performing stacks.
- The shift to heavy duty (HD) increases the relevance of polymer electrolyte membrane fuel cells (PEMFCs). This consortium brings together a broad range of expertise at the national laboratories. They have already announced a few funding opportunity announcements (FOAs) demonstrating their commitment to bringing in outside expertise from industry and academia. The proposed approach is a logical integration of all members and resources.
- There is not much to say here. This looks really great. One thing that the team might want to keep in mind is that there does not appear to be any evidence that the accelerated stress test (AST) is truly indicative of million-mile performance. The team plans to use the same AST but move to 90,000 instead of 30,000 cycles. However, HDVs are often operated much differently from light-duty vehicles (LDVs), with much of the lifetime spent operating at near-constant load (driving on highways and not in cities, towns, etc.). Surely, this can be reflected in the AST.
- The overall approach is sound, with the “team-of-teams” approach providing comprehensive and integrated activities to address the challenges. The project correctly places a high emphasis on durability, benchmarking, and models for Year 1. The high-level overview slides on the approach are all well-thought-out and show a very comprehensive approach, i.e., in building goals and in the interactions, length and time scales, advanced characterization approaches, etc. The advanced computing approach will be very useful if the researchers are able to create the digital twin. The monolayer studies for the membrane seem to transition into the catalyst as well. However, the membrane goals do not appear to be clearly stated. The multivariable parameter sensitivity analysis will be valuable to drive experimental studies, once validated. While the system-related analysis is very useful and should be done, it may be better for it to report out as a separate project. This team excels at activities related to fuel cell MEA development, and that is where the researchers should keep their focus.
- A team of national laboratory scientists is working together to attempt to make long-endurance fuel cells. While the concept is good, the approach is risky. The researchers have no controls engineering, the key to fuel cell management. Rod Borup reminded everyone that U.S. Department of Energy laboratories predicted poor stability of Pt-Co electrocatalysts, but their reverse engineering of a Mirai showed the catalyst intact because of controls. Controls are really cheap compared to materials invention and characterization. The team should really be focused on understanding when materials are robust and when they are at risk, and the project should publish the parameters. Control engineers can then use the information to write controls. The team organization is confusing. For instance, it is unclear why a leading expert in microscopy (Cullen) is being reassigned to a communications job. It would make more sense for researchers to do research and then use a communications specialist to communicate. The group is also going to be soliciting proposals, so the team will be bogged down in contract awards and program reviews. In theory, this might make sense, but the organization chart looks very top-heavy and loaded with scientists in contract and management jobs. The presentation was surprising in terms of the lack of new topics being studied. There are tens to hundreds of papers on sulfate anion adsorption. It is unclear why this is being

studied again. A thorough literature review would be adequate. Likewise, there has been significant work on Pt on oxides. The key issue was that the rotating disk electrode results did not match the MEA results because of hydrophobicity issues. The key to this work is water management, not repeating synthesis and characterization approaches from 10–15 years ago. The only thing somewhat new is the machine learning. This will be very tough because it is hard to model an unknown. Machine learning is very much based on labeling, meaning that you need to know what is most important. Perhaps a neural net would be a better approach. There needs to be more focus on water management and humidification at start-up and shutdown.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- All of the work shown appears to be well-thought-out and focused appropriately on elucidating key mechanisms and/or improving materials and designs. There is so much work shown that it is difficult to go into detail on any one subject to fully explain work being completed. Not all charts have full legends, and the reader can only assume the meaning, e.g., the right-hand plot on slide 33, with three PtCo/C values, showing the lowest change in power density although it is stated to have the highest performance loss. Adding the hydrophobic layer to the gas diffusion layer is an interesting concept to reduce cation migration. There are also data in the additional slides showing some good performance increase. Novel materials work (catalyst, ionic liquid) is showing good promise. Some of this work also appears to be reviewed under separate projects; therefore, it is not clear how much is done under Million Mile Fuel Cell Truck (M2FCT). It seems that this may be just an integration of concepts from other projects.
- The consortium is still in its early stages. However, the team has made progress on identifying critical target metrics, impacts of aging on critical materials, baseline testing, and funded FOAs.
- Many interesting results have been obtained during the first year of the project (analysis of operating conditions, performance and efficiency, durability measurements at projected HD loadings within development of HD-related ASTs, catalyst inks to performance and catalyst layer analysis, and some material developments). It appears that, considering the HDV operation conditions and defining accordingly, the different AST protocols appear as a critical point to which high attention has to be paid, in particular, when adapting AST protocols developed for LDVs. The system model considers that there will be no humidifier anymore. It is unclear whether this has been validated by the HDV manufacturers for all HDVs.
- The project is very new. The team seems to be focused on organizing the project.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The organization chart presented appears well-adapted to ensuring an efficient and fluid collaboration between the project partners. Special attention has to be paid to the regular exchanges with industrial partners implementing the new materials and components in their stacks. Regarding outreach activities, organization of regular webinars with international institutions is encouraged, in particular on the AST protocols.
- So far, this is extremely laboratory-focused, which is good, given the capabilities at the labs. The industry interaction is clear here. There is limited room for fundamental academic work.
- There is great integration of resources and personnel.
- Significant collaborations and collaboration mechanisms are well-described.
- The DOE team is attempting to work with new organizations and even award some funds to new contributors. Unfortunately, the management team is an old group of colleagues. It would have been very pleasing to see a new name, someone with knowledge of heat transfer or manufacturing or packaging (surely the DOE laboratories have this expertise). With the same group of colleagues, there will be little room for innovation. Industry is poised to have a small voice.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Hydrogen-fueled mobility applications will become more and more important during the decade. In complementarity with batteries, the hydrogen solution is the most relevant for the need of high payload, high autonomy, while keeping the flexibility of today’s thermal engines. Therefore, developing specific components adapted from LDV developments for HDVs is of utmost importance. This project will provide results of high impact for the industrial development of HD hydrogen transportation, in line with DOE targets.
- There is great potential for this consortium—not only in bringing together disparate resources at multiple national laboratories but also in highlighting targets, publishing benchmarks, and developing drive cycles and AST protocols for HD. There is great promise here not only to develop new materials but also to aggregate and promote best practices for testing and assessing new materials. One thing that has been missing in materials development is a standardization of how those materials can be integrated and accurately tested in PEMFCs. This consortium has the opportunity to develop the needed standardized synthesis, integration, and testing of new materials.
- The project is highly focused on advancements required to meet HDV and medium-duty truck targets.
- The project is extremely well-aligned.
- At this point, the project is poised to have low impact because the team is a group of long-term colleagues who are doing work that they have been doing for years. Yes, durability is very important, but the focus is not clear. Durability is challenged with start-up/shutdown conditions of stacks, uneven fuel distribution, and poor humidification. So much is systems-level-dependent. It is not clear how the basic research is being poised to affect real-world durability.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The proposed work covers many topics in line with the project objectives. Most of the presented results relate to the electrodes. As durability is key for HDVs, it is expected that membrane stability will also be covered in the coming years. As, up to now, stacks using metallic bipolar plates have not demonstrated durabilities of tens of thousands of hours, the impact of bipolar plate corrosion products either affecting the contact resistance or polluting the MEA should be investigated. Shutdown/start-up testing is foreseen. Freeze start testing may also be considered, even if occurrences should be lower than for LDVs.
- There is no need for comments here. The project is outstanding.
- Proposed work is well-defined and critical for the advance of HD PEMFCs.
- The proposed future work is appropriate. The project should include a manufacturability and cost assessment with delivered MEAs.
- As noted above, the proposed work has largely been done in the past at DOE laboratories and elsewhere.

Project strengths:

- Really, everything is a strength. The team is great. The institutional structure is very good. The project is tackling the correct problems.
- The team and collaborations, baseline testing and standardizations, and incorporation of academia and industry through FOAs are all strengths.
- The project has a very strong team, excellent analytical capabilities, and the latest approaches, e.g., machine learning. There is excellent collaboration.
- The “team-of-teams” approach grouping well-recognized experts is a real strength of this project.
- The goal of the project, understanding how to increase the durability of fuel cell MEAs, is important.

Project weaknesses:

- Even if considering all stack components in the scope of the project, it appears to be very focused (perhaps too much so) on MEA developments for HDVs. Connections with ongoing DOE-funded projects on MEAs, membranes, and stacks seem to be put in place, and it will be important to ensure regular effective exchanges.
- The project may be too large and all-encompassing for effective management.
- The project is not tailored to guide controls designs, and there are few new ideas in the project/presentation.

Recommendations for additions/deletions to project scope:

- The DOE researchers need to do a comprehensive literature review of much of the proposed work and determine whether the proposed experimental work needs to be completed, or whether controls parameters can be recommended on existing publications and patents. The team must include one or two people from outside the DOE fuel cell community who can offer a fresh perspective; otherwise, this appears to be just a jobs program. The researchers should not be in administrative roles. If possible, the researchers should do a review of where their prior projects successfully affected the fuel cell industry (licensed patents), take those lessons learned, and try to replicate in this project.
- The project is so large and includes so many different activities that it feels like a shotgun of work. It may be better to separate out some of the work for separate reviews, rather than review all the work together. There could still be a high-level review of the consortium/approach in one normal-length review session. The team might consider studies to support freeze-start operation, such as material and MEA properties under sub-zero conditions.
- The scope of the project is quite large and ambitious. The challenge will be to cover all the foreseen items and to ensure effective coordination.

Project #FC-341: Advanced Anion Exchange Membrane Fuel Cells through Material Innovation

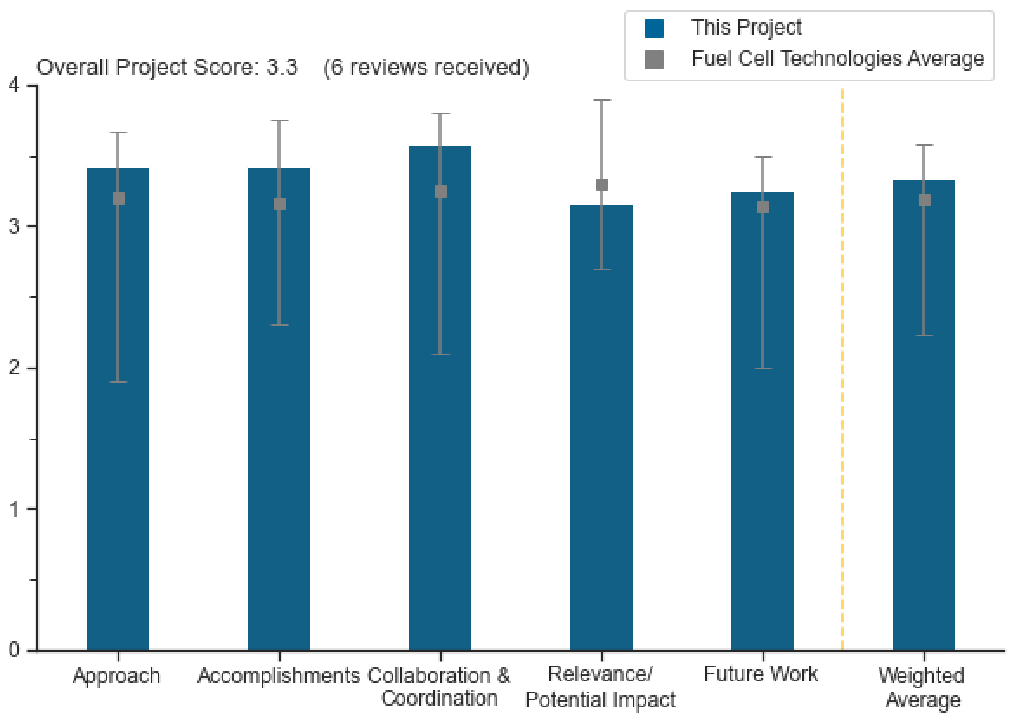
Yu Seung Kim, Los Alamos National Laboratory

DOE Contract #	WBS 1.3.0.440
Start and End Dates	8/1/2020
Partners/Collaborators	Sandia National Laboratories, Oak Ridge National Laboratory
Barriers Addressed	• Cost • Electrode performance • Durability

Project Goal and Brief Summary

The project team is working to develop advanced anion exchange membrane (AEM) fuel cells (AEMFCs) through materials innovation and deliver 50 cm^2 membrane electrode assemblies (MEAs) that meet Hydrogen and Fuel Cell Technologies Office (HFTO) performance and durability milestones. The goal is to improve AEMFC performance and durability while working toward a commercially viable system. The project could also provide scientific knowledge of AEM stability that can be transferred to other AEM-based technologies, such as an AEM electrolyzer. Los Alamos National Laboratory (LANL) is collaborating with Sandia National Laboratories (SNL) and Oak Ridge National Laboratory (ORNL) on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Note: This is a new project in 2021. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The overall approach is sound. This is exactly the kind of work that a national laboratory should be doing – understanding the fundamental principles of how AEMs work and how to improve them. Reading Dr. Kim's papers and listening to his presentations are always enjoyable. They are very informative. The problem is that there are at least a dozen ionomers competing for the AEM crown, and we need a core understanding of these ionomers, their structure, test methods, etc. to be able to (1) understand how they work and (2) develop more advanced polymers and electrochemical systems. This work is therefore extremely valuable.
- The ideal approach would make the ionomer/membrane insensitive to CO_2 and would focus on non-PGM-based MEAs. However, the proposed work is also very valuable, assuming the oxidant fuel cell feed will be CO_2-free air. An aryl ether-free backbone, along with stable fixed cations, appears to be the logical way to go.
- The approach is good and very clear.
- The approach addresses durability and water management, which are major barriers for AEMFCs. The approach to use high-platinum-group-metal (PGM)-loaded catalysts in MEAs may lead to conclusions that are not applicable to PGM-free or low-PGM catalyst layers.
- This project focuses on AEM materials for the AEMFCs. The proposed AEM materials show some novelty. However, the AEMFC has been progressed significantly in the past using PGM catalysts and hydrogen–oxygen. More focus should be on AEMFCs with PGM-free catalysts and hydrogen–air (with trace amounts of CO_2) performance. In addition, LANL AEMFCs have been funded before. This project is the development of new AEMs (from ORNL and SNL). It is not clear why LANL does not use the previous AEM materials but focus on electrode design.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There has been a systematic analysis of polymer degradation for a variety of structures, and there is new insight gained by the work. We need much more of this type of work for AEMs to emerge as viable options for major electrochemical applications.
- Most strategies have been implemented in the approach, such as saturated hydrocarbon, polyfluorene, polyphenylene, and styrene-based ionomers, typically with thickness of 37 microns, water uptake of 76%, and good ionic content (International Electrotechnical Commission [IEC] 1.7).
- This is a relatively new project, but a significant number of valuable data have already been collected. The team's findings regarding MEAs with asymmetric electrodes are particularly interesting.
- New development of different ionomers for the anode and cathode (asymmetric ionomers) provides another dial to turn to help with water management and should prove useful. Development of a homogeneous method for functionalization of polyphenylene polymers provided significant improvements in membrane durability in ex situ testing. While ex situ membrane stability has been increased substantially, stability of ionomers still appears to be an issue, with significant degradation over hundreds of hours of operation in an MEA.
- The project is progressing well.
    - Durability is still variable (slide 12). This needs to be addressed. Based on the data, there is also a need to refresh the cell with KOH periodically. This is also a limitation, as it is not needed with some other systems and is not generally practical.
    - Loading of 0.6 mg/cm^2 is not really "low." It is suggested that this low-loading target be moved to be in line with Thompson et. al and have a final target of 0.125, or maybe slightly above, such as 0.2.
- This is a new project. Its current progress is fair.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration between partners is effective. Yu Seung's collaboration with others in the AEM community is apparent through his publications and work co-leading the membrane working group.
- Dr. Kim has reached out to a wide range of institutions—not just his contractual partners in the project. This reviewer knows from firsthand experience that he keeps them regularly informed of his progress.
- The project work is spread out over LANL, ORNL, and SNL, with well-defined roles and responsibilities to optimize meeting all targets.
- This project has twelve collaborators and two partners; it is an excellent example of teamwork.
- It is good to have three approaches for the polymers, but it is clear that one institution is producing the best results so far.
- This project is just a collaboration with national laboratories. An industrial participant will be helpful.

Question 4: Relevance/potential impact

This project was rated **3.2** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- AEMs are sort of a holy grail. They offer the potential for significant cost reduction in catalysts and membranes for many critically important devices such as fuel cells, electrolyzers, and flow batteries. A fundamental understanding of AEM properties and performance in situ is key to improving these materials for these applications. It is the next big breakthrough as hydrogen technologies and the hydrogen economy emerge commercially. This will make a huge impact.
- The project aligns well with the DOE Hydrogen Program objectives. The work on polyphenylene-based AEMs can be of great value.
- This project is targeted at AEMFC technology, which is a potential alternative to PEMFCs. Over the past decade, the performance of AEMFCs has been greatly improved, but research activity is still needed to improve durability, increase carbonation tolerance, decrease gas flow rate, and implement low-PGM or PGM-free catalysts. This project focuses on AEMFC performance under hydrogen–air (CO_2-free and CO_2-containing) and low RH conditions.
- This project is partially relevant to DOE fuel cell research, development, and demonstration objectives.
    - Provided significant progress in reducing Pt loading has been made in polymer electrolyte membrane fuel cells (PEMFCs), the development of AEMFC gas becomes less meaningful.
    - If AEMFCs will be pursued, the integration of AEM materials with PGM-free catalysts is a must and more significant.
    - Water management of AEMFCs is more complex, making the application less viable.
- The project is clearly targeting the AEMFC goals well, although the "low PGM" in the project is not really low PGM.
- AEM and ionomers are relevant to the HFTO goals, as these technologies have potential to reduce fuel cell and electrolyzer costs by reducing PGM content and enabling use of lower-cost bipolar plate materials. AEMFCs with high PGM loadings are not relevant to the HFTO goals.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- There is a clear, systematic approach to the work, as can be seen from the polymer variants studied sequentially. The presentation and data make sense.
- All the proposed materials synthesis work and MEA and fuel cell fabrication and testing are well-aligned with the project goals.
- Noteworthy future work includes the following:

    - AEM and ionomer optimization (ORNL, SNL, and second-year LANL [end-of-year milestone, July 31, 2022]) AEMFC performance: 0.65 V at 1 A cm^2 on hydrogen–oxygen at 80°C
    - Demonstration of target performance and P = 150 kPa durability, (LANL) AEMFC durability: <10% voltage degradation after 1,000 hours, 1 A/cm^2 operation (total PGM loading = 0.6 mg/cm^2)
    - Synthesis and characterization of fluorinated first-year go/no-go milestones (July 31, 2021): poly(fluorene) ionomers (LANL), poly(phenylene) AEMs with technoeconomic analysis and piperidinium cationic groups (SNL) and polyolefinic AEMs via ring-opening metathesis polymerization (ROMP) (ORNL).
- Using fluorinated polymers is not a good idea. Avoiding fluorination would be a huge bonus over polymer electrolyte membranes. It would drive down cost and environmental impact. It should be noted that not all of the performance issues require a new polymer. It is suggested that the team also do work on the electrode composition and MEA methodology.
- Future catalyst layer ionomer work should focus on PGM-free catalysts, as their hydrophobicity and water transport are significantly different from those for high-PGM-loaded catalyst layers.
- The focus of future work is still on AEM materials development. More focus should be on electrode design using PGM-free catalysts.

Project strengths:

- The project has good fundamental data on a variety of different candidate polymer structures. These data are very useful. There is also good systematic testing of candidate polymer performance. There are clues in the test results that suggest new directions for polymer development. The project has very large, wide-ranging direct and indirect partners, which is a strength. The project is designed inherently to share knowledge widely and encourage technology commercialization.
- This is a well-planned and -executed project. Better AEMFC membranes/ionomers are needed, which necessitates a better understanding of the unique features of AEMFCs as compared to PEMFCs. The project team consists of world-class experts, so significantly improved membranes, MEAs, and new knowledge are highly likely to become available through this project.
- The project has a very strong membrane team, the project's AEM materials are innovative, and LANL has good small device integration experience.
- The principal investigator and collaborators have been leaders in the AEMFC field and have determined the main AEM degradation modes.
- This project has smart approaches that target defined, known issues.
- This project demonstrates good teaming.

Project weaknesses:

- This is a very difficult problem. Membrane durability is a critical and complex issue. There are many approaches and many angles that have to be investigated. The problem is simply too large for this one research project. There must be ongoing research and expansion of the overall effort to address this most critical of issues. A breakthrough on durability could literally catapult the hydrogen economy forward.
- It would be good to bring in one or two things that are not related to just the polymer, but this is minor and should not be considered a fundamental project weakness.
- There has been great progress in AEM performance, but AEMs continue to be speculative and necessitate a focus on effects of CO_2 and non-PGM catalysts and catalyst durability issues. Making a great laboratory demonstration on hydrogen and oxygen with high platinum loading will not make a commercial fuel cell or electrolyzer.
- The use of catalysts with high PGM loadings in the MEAs provides electrodes with substantially different water transport characteristics not representative of the desired end product and may lead to conclusions that do not apply when a PGM-free catalyst is finally used.
- The project still focuses on hydrogen–oxygen (no CO_2 impact will be investigated). The project also still uses PGM catalysts (no PGM-free catalyst is planned). AEM mechanical durability needs to be examined.

- The project does not promise CO_2-resistant membranes/ionomers. The cost of the proposed materials is also not addressed.

Recommendations for additions/deletions to project scope:

- The project should expand funding, increase the overall scope of this research, and add more scientists; this effort should be elevated to a Manhattan-Project-style effort. The project is addressing a critical issue, a critical problem that must be solved.
- The project should add PGM-free catalyst integration with membranes and ionomers. Also, the project needs to investigate the impact of CO_2 on the membrane and mitigation strategies.
- The project should have more focus on effects of CO_2 and non-PGM catalysts and catalyst durability issues.
- Testing with PGM-free cathode catalysts should be added.
- The “low loading” issue, noted above, should be addressed.
- The project should include cost estimation of the proposed materials.

Project #FC-342: Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells

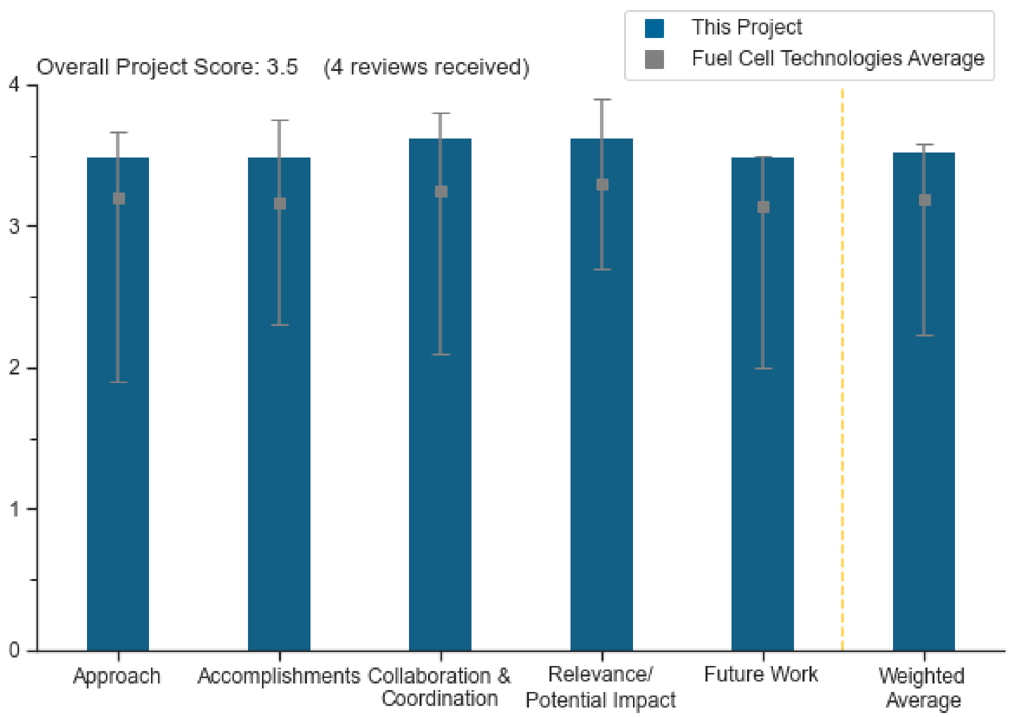
Bryan Pivovar, National Renewable Energy Laboratory

DOE Contract #	WBS 1.3.0.540
Start and End Dates	10/1/2020
Partners/Collaborators	Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Colorado School of Mines, 3M
Barriers Addressed	• Durability • Cost • Performance

Project Goal and Brief Summary

This project aims to improve the performance, durability, and operating window of alkaline membrane fuel cells (AMFCs) and enable them to function with electrodes with minimal platinum group metal (PGM) content. If successful, the project will produce AMFCs with durability equal to polymer electrolyte membrane (PEM) fuel cells, addressing greenhouse gas emissions, air quality, and environmental justice concerns while enabling domestic energy competitiveness.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Note: This is a new project in 2021. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This research looks at a set of critically important problems involving membrane, electrode, and catalyst performance and durability. It is a very broad subject, but it must be investigated and understood in order to support a breakthrough in cost for many different components of the hydrogen technology stream and, therefore, hydrogen economy. The overall approach is sound. The National Renewable Energy Laboratory (NREL) obviously has the core competence and the tools to do this work. The overall project appears to be well-sequenced, and the data presentation is logical and systematic.
- The project has a very nice set of materials and approaches.
- The project focus on performance and durability is appropriate. The project approach of using techniques that have been successful in determining where degradation is happening in PEM systems (such as electrochemical impedance spectroscopy and voltage loss breakdown) should prove effective. There is a disconnect between how alkaline electrolyte membrane fuel cell (AEMFC) systems are marketed as potentially low-cost options that can utilize PGM-free catalysts and how this work is being performed (both this project and the one at Los Alamos National Laboratory [LANL]). It appears a significant effort is being put into optimizing these very high Pt loading electrodes that do not appear to be economically viable for applications of interest. Water management, which is key to AEMFC operation and likely plays a large part in durability, will be quite different for high-Pt-loading and PGM-free catalyst layers (and likely for low-loaded Pt catalysts). PGM-free catalyst hydrophobicity is different from that for PGM-based catalysts, and ionomer interactions with PGM-free catalysts with atomically dispersed active sites are different from those with Pt-based catalysts with Pt particles. It is not clear that learnings from high Pt-loading catalysts will be transferable to fuel cell systems that may be of interest commercially (with PGM-free or low-PGM-loading electrodes).
- The proposed approach involves a combination of alkaline electrolyte membrane polymer development, membrane electrode assembly (MEA) fabrication, and fuel cell testing. It is not clear where the focus is, but all the aspects of the proposed work are of great interest of the AEMFC community and the U.S. Department of Energy Hydrogen Program (the Program).

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The researchers very systematically looked at improving the performance of the electrode(s), then looked at improving the performance and degradation of the membranes, and then looked at improving cell design and engineering. This is precisely the order in which the work should be done, and thus the team was able to demonstrate some clear improvements and, therefore, accomplishments in overall system performance. The researchers moved the needle forward. They can make progress toward a PGM-free system and identify good membrane candidates for cell engineering.
- The project has begun work integrating PGM-free cathode catalysts. It is important to work with PGM-free catalysts rather than the very high-PGM-loading MEAs being studied, as the PGM-free catalysts are integral to achieving the promise of lower costs for AEMFCs. The project has identified cathode catalyst degradation and particle growth as an important degradation mode. Given the timing of the start of this project and COVID-19 restrictions, the researchers have managed to accomplish quite a bit. They have a long way to go to meet the identified target for the fourth quarter of 2021: 100 mA/cm^2 at 0.8 V in hydrogen–air for loading of 0.2 mg PGM/cm^2. Most of the work has been with much higher loading (four times the target or more), and data shown with the PGM-free cathode appears to be a long way from the target.
- So far, the team is hitting its targets. It would be nice to see the project be more aggressive with its cell-level low-PGM target. The team has also improved its demonstrated durability.
- Impressive results of the electrode performance improvements have been reported, mainly involving ink composition and processing conditions. There is interesting work on powder processing versus dispersion processing. Not exactly sure what was “unique” and “advanced” in the reported degradation diagnostics.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- NREL's team of industry partners is impressive. There is widescale coordination and very high-quality information exchange across all stakeholders with interest in the work.
- There is a very impressive portfolio of collaborators.
- Collaborations are apparent in the water transport study. Collaborations could be expanded to include LANL and others, particularly in the PGM-free catalyst area.
- Right now, it seems that most of the work is at NREL. It would be helpful if the Colorado School of Mines work were better highlighted. It is also less clear in the presentation what 3M is doing. However, the role that ORNL can play is clear.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is the holy grail of the hydrogen economy. If the project is able to move to non-PGM electrodes and low-cost membranes for critical devices, such as fuel cells and electrolyzers, the cost breakthrough (and opportunities) would have a dramatic impact on the future trajectory of this industry and the global energy picture. This is a crucial project that is very relevant and important, with very high potential impact.
- Improvements in performance and durability and the introduction of non-PGM catalysts into AEMFC MEAs are perfectly aligned with the Program goals. The proposed work, if successful, might lead to significant advancement of AEMFC technology.
- The work is very focused on DOE goals.
- AEMFCs have promise to provide lower costs and may help reach cost targets if they can reach performance and durability targets. This work is directed at meeting the performance and durability targets. Whether reduced costs can be achieved is likely dependent on using PGM-free catalysts. The majority of the current work has been with very high-PGM-loading MEAs, which are not relevant to the Fuel Cell Technologies subprogram. Alkaline membrane systems may be more applicable in electrolysis and reversible fuel cells.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The proposed future work addresses the appropriate barriers and is moving toward low-PGM and PGM-free catalysts.
- The only concern is that the work on segmented cells, which is obviously important and novel, should be pushed back, and the project should focus more on the first three components of the research. The first three components are critically important, and those problems are so big, important, mysterious, and not fully understood that all resources in this project and beyond—i.e., a Manhattan-Project-style program with vast resources—should be applied to study them and come up with a real pathway forward.
- Future work is well-defined. It may occur that switching to non-PGM catalysts will make some data obtained with Pt-based catalysts obsolete.
- It seems that the project will move in the right direction, but the listed items are pretty vague.

Project strengths:

- There is an excellent research plan and excellent team; this combination will most probably lead to very important findings. Inclusion of modeling is also a great idea. The future belongs to computers and to the software.

- The overall competency of the research team and access to important testing and analytical tools are impressive. The analytics and diagnostics effort is excellent and very important and informative. Real progress has been demonstrated, which suggests the project is well-managed and systematic.
- The project team's capabilities in fuel cell diagnostics and methods to determine where degradation is occurring are strengths.
- There is a good group of researchers at NREL using their capabilities well.

Project weaknesses:

- The new cell designs, while being very important, should take a back seat to fundamental work on the electrodes, membranes, etc. Really great material options that work and that are durable are needed first, before we look at new cell designs.
- The current focus on high-PGM-loading catalysts is considered a weakness.

Recommendations for additions/deletions to project scope:

- The planned move to PGM-free and low-PGM catalysts will be beneficial.
- The project should drive down the PGM loading for the fuel cell later to be more in line with the work performed by Simon T. Thompson, et al., and reported in the *Journal of the Electrochemical Society* (167 084514, 2020).
- New cell designs, while very important, should take a back seat to fundamental work on the electrodes, membranes, etc. Material options that work and that are durable are needed first, before we look at new cell designs.
- There needs to be more focus on non-PGM catalysts and inexpensive ionomers/membranes, such as the possibility of the elimination/minimization of the effect of CO_2 on AEMFC performance.

Project #FC-343: Fiscal Year 2020 Small Business Innovation Research Phase II: Improved Ionomers and Membranes for Fuel Cells

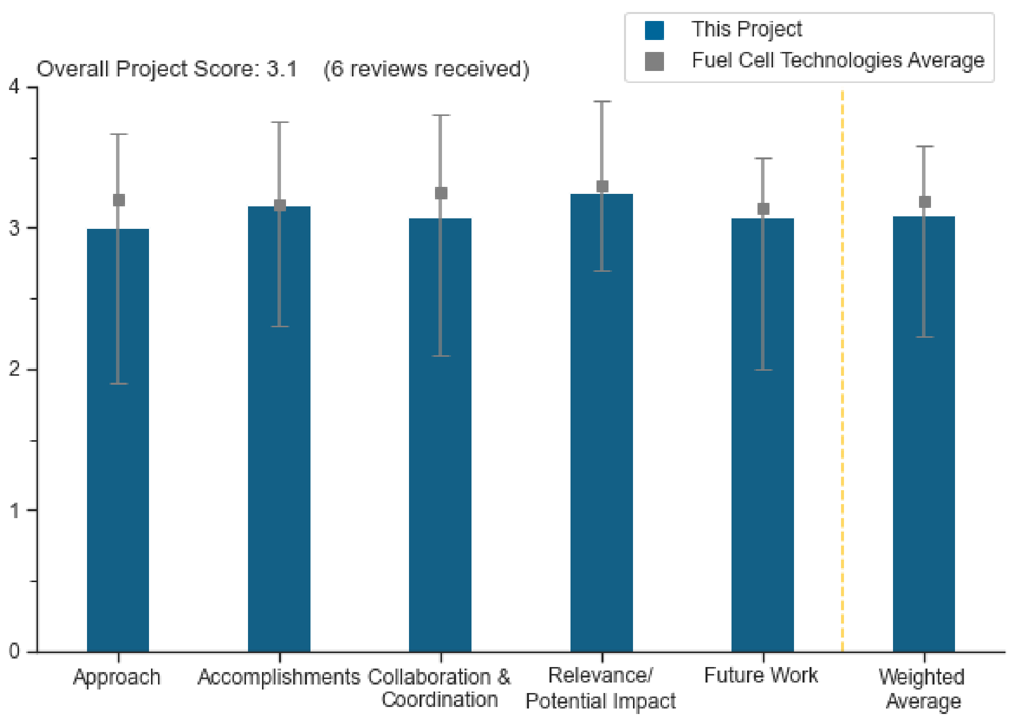
Chris Topping, Tetramer Technologies, LLC

DOE Contract #	DE-SC0019980
Start and End Dates	7/1/2019 to 8/23/2022
Partners/Collaborators	Commercial Fuel Cell Systems Manufacturer, National Renewable Energy Laboratory
Barriers Addressed	• Stable, enhanced performance across a range of temperature and humidity conditions • Reduced gas crossover (hydrogen and oxygen) • Reduced costs

Project Goal and Brief Summary

The project objective is to develop cost-effective, high-performance, durable polymer electrolyte membranes (PEMs) that do not use perfluorosulfonic acid (PFSA) as a base. Tetramer Technologies, LLC (Tetramer) will work with the National Renewable Energy Laboratory (NREL) and a commercial fuel cell systems manufacturer to produce new cost-effective PEMs for integration into existing and future commercial fuel cell devices. These membranes will meet U.S. Department of Energy and industry performance and cost targets that are not attainable with currently available materials.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Fuel Cell Technologies projects.

Note: This is a new project in 2021. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Tetramer makes the polymer and works with customers to do the testing. The approach of using block copolymer with hydrophobic and hydrophilic parts with lower projected cost is great. Unfortunately, the presenter could not reveal the customer and did not provide too much detail on the approach to testing and evaluation. Typically, the team plans to do 500-hour tests (not enough details). If these are accelerated stress tests (ASTs), then it makes sense, but 500 hours of simple fuel cell testing is not enough to evaluate these membranes. It would also be useful to provide more details on what the elected degradation mechanisms for these membranes are and evaluate them in ASTs that accelerate those mechanisms.
- The block copolymer approach employed by the Tetramer team has the potential to advance hydrocarbon PEMs to be competitive with PFSAs. There is an understandable need to provide generalized structures until all the intellectual property is secured. However, it is difficult to evaluate the project merits based on blocks “A” and “B” and to compare against other hydrocarbon systems. The principal investigator addressed this issue during the poster discussion session. Low humidity performance and chemical stability have been traditional barriers to hydrocarbon membrane success, and the Tetramer team should prioritize these aspects if this approach is to be a genuine advance over previous work.
- The overall concept underlying the research project is important and sound. Based on the slides provided, it was hard to tell what polymer development program was being pursued. The test data were helpful and clearly an important part of the work and presentation.
- The team is preparing several new hydrocarbon ionomers based upon block copolymer designs for use as PEMs in fuel cells. Much of the information about the chemistry and block copolymer characteristics (such as morphology, molecular number, and block lengths) was missing because that information is confidential and proprietary. The central premise of the project asserts that the tunability of the different blocks can give rise to desired properties that maximize ionic conductivity while also providing robust mechanical properties. There are no plans to assess chemical durability of the new ionomers. It is unclear whether the team is selecting chemistries that can tolerate reactive oxygen species or whether free radical scavengers will be incorporated to ensure PEM durability.
- The systematic approach to membrane synthesis is valuable and has yielded interesting initial results, but there is not enough focus in the early evaluation stages on durability (the focus seems to be primarily on performance, which is important but not sufficient).
- The approach is very difficult to determine; there were not enough technical details to determine whether the approach is viable.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- All of the new hydrocarbon PEMs achieved <0.02 ohm cm^2 at 80°C. Some, such as membrane Type 2, showed less than 0.01 ohm cm^2. This was a key metric in Year 1 of the project. PEMs Type 1 and Type 2 also showed hydrogen crossover less than 2 mA/cm^2. The new block copolymer ionomer PEMs have been characterized, but these data were not shared. Polarization curves were also generated, but the cell voltage data were not included. Overall, the project team has accomplished the goals for Year 1 of the Phase II Small Business Innovation Research project. No information has been provided yet on whether the team could hit the membrane cost (high volume) of $\$20/m^2$.
- DOE goals are clear and are clearly laid out for this research project. The work is obviously targeted at meeting those goals. It was not clear what polymer was being developed. The fuel cell test data did, however, suggest that the work was moving in the directions laid out by DOE.
- It is difficult to determine the amount of progress; the polarization curves do not even include voltage numbers on the y-axis. The team could have solved this by applying a benchmark such as the NR-211 in the polarization curves, but the presenter showed only the area-specific resistance (ASR) comparison to

NR-211. Nafion™-based catalyst layers married to new non-PFSA membranes have traditionally become an issue.

- The progress and accomplishments to date are reasonable for this stage of the project. Preliminary data at 100% relative humidity (RH) shows good progress; however, low-RH conductivity and fuel cell performance are necessary to be competitive with PFSA incumbents. Ionomer swell and water uptake data would be helpful for comparing to other technologies.
- The project has successfully made four different ionomers, and the progress in the synthesis sections is good. However, it is very difficult to evaluate this when few data were presented on the performance. Polarization curves alone are not very informative for evaluating a membrane. The ASR data were excellent, but they were presented only for 100% RH and 80°C. Moreover, the pol-curves had no correlation to the ASR. Additional characterization, including electrochemical impedance spectroscopy, should be presented to show feasibility. Crossover measurements should be presented under various conditions and directly compared to, say, NR-211. It is unclear under what conditions the <2 mA/cm^2 crossover was measured. A better comparison of these membranes to a baseline NR-211 or a state-of-the-art chemically and mechanically stabilized PFSA membrane would be great.
- Progress to date has yielded interesting results that address project objectives (performance characteristics of block copolymer membrane), but some barriers (durability) will not be adequately addressed by performance alone.

Question 3: Collaboration and coordination

This project was rated **3.1** for its engagement with and coordination of project partners and interaction with other entities.

- NREL is a great partner. The "leading" fuel cell developer's name was not disclosed.
- Collaboration with NREL looks to be well-coordinated, and NREL is a good partner in this project. The "commercial fuel cell systems manufacturer" is a curious choice. This reviewer is not aware of another instance in which a partner identification is kept secret or of the business advantages of this secrecy. It is to be hoped that the partner can be named at the next review.
- The quality of the level of coordination is difficult to judge from the poster materials but, at face value, seems to go in the right direction.
- There is a good collaboration between Tetramer and NREL. The commercial fuel cell systems manufacturer was not identified. It was unclear whether NREL or the manufacturer prepared the membrane electrode assemblies. Some of the tasks for this manufacturer and NREL seem to overlap. NREL has generated quality polarization curves with the PEM ionomers. However, the electrode composition is missing. It is not clear whether the team will use the new ionomers as electrode binders.
- The project has industrial partners to evaluate the membrane, and NREL is doing some durability testing. The project could engage the Million Mile Fuel Cell Truck (M2FCT) consortium to evaluate these membranes under the various DOE-specified ASTs, or the team could engage other industrial partners to get more data on these newer materials.
- The presentation did not even disclose the team members.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The impact of developing a lower-cost, higher-performing, higher-durability membrane is excellent.
- The Tetramer team is addressing the key DOE membrane targets. The team deserves credit for taking on the challenging work of exploring hydrocarbon membrane technology from the perspective of molecular architecture to address the traditional shortfalls of hydrocarbon membranes. The plan for systematically studying block copolymer architectures is unclear. While some degree of "trial and error" is necessary to establish feasibility, more systematic approaches need to be employed to optimize the system for maximum performance.

- The relevance of this project is excellent; low-cost membrane alternatives are essential to the success of the Program objectives. However, durability should be given more priority to align better with Program goals.
- The project team has hit the 80°C ASR and hydrogen crossover requirements for the Hydrogen and Fuel Cell Technologies Office multi-year research, development, and demonstration plan. There are not results for 120°C, which is important for heavy-duty vehicles, or for 30°C. Mechanical property and durability information for the new PEMs is also missing.
- It is difficult to determine the real potential here since very little technical information is given on the approach and the results.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The future work plan proposed is described well and is certainly in line with what needs to be done going forward.
- Working on enhanced performance and durability is great. More details need to be provided on the types of tests that are to be run. In addition to open-circuit voltage (OCV) testing, combined RH cycling–OCV testing (similar to the DOE protocol for the combined mechanical–chemical stability or the General Motors highly accelerated stress test) should be performed.
- Future plans include ASR and fuel cell performance assessments at 90°C to 120°C, as well as durability tests and swelling tests. There are plans to supply materials to a fuel cell manufacturer for stack testing and field testing with a system.
- Durability has long been an obstacle for block copolymer structures and should be addressed earlier in the project (it should be part of a go/no-go decision point).
- The Tetramer team has outlined the necessary future steps in broad terms. However, the work around optimization is not well-defined. It is unclear whether this will be iterative or will include design of experiments or other approaches.
- The team did not show any durability data, and this is a typical issue with new materials. More durability data would help in the down-selection process. Building stacks prior to any of these durability and DOE target demonstrations on single cells is premature.

Project strengths:

- Hydrocarbon block copolymers are a good idea for realizing optimized PEMs that provide good proton conductivity and mechanical properties. Using cheap monomers as starting materials could hit the manufacturing cost target of <$20/m^2. The project team has demonstrated that several of the new PEM variants can meet both the conductivity and hydrogen crossover requirements. The team has a good collaboration with NREL and a fuel cell manufacturer to demonstrate actual performance in a few cell devices.
- The block copolymer approach to hydrocarbon PEMs is likely the most productive path to hydrocarbon membranes that are competitive with PFSAs. This project builds on past hydrocarbon technology and is poised to advance this technology. The Tetramer team has the polymer, membrane, and fuel cell expertise to successfully complete this project. Collaborations with NREL and a fuel cell manufacturer provide complementary expertise.
- Polymer synthesis ideas are good, and good materials to test seem to be provided. Testing data are sensible and provide encouraging outcomes.
- Polymer synthesis is the team’s strength. It seems like good progress is being made on this front.
- The high-risk approach could yield a breakthrough.
- There is strong initial success with meeting performance objectives.

Project weaknesses:

- This is a difficult project to assess because much of the pertinent information is confidential and proprietary. This is understandable. The team has made good progress on ASR at 80°C and hydrogen crossover and has generated reasonable polarization curves. It was unclear what the electrodes were for the polarization curves (e.g., platinum-group-metal loading). The team needs to make a statement as to whether the new block copolymer chemistries can potentially tolerate reactive oxygen species.

- The exact polymer structure could not be determined, and any "weakness" in the project would be associated with the starting materials and the core technology being developed. It is therefore not possible to comment.
- The true test of hydrocarbon membrane technology is low-RH performance and accelerated durability. Until those are demonstrated, the potential of this project cannot be fully evaluated. Optimization tasks lack clarity. Variable space for di- and tri-block copolymers can get out of hand without a focused approach. More mechanical property data are necessary for full evaluation.
- Characterization of the fuel cell performance and durability of these materials is weak at this point. More emphasis needs to be placed in this area in collaboration with the existing partners, or new partners need to be added to advance this further.
- It is very difficult to determine because of the limited technical details given in the presentation.
- Failure modes should be addressed earlier in the project.

Recommendations for additions/deletions to project scope:

- The project is not clear on a pathway to commercialization and issues related to that, such as monomer cost, scale-up issues, toxicity of intermediates, and potential environmental impact. No real analysis appears to have been done on a pathway forward to the market.
- The project should perform the DOE-recommended AST protocols on these advanced membranes. The team should better understand degradation mechanisms in these membranes with fuel cell testing and develop ASTs to study these materials better.
- The project should include screening criteria at an earlier phase that address other barriers mentioned on slide 18.
- Mechanical property assessment and durability should be added as a project goal.
- More technical details should be given for reviewers to do a proper review of the project.

Technology Acceleration – 2021

Subprogram Overview

Introduction

Technology Acceleration aims to address technology barriers, systems and systems-integration challenges, and other crosscutting activities to enable the H2@Scale vision and support the Hydrogen Energy Earthshot. The subprogram pursues these aims by:

- Identifying hydrogen applications and system configurations that can provide more affordable and more reliable clean energy
- Validating and testing integrated system development
- Bridging the gaps between component-level research, development, and demonstration (RD&D) and industry's role in commercialization by integrating technologies into functional systems, reducing costs, and overcoming other barriers to deployment.

Demonstrations conducted during verification and validation activities provide valuable data feedback to research and development conducted through the U.S. Department of Energy's (DOE's) Hydrogen Program subprograms. The data are also used in technoeconomic assessments of various market scenarios to provide essential information regarding market readiness to manufacturers, investors, and potential end users. The remaining subprogram activities—including manufacturing RD&D; safety, codes and standards RD&D; and workforce development—fill out an integrated portfolio that addresses other significant barriers.

The Technology Acceleration subprogram focuses its activities on key emerging markets (or technology applications) based on preliminary findings of the Systems Analysis subprogram, which identifies technologies and markets with the potential to enable economies of scale for hydrogen and fuel cell systems in alignment with the H2@Scale vision. Based on this analysis, the Technology Acceleration subprogram is currently focused on four technology application areas:

- **Grid energy storage and power generation** applications focus on grid integration and renewable hybrid systems, nuclear hybrid systems, and distributed and back-up power generation. Projects are designed to produce low-cost green hydrogen from intermittent and curtailed renewable sources, provide grid reliability, demonstrate dynamic response to match grid demands, support market penetration of renewable energy systems such as wind and solar, and provide additional revenue streams for nuclear power plants.
- **Chemical and industrial processes** are focused on decarbonizing hard-to-decarbonize industrial sectors through integration of hydrogen technologies. These end uses include iron- and steelmaking and ammonia, fuel, and chemicals production, among others. The integration of green hydrogen will reduce greenhouse gas emissions, add jobs, and provide environmental justice in these energy-intensive processes.
- **Transportation** includes medium- and heavy-duty trucks, maritime, rail, and other emerging applications such as construction, mining, and agriculture. The focus for heavy-duty vehicles is to demonstrate and validate fuel cell durability and performance under real-world conditions. Projects will also demonstrate and validate high-flow fueling to support these vehicles. Maritime projects aim to develop and validate power supply systems and hydrogen infrastructure at ports, portside power to supply oceangoing vessels, and onboard hydrogen/carrier storage systems. Demonstrations for rail and other emerging applications focus on the integration of hydrogen production, storage, distribution, and refueling infrastructure.
- **Enabling activities** include manufacturing RD&D; safety, codes and standards RD&D; and workforce development. Manufacturing RD&D projects aim to identify and pursue high-value processing routes to accelerate scaling and to develop techniques to produce advanced components and sub-systems to enable multi-megawatt-scale hydrogen systems at high production volumes. These demonstrations also focus on developing technology and analysis tools for quality control and reliability issues. The Safety, Codes and Standards activity area develops codes and standards to enable bulk utilization of hydrogen, as well as safety and permitting guidance to enable deployment of hydrogen for novel applications (see the Safety, Codes and Standards section of this report for more details). Workforce development activities support the development of training programs to enable the safe and effective deployment, use, and maintenance of hydrogen and fuel cell technologies across various applications.

Goals

The overarching goal of the Technology Acceleration subprogram is to identify new and promising hydrogen end users, expedite the commercialization of hydrogen and fuel cell systems by the private sector, validate the performance of these systems, and achieve economies of scale as envisioned in the H2@Scale initiative.

Key Milestones

Key milestones for the Technology Acceleration subprogram are summarized below.

Grid Energy Storage and Power Generation

- Validate large-scale electrolysis systems for energy storage, grid stabilization, resilience, and dispatch management of electric grid systems with high renewable energy penetration.
- Validate efficiency, costs, and benefits of hydrogen production systems integrated with nuclear power.
- Validate 90% efficiency for high-temperature electrolysis systems operating at nuclear plants utilizing onsite waste thermal energy.
- Validate an integrated distributed and back-up power generation system in real-world operations for power demands up to 2 MW.

Chemical and Industrial Processes

- Validate 100,000-hour electrolyzer durability and verify green hydrogen system cost and technical performance comparable with incumbent technologies for metals production.
- Validate 100,000-hour electrolyzer durability and demonstrate green ammonia production processes for emission reductions; verify costs and validate technical performance.
- Integrate emerging concepts with industrial processes for production of synthetic fuels and chemicals; verify costs and validate technical performance.

Transportation

- Validate 25,000-hour durability and 68% peak efficiency for fuel cells in in heavy-duty truck applications.
- Validate integrated portside power systems, and validate a 35,000-hour durability target for ferry boat shipboard applications.
- Validate onboard hydrogen storage and locomotive power systems for long-distance trains, including a 35,000-hour durability target.
- Validate technical and economic potential of hydrogen and fuel cells for off-road applications.

Enabling Activities

- Develop manufacturing and supply innovations to commercialize multi-megawatt-scale electrolyzers that can produce hydrogen at <$1/kg.
- Develop crosscutting low-cost manufacturing processes with scalability in mind to support domestic supply chains.
- Identify ways to reduce the siting burdens that prohibit expansion of hydrogen fueling stations by using hydrogen research and development that enables a 40% reduction in station footprint, as compared to the 2016 baseline of 18,000 square feet, by 2022.
- Validate hydrogen sensor technology capable of detection speeds of less than one minute, with <$1,000 annual operating cost.
- Initiate at least three new non-automotive-related applied risk assessment and modeling efforts pertaining to large-scale hydrogen deployment applications.
- Establish a skilled workforce to effectively respond to the expected growth in hydrogen-supported industries.

Fiscal Year 2021 Accomplishments

Subprogram-Level Accomplishments

Technology Acceleration fiscal year (FY) 2021 accomplishments are summarized below.

Grid Energy Storage and Power Generation

- Awarded the world's first large-scale hydrogen-fuel-cell-powered data center project (Caterpillar Inc.).
- Established an integrated megawatt-scale hydrogen production, storage, and fuel cell system at the Advanced Research on Integrated Energy Systems (ARIES) facility (National Renewable Energy Laboratory).
- Validated two high-temperature electrolyzers from industry, including a 25 kW stack that surpassed 4,000 hours with <0.5% degradation per 1,000 hours (Idaho National Laboratory).
- Released H2@Scale cooperative research and development agreement (CRADA) call supporting ARIES in FY 2021, focused on integrated hydrogen energy system testing and validation.

Chemical and Industrial Processes

- Initiated two first-of-their-kind hydrogen for steel ("HySteel") projects in the United States to demonstrate use of hydrogen to decarbonize iron and steel production (University of California, Irvine, and Missouri University of Science & Technology).
- Hosted the H2@Scale Workshop focused on ammonia as a viable clean-hydrogen carrier serving diverse end uses.

Transportation

- Awarded the world's first renewable hydrogen production refueling barge to fuel the first hydrogen passenger ferry in the western hemisphere (Hornblower).
- Initiated a CRADA project on high-flow fueling protocol, in concert with the international Protocol for Heavy-duty Hydrogen Refueling (PRHYDE) project (National Renewable Energy Laboratory).
- Released the SuperTruck III funding opportunity announcement (FOA) in collaboration with the Vehicle Technologies Office.
- Supported the launch of Mission Innovation's hydrogen-related missions: the Shipping initiative, which is an international effort focused on decarbonizing marine applications, and the Clean Hydrogen Mission, which included hosting a workshop on hydrogen for mining, agriculture, and construction equipment/vehicles.
- Hosted the H2@Airports Workshop focused on hydrogen use in aviation.

Enabling Activities

- Initiated the Hydrogen Education for a Decarbonized Global Economy (H2EDGE) workforce development project (Electric Power Research Institute).
- Hosted an international workshop on quality control for electrolysis and fuel cells with the National Research Council of Canada and Germany's Fraunhofer Institute for Solar Energy Systems (National Renewable Energy Laboratory).
- Released the first-ever federal regulatory map report to identify hydrogen-infrastructure-related status and gaps across federal agencies (Sandia National Laboratories).
- Released the H2@Scale CRADA Call, which was focused on applied risk assessment and modeling for H2@Scale applications as well as next-generation sensor technologies.
- Accelerated progress on safety, codes and standards (see Safety, Codes and Standards section for specific program- and project-level accomplishments).

Project-Level Accomplishments

Grid Energy Storage and Power Generation

Frontier Energy partnered with several industry stakeholders on an integrated hydrogen demonstration project in Texas. The main objective was to determine how hydrogen production costs can be minimized by using multiple generation sources and by co-locating multiple end uses (stationary power generation and hydrogen vehicle fueling). A five-year plan was also developed for the Port of Houston. Site plans have been completed, and one years' worth of load data (modeled with hydrogen and fuel cell power) have been collected. In support of the plan for the Port of Houston, a preliminary model with supply and demand hubs was developed.

Plug Power partnered with several industry stakeholders to develop an integrated demonstration project in Florida that leverages intermittently available, low-cost electricity from renewables to provide hydrogen in multiple value streams (vehicles, emergency back-up power, and grid). The required storage system was sized to meet various (stationary and vehicular) hydrogen delivery demands. Site and integrated system design, dynamic power simulations, and technoeconomic analyses are under way. Initial deliveries of system equipment were completed.

Exelon Corporation plans to install a 1.2 MW polymer electrolyte membrane (PEM) electrolyzer at a nuclear power plant to provide low-cost supply of in-house hydrogen (used for cooling) and to simulate operation of a larger electrolyzer in nuclear power markets. Nine Mile Point in New York was selected as the demonstration site. Initial engineering design is under way, while an electrolyzer supplied by Nel Hydrogen has gone through acceptance testing (by the National Renewable Energy Laboratory [NREL]), demonstrating less than 0.1% degradation over 500 hours of operation. Initial market demand analysis for similar deployments at various sites was conducted by Argonne National Laboratory. Moreover, Idaho National Laboratory (INL) developed a front-end controller for optimal electrolyzer dispatching.

FuelCell Energy—in partnership with INL and Versa Power Systems—plans to demonstrate the integration of a 250 kW solid oxide electrolyzer with a nuclear plant emulator at INL to validate a high-efficiency and low-cost pathway for production of hydrogen using electricity and waste heat from the nuclear power plant. The project is newly under way but aims to increase operating flexibility and provide an additional revenue stream for nuclear plants by switching between power and hydrogen generation.

Idaho National Laboratory developed a high-temperature electrolysis test stand integrated with a nuclear power plant emulator to accelerate solid oxide electrolyzer competitiveness in the United States, independently validate stack performance, and provide nuclear-simulated integration and testing. The project plans to validate commercial stack performance from industry partners, including Bloom, Nexceris, OxEon, FuelCell Energy, and Haldor Topsoe. To date, two electrolyzer stacks have been tested, including a 25 kW stack that was tested for over 4,000 hours with degradation levels less than 0.5% per 1,000 hours of operation, and three more stacks are being prepared for testing and validation.

Pacific Northwest National Laboratory, in partnership with INL, is collaborating with industry to solve cost and degradation issues through membrane electrode assembly development, modeling, post-mortem analysis, accelerated stress testing development, and manufacturing. A process to produce 300 cm^2 active-area solid oxide electrolyzer cells was developed, and cell performance was validated in multiple single cells. Several cells were tested over 2,800 hours at 750°C and 1.3 V to confirm minimal degradation. A stack repeat unit fabrication process was established, and two 1 kW short stacks were assembled and tested with a goal of building and testing a 5 kW stack.

The ***National Renewable Energy Laboratory***, through the ARIES initiative, is designing and commissioning a 1.25 MW PEM electrolyzer, 600 kg hydrogen storage system, and 1 MW fuel cell generator at NREL's Flatirons Campus to support H2@Scale goals. The system is designed as a testbed to demonstrate systems integration, grid services, energy storage, direct renewable hydrogen production, and innovative end-use applications such as heavy-duty transportation and natural gas blending. Overall site layout and safety reviews have been completed, and most key pieces of equipment have been ordered. Systems integration (controllable grid interface, thermal, water, gas, electrical) is under way.

Caterpillar Inc. was awarded funds to install the world's first large-scale hydrogen-fuel-cell-powered data center—a 1.5 MW stationary fuel cell at a Microsoft data center in Washington state. It will provide 48 hours of liquid hydrogen onsite and increase confidence in hydrogen and fuel cells for the information technology industry by performing technoeconomic analyses, modeling, and simulation to identify data requirements and gaps.

Chemical and Industrial Processes

Missouri University of Science and Technology is developing and demonstrating a grid-interactive steel production system that combines a hydrogen-direct-reduction furnace for ironmaking and electric melting for steelmaking. The system will use variable hydrogen/natural gas content, with one-ton-per-week iron production capacity. The reactor model will then be scaled up to simulate a production pilot facility with a planned capacity of 5,000 tons per day.

University of California, Irvine, is demonstrating and optimizing a thermally and chemically integrated solid oxide electrolysis cell system, as co-producer of hydrogen and oxygen, with a direct reduction iron plant at one ton per week of product scale, scaling up to capacity of two million tons per year.

Transportation

The ***Center for Transportation and the Environment*** partnered with UPS and others to demonstrate fuel cell hybrid electric delivery vans with fuel cell range extenders (75- to >125-mile range), thereby reducing petroleum consumption and related emissions and increasing the commercial viability of electric drive medium-duty trucks. Five trucks have been built and are undergoing testing (a 169-mile max range test was completed), while ten more trucks are currently in various stages of assembly, with expected completion in 2021. The UPS trucks will operate in a disadvantaged community in California and provide benefits aligned with the Biden administration's emphasis on environmental justice.

The ***National Renewable Energy Laboratory*** continues its fuel cell electric bus (FCEB) evaluations to validate performance and cost using real-world data. Of the 38 FCEBs tracked, 12 of them surpassed 25,000 hours of operation, while one FCEB demonstrated over 32,000 hours of durability. The average fuel economy of these FCEBs was found to be approximately 9 miles per diesel gallon equivalent (mpdge) (up to two times greater than fuel economy for compressed natural gas or diesel buses), and a range of approximately 300 miles was achieved with the buses running on 37.5 kg of hydrogen.

Hornblower Energy, LLC, was awarded funds to develop the world's first maritime hydrogen refueling infrastructure on water (at the San Francisco waterfront), with refueling capabilities of up to 530 kg H_2/day. This will be an integrated system of green hydrogen production via electrolysis (to fuel hydrogen fuel cell marine vessels) and power generation via fuel cell (to charge hybrid electric vessels), both mounted on a barge, bringing commercial hydrogen technology to the maritime sector. Hornblower is collaborating with the Port of San Francisco, Sandia National Laboratories, and various industry stakeholders to evaluate the performance, efficiency, and feasibility of such a system, while developing related safety protocols.

Argonne National Laboratory is conducting total cost of ownership analyses to determine how hydrogen and fuel cells compare with incumbent technology in applications in rail, maritime, and aviation and what performance metrics are needed for them to be able to compete on a cost of ownership basis. Results showed that fuel cost dominates total cost of ownership for heavy-duty applications. In one example, it was determined that achieving a fuel cell cost of $60/kW and liquid hydrogen bunkered cost of $4/kg H_2 would likely make hydrogen fuel cell ferries cost-competitive with incumbent technologies. In another example, Argonne found that multiple-unit hydrogen electric locomotives are likely to be cost-competitive at a fuel cell cost of $60/kW and liquid hydrogen cost of $3.50/kg H_2.

Electricore is working on developing a high-pressure, high-flow-rate dispenser and nozzle (100 kg H_2 in 10 minutes at 70 MPa) for heavy-duty vehicles. The system will be demonstrated at NREL. An industry survey of 27 organizations was completed, with the objective of determining specifications. The project team also conducted initial design work, including component selection, computational fluid dynamics analysis, and failure modes and effects analysis. Nozzle technology provider WEH Technologies Inc. and dispenser technology provider Bennett Pump Company are collaborating with Electricore on this effort.

Electricore is also developing an advanced mobile hydrogen refueler capable of fueling 20–40 vehicles per day (70 MPa at -40°C, 3–5-minute fill, 200 kg H_2). The refueler can operate without remote power connections, is modular for easy transport and deployment, and can provide expanded daily capacity and multi-day operations using delivered gaseous hydrogen. The design, assembly, and initial testing are complete, and the refueler is soon to be available for public fueling in Ontario, California. Fueling data will be sent to NREL's Technology Validation team for analysis.

New Project Selections

In FY 2020, the subprogram added projects through FOAs. FY 2021 selections are pending from the Office of Nuclear Energy industry FOA, the SuperTruck III FOA, and the H2@Scale CRADA Call supporting ARIES.

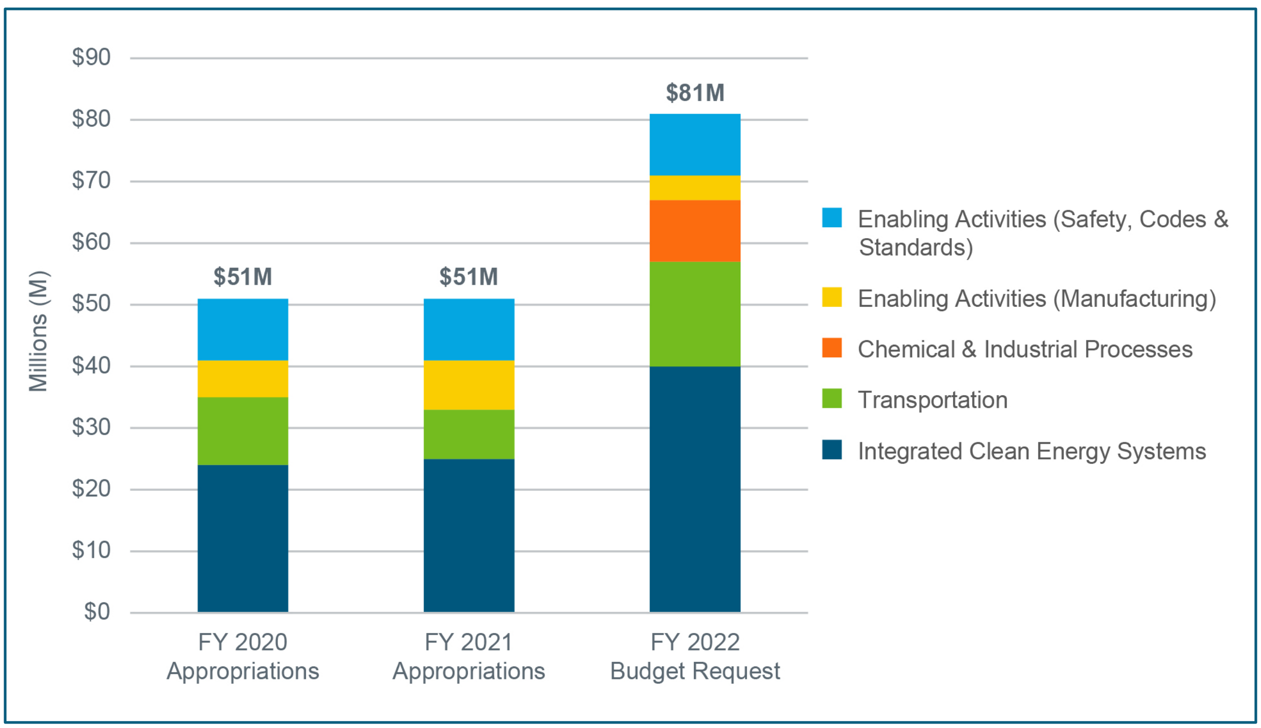
FY 2020 selections included the following:

- FuelCell Energy, Inc. – Solid Oxide Electrolysis System Demonstration
- University of California, Irvine – Solid Oxide Electrolysis Cells Integrated with Direct Reduced Iron Plants for Producing Green Steel
- University of Missouri System – Grid-Interactive Steelmaking with Hydrogen
- Hornblower Energy, LLC – San Francisco Waterfront Maritime Hydrogen Demonstration Project
- Caterpillar Inc. – 1.5 MW Polymer Electrolyte Membrane Fuel Cell for Data Center Power: Development and Demonstration
- Electric Power Research Institute, Inc. – Developing a Workforce for a Hydrogen Technology Economy

Budget

The budget for the Technology Acceleration subprogram remained constant in FY 2020 and FY 2021 at $51 million. The FY 2022 budget request includes a significant increase of $30 million to accelerate efforts to demonstrate, validate, and integrate low-cost hydrogen production with various end uses to enable decarbonization and support the H2@Scale vision. Subject to appropriations and congressional direction, the FY 2022 distribution of funds in key application areas is shown below.

Technology Acceleration RD&D Funding



*$8 million in FY 2020 funding for HySteel projects is now managed under Technology Acceleration – Chemical and Industrial Processes.

Annual Merit Review of the Technology Acceleration Subprogram

Summary of Technology Acceleration Subprogram Reviewer Comments

The Hydrogen Program (the Program) reviewers applauded the Program's development of facilities to validate and integrate hydrogen and fuel cell systems, noting the value of these facilities in de-risking implementation and commercialization and lowering capital risk. Reviewers commended the Program's recent shift toward RD&D on hydrogen applications in decarbonizing CO_2-intensive industries, such as iron, steel, refining, concrete, and fertilizer, as well as RD&D on energy storage applications and blending hydrogen with natural gas. Program reviewers also expressed support for projects that integrate hydrogen applications, such as green steelmaking and transportation applications. However, reviewers also expressed concern that the Program's shift in focus away from light-duty vehicle applications is premature, noting that light-duty transportation applications still require RD&D.

Program reviewers recommended increasing the funding levels for Technology Acceleration activities to enable deployment of mobile and stationary fuel cell systems and hydrogen infrastructure. Reviewers suggested increasing both the number and scope of Technology Acceleration projects, establishing a Technology Acceleration tech team or industry advisory group, and prioritizing end-use demonstrations for hydrogen production. Reviewers supported the use of prizes like the H2 Prize to accelerate technology implementation but cautioned that prizes should be limited in size and scope, focused on outcomes that industry would not achieve without the prize, awarded only if all the prize criteria are met, and used for novel applications or needed integration of existing technologies.

Program reviewers highlighted the need for efforts to accelerate technology commercialization and market acceptance, such as increased engagement with regional, state, and local stakeholders and more education and outreach activities. The Program was encouraged to increase international leadership and cooperation, industry collaboration, partnerships, and environmental justice efforts. The value of collaboration across various DOE offices and federal agencies to Technology Acceleration efforts was also emphasized, with specific mention of the U.S. Department of Defense, DOE's Office of Basic Sciences, DOE's Advanced Manufacturing Office, and the National Science Foundation.

In addition to the Program reviews, project reviewers evaluated 26 individual Technology Acceleration projects during the 2021 Annual Merit Review. The projects received scores ranging from 2.8 to 3.6, with an average score of 3.3.

Project reviewers described the Technology Acceleration activities as well-coordinated and well-managed, relevant, potentially impactful to market readiness and/or market acceptance of the technology, aligned to key DOE objectives, and focused on eliminating the most important barriers. Many projects were commended for their flexibility and excellent progress during the COVID-19 pandemic. Project teams were described as strong and were praised for their choice of partners; the quality of the research facilities was admired. Project reviewers appreciated methodical, systematic approaches and projects with balanced approaches that included experimental, characterization, and numeric/modeling components. There was praise for demonstration and deployment projects that included input and/or hydrogen offtake commitments from potential end users, as well as projects developing versatile systems or components with broad applicability across applications, sites, etc. Projects were lauded for leveraging past experience, other DOE-funded projects, and industry input.

Across the Technology Acceleration activities, reviewers identified a need to conduct technoeconomic analysis to demonstrate the competitiveness of the technologies, compare costs and performance to those of conventional incumbent technologies and alternative competing technologies, and validate the economic models with real-world data and industry input. Reviewers expressed concern for material costs, the scalability of some of the technologies, and the viability for high-volume manufacturing. Data challenges faced by some of the projects were recognized, and projects were encouraged to formally document and publicly share their lessons learned and best practices, as well as to identify codes and standards needs and limitations.

Following this subprogram introduction are individual project reports for each of the projects reviewed. Each report contains a summary of the project, the project's overall score and score by question, and the project-level reviewer comments.

Project Reviews

Project #TA-001: Membrane Electrode Assembly Manufacturing Research and Development

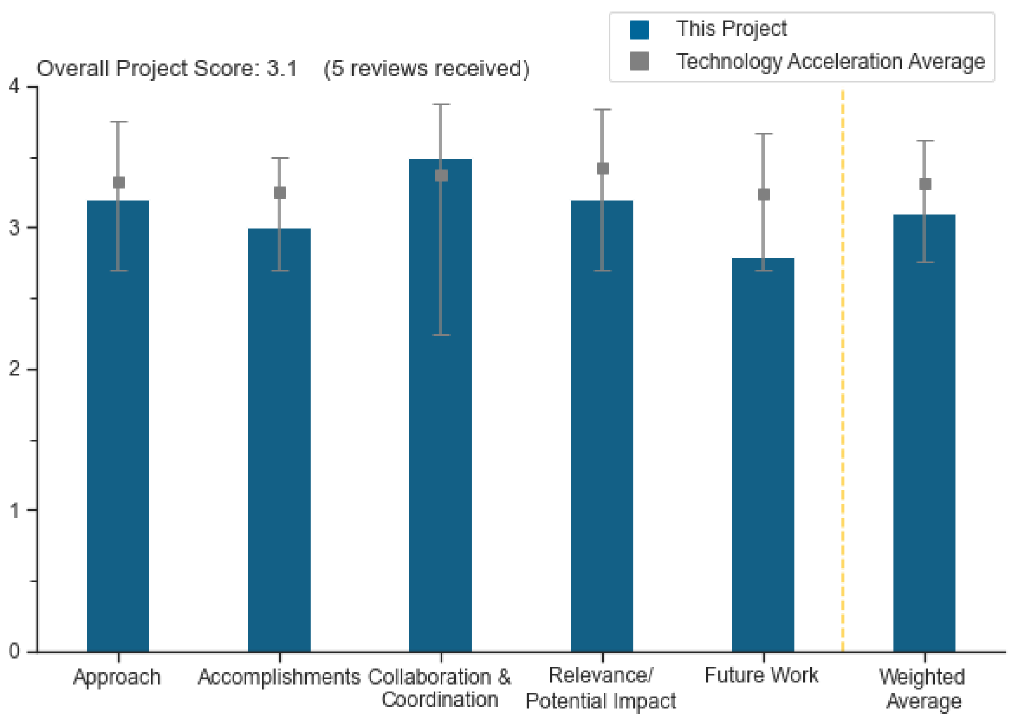
Michael Ulsh, National Renewable Energy Laboratory

DOE Contract #	WBS 10.1.0.501
Start and End Dates	7/1/2007
Partners/Collaborators	General Motors, Mainstream Engineering, Gore, 3M, Nel/Proton, Giner, Inc., Plug Power, AvCarb, Lawrence Berkeley National Laboratory, Colorado School of Mines, National Research Council–Canada, Fraunhofer-ISE
Barriers Addressed	• Lack of improved methods of final inspection of membrane electrode assemblies • Low levels of quality control

Project Goal and Brief Summary

The objectives of this project are to (1) understand quality control (QC) needs from industry partners and forums, (2) develop diagnostics by using modeling to guide development and in situ testing to understand the effects of defects, (3) validate diagnostics in-line, and (4) transfer technology to industry partners.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Fourier transform analysis for the Nafion™ HP (high-performance) membrane using a hyperspectral image of new/unhandled HP samples and measurements from both silicon (ultraviolet–visible) and InGaAs (near-infrared [IR]) fast spectrometers clearly identifies peaks associated with the membrane thickness, and the high-speed, low-heating case led to the least error and a good opportunity for the mapping method. Pinhole studies with reinforced membranes were done as accelerated stress tests with process-induced membrane irregularities (PIMs) for beginning-of-test (BOT) performance and other parameters.
- The optical hyperspectral approach for membrane electrode assembly (MEA) QC makes sense within the thickness limitations of the approach. Rapid MEA inspection is critical toward the development of durable fuel cells.
- QC is obviously a key indicator tool for lifetime, where the project understands the key failure modes expected through membrane failure.
- Objectives and barriers are defined; however, they are somewhat amorphous and lacking in quantifiable details. This is understandable, given that most industry partners are probably unwilling to share much in the way of confidential data.
- The project approach is focused on MEA manufacturing quality control and defect studies. The approach does not seem particularly innovative or likely to result in significant advancements. There is little evidence that this project can advance the state of the art in MEA manufacturing.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Multiple techniques have been evaluated successfully; it would be beneficial for the partners involved to do a cost comparison of the existing equipment and the cost savings due to the efforts within this project. The implications of a pinhole formed are clear and have been demonstrated with a hole made on purpose, but a key performance indicator that can be defined mathematically based on thickness consistency or overall surface quality would be beneficial, taking into account a variety of thinning spots within the produced membrane that may be the size of a pinhole but may not go all the way through the membrane. In other words, the possibility of quantifying the gray zone rather than doing black-and-white pinhole counting should be explored.
- Peaks associated with the membrane thickness were clearly identified, and the high-speed, low-heating case led to the least error and a good opportunity for the mapping method, but samples that are overly handled and in poor condition are difficult to characterize for thickness. Detectable BOT IR response was observed from laser-drilled pinholes of 20–100 µm, and cells with 100 µm pinholes failed reproducibly about 10 times faster than pristine MEAs. The project developed a modeling framework to understand the underlying mechanisms driving membrane degradation in the case of a membrane pinhole.
- The project has been ongoing since 2007. While there was a gap in funding and the COVID-19 pandemic limited work, progress was made toward correlating defect findings from the optical inspection with the durability of fuel cell MEAs.
- Key accomplishments were reported in membrane thickness mapping. There was also some progress in studying effects of defects on performance and durability. These results represent incremental progress, but it seems unlikely that this project is providing information not already known to MEA manufacturers.
- This project has been ongoing for some time now. The project should revisit the specific problem being addressed. It is unclear what has changed since the project started. A chart showing the impact of manufacturing-related defects on overall fuel cell cost (listed as barriers on slide 3) would be beneficial. It is unclear whether the current efforts are properly directed to address those manufacturing problems and how much of an impact the developed solutions have against those problems.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The project collaborates with the major MEA manufacturers, and the researchers actively drive the dialog through sponsored symposia of MEA quality assurance/QC. The project is also well-coordinated between the Tier 1 suppliers, experimentalists, and modelers.
- National laboratories are working closely with 3M, Nel Hydrogen/Proton, Giner, Inc., GM, Plug Power, and AvCarb to understand industry directions and challenges. Industry partners provide materials and QC requirements.
- It is impressive to see the number of international collaborations with partners. A general summary of shared interests and issues would provide more insight on the state of the art.
- The project clearly works with as many industrial partners as feasible, both on commercializing developed solutions and by pulling guidance from fuel cell manufacturing companies. While it is probably not realistic to expect industry to share detailed manufacturing defect and scrap data, this would be the best case for directing this project to the most relevant manufacturing problems.
- The project features valuable collaborations with W.L. Gore and General Motors (GM), among others.

Question 4: Relevance/potential impact

This project was rated **3.2** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Current results show correlation with crossover associated with pinhole formation (and thinning of membranes). There is obviously strong interest from the network of partners, and going forward, roll-to-roll processing will develop stronger dependency on in-line QC tooling. It is key to demonstrate that this work solves current (proprietary) industrial issues without revealing sensitive information.
- Membrane durability is a key issue for the widespread implementation of fuel cell technology. An understanding of the effects of membrane manufacturing defects on the overall fuel cell lifetimes is critical toward achievement of the aforementioned goal.
- National laboratories and industry partners give an effective way to identify key needs toward commercialization of fuel cells for specific applications.
- Fuel cell manufacturing industry data would help direct and validate the focus of this project.
- This project addresses MEA manufacturing, which on the surface is highly relevant, but it is not clear that the project is providing any real innovations. It seems unlikely to advance the state of the art or result in knowledge not already available to MEA manufacturers.

Question 5: Proposed future work

This project was rated **2.8** for effective and logical planning.

- The proposed future work is very strong. It might be good to have an additional effort that couples other inspection techniques, such as x-ray imaging and membrane permeability methods, to further correlate the validity of the work.
- The team is proposing to continue to work on a number of spectroscopic tools for new properties, such as opaque-layer thickness measurement, the effects of relevant defects on cell performance and lifetime, and the development and application of predictive models to assist in understanding the performance and lifetime impacts of defects. This work is needed, but the statement of future work is a little vague.
- The proposed future work on effects of defects could be valuable to improving understanding of MEA degradation mechanisms. The future work on manufacturing diagnostics does not seem as valuable, owing to lack of novelty.
- Perhaps updated data are available to help guide this project to best support fuel cell companies. It would be good to know the following:
    - Which current manufacturing defects the project needs to address next
    - What new materials are coming up (membrane, catalysts, gas diffusion layer [GDL], stack components), and how manufacturing defects and difficulties might change with those new

  - materials—for instance, alkaline membranes and polymer electrolyte membranes might have different sensitivities
  - How the project can use this topic area to address hydrogen generation.
- The future work is vaguely defined. A response was expected to the sense of urgency to scale up production volumes and extend lifetime at the same time, increasing the inherent necessity for QC analysis and data processing. The hydrogen industry is stepping up, and the QC expertise should ramp up accordingly.

Project strengths:

- The project has a world-class research team. There is excellent coordination between industry and national laboratories. There is a viable method for rapid materials inspection.
- There is huge potential to lift the hydrogen industry to a higher level of manufacturing readiness by having good control over QC at higher line speeds.
- The project has good interaction with industry and uses National Renewable Energy Laboratory capabilities in MEA manufacturing.
- There is teaming and a straightforward approach.
- There is continued effort to pull involvement from industry. There is transfer of developments to commercialization.

Project weaknesses:

- As the presenter commented in response to one of the questions, most of the detailed analysis techniques are not on the coating line. Therefore, the application is connected to manual activity to execute deeper investigations into individual trouble areas. Findings would be more valuable if they translated back to in-line damage severity assessment.
- The project needs more correlation studies between defect types as detected by hyperspectral imaging and MEA durability. The technique is not able to characterize the GDL–MEA interface characteristics. There are limitations of thickness measurements by optical measurements.
- There is little innovation or potential for more than incremental advances in this project. It seems unlikely to move the needle in MEA manufacturing.
- There is a lack of hard data to link these efforts to actual impact on fuel cell cost.
- Innovation is limited.

Recommendations for additions/deletions to project scope:

- Project scope should include more in-depth characterization of MEA defects detected by the optical method. This could include transmission electron microscopy (TEM), scanning electron microscopy (SEM), Raman microscopy, and x-ray imaging.
- The attempt to bring QC on different thickness membranes under the same common denominator may actually indicate that different approaches are needed. The project should consider future trends to anticipate market requirements.
- The project should consider hydrogen generation, such as manufacturing of new electrolysis materials. It is unclear how difficult it will be to manufacture alkaline membranes (compared to polymer electrolyte membranes) or catalysts—or to control quality.
- A more science-based approach or a more innovative work scope with respect to developing novel manufacturing methods would make the project more valuable.

Project #TA-005: In-Line Quality Control of Polymer Electrolyte Membrane Materials

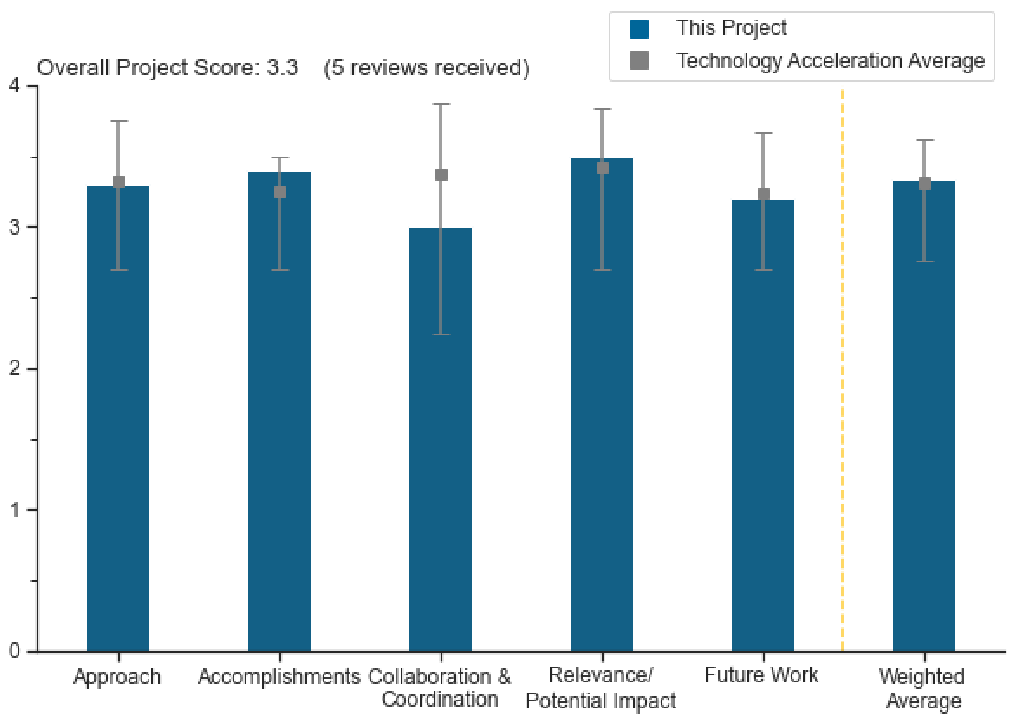
Andrew Wagner, Mainstream Engineering

DOE Contract #	DE-SC0013774
Start and End Dates	8/21/2020 to 8/21/2022
Partners/Collaborators	Ionomr Innovations Inc.
Barriers Addressed	• Lack of improved methods of final inspection of membrane electrode assemblies • Low levels of quality control

Project Goal and Brief Summary

With the goal of improving the reliability and reducing the cost of automotive fuel cell stacks, Mainstream Engineering (Mainstream) seeks to improve in-line quality control technologies that are used in the manufacture of polymer electrolyte membrane (PEM) materials. To achieve this goal, the project team will build a prototype system capable of simultaneously measuring defects in a moving membrane web and membrane thickness over the full web width. The developed system will scan the manufactured membrane with 100% coverage, marking and logging defective regions.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project is well-managed. The project participants are skilled. This is a continuation of a multiyear endeavor to pioneer the fuel cell/electrolyzer future. The national laboratories provide technical horsepower and continuity. As new U.S. companies join this path, the necessary key technology base is there. This plan is excellent.

- The approach is clear, with efforts directed at eliminating the barriers associated with high-volume production and reducing fabrication costs via automation. The integration with the National Renewable Energy Laboratory (NREL) on defect specifications is especially encouraging and appears to be a solid collaboration. The approach of creating a continuous inspection line that can also be used on piece parts is very good for the current market.
- Methods have made good progress since earlier reviews, such as accuracy, capability, speed, etc. This project is critical in terms of increasing manufacturing speeds based on the need to concurrently increase inspection speed.
- This project employs a great approach to addressing an objective that some component manufacturers may value (others may prefer to develop this in-house instead).
- The approach is appropriate for bringing a commercial system to market.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There is good technical progress on loading distribution on gas diffusion electrodes or catalyst-coated membranes (CCMs) and ability to tune the method based on the ink formula. In addition, commercially required elements such as manuals, training material, and calibration procedures are being defined.
- The Mainstream team has shown significant progress in defect detection and marking, as well as putting together training documentation. The system is versatile and can be used for many different products ranging from CCMs to gas diffusion layers. The catalyst loading and continuous thickness mapping ability is a strong addition to the defect inspection procedure. One area of concern with the current design is the ability to process large rolls of delicate materials. For instance, some materials (such as rollable paper gas diffusion layers [GDLs]) cannot be wound around three-inch rollers, and the current design does not allow for 1,000-meter-long rolls, which can be over three feet in diameter. Overall, the design looks very promising for demonstration and moderate-volume production but will need adjustment for true volume production predicted within the next three to seven years.
- The project has achieved excellent results; the team has developed equipment with more capabilities than expected.
- Manufacturing quality improvement has a direct impact on reliability and cost. The best step in accomplishments and progress will be market acceptance/sales and use. The data leading the team to identify the need for these specific inspection points were not shown. It is unclear how many of each defect have previously escaped manufacturing. The cost associated with those defects (both scrap and downstream costs at the system and field levels) is unknown. It is unclear how much this machine will save in those areas.
- The team made good progress on manufacturing details. Details such as particle size, etc., are critical, and data show good progress. Even so, many of the details are not described. There is no mention of test specimens or samples with proscribed damage.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- The very evident partnerships are well-described and show thoughtful selection to assign responsibility among the participants. There are excellent modeling results of dynamics during the coating processes. The presentation stresses the collaboration, and such success is absolutely necessary.
- This project is a good example of government funds being used to produce a useful technology (thanks to national laboratory and industry partners, which will hopefully lead to customers for the machine).
- This small project really allows for only one collaborator, but most usefulness would be gained by incorporating multiple collaborators in similar industries but using different materials to show the translatability of the methods. These collaborations are being discussed but do not appear to be formalized yet.
- There is good collaboration with NREL and Ionomr Innovations, but additional industrial partners should be involved in this process. It is promising that there have been multiple demonstrations and discussions

with various large-scale and small-scale manufacturers, but reaching a universal standard will require additional input about material widths, roll diameters, tensioning requirements, etc. It would be interesting to have at least one high-volume industrial partner for each critical market (e.g., membranes/CCMs, GDLs/gas diffusion electrodes, and electrolyzers) for improved handling definitions and limits to make such a product truly universal.

- It is good that the project now has one highly engaged partner, Ionomr Innovations. However, this membrane developer is unlikely to "be at scale where automated [quality control] outweighs man-hours" anytime soon. The team needs to engage with developers who are at, or near, this scale, e.g., Plug Power or IRD Fuel Cells (for CCMs) and DuPont or W.L. Gore (for membranes).

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Inspection will be a critical piece in meeting DOE objectives, since roll-to-roll coating and similar methods will need rapid feedback on coating quality to avoid generating significant scrap. In addition, at high manufacturing capacity, slow, labor-intensive inspection methods will become a major bottleneck in stack production.
- There is a strong need for consistent defect definition and automated inspection with defect marking in the very near future based on the projected volumes in these markets. Currently, manufacturers are left working with each customer independently to define different defect parameters based on different system configurations, and most visual inspection is done manually. If the project is successful, and the information generated from this work is made widely available, then this project could have a large potential impact in advancing the learning curve for next-generation manufacturing best practices.
- There is no assurance that the "best" technology will be developed using the described approach. However, there is one clear way to make progress: by learning and perfecting the processing steps. This dedicated "long and hard" activity is critical. It is also critical that the processing steps are well-documented so that replication is possible. There is no assurance that any of this will have commercial value, but there is absolutely no way to hope for such success without having a skilled and dedicated team, such as the one here, involved. The missing step is any mention of the "competition."
- Commercialization and sales will be the best indicator of relevance. It will be interesting to see how well the machine moves into the market in coming years.
- This is not a critical barrier, but it is a good contribution at a very modest budget.

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- The milestones for the demonstration seem appropriate and relevant for industrial applications. Expansion of partnerships will also provide more accurate assessment of the potential for the instrumentation and applicability to other industries (flow batteries, etc.).
- The proposed future work for this project is adequate for demonstration of capability on the current line. It seems like it would be beneficial also to conceptualize how such a design could be expanded for real production volumes (widths ≥ 1 m and lengths ≥ 1,000 m). A cost–benefit analysis of the installation of such a system versus the cost of manual labor and the risk of defects reaching final production would be helpful as well.
- The project has good future plans. Emphasis should be placed on expanding manufacturing partners.
- The future remains mysterious. Clearly, manufacturing engineering remains a critical task. New components, such as membranes and catalysts, will be introduced. However, this team has critical skills, and that knowledge is a U.S. asset. A sensible federally funded activity would include detailed analysis of competing products. This team might also have tasks to evaluate degradation mechanisms, working always to achieve long device life. Those who know how something is made are those who can evaluate how something fails. There is emphasis on hardware from a single vendor. Technical efforts in fuel cells are global in extent. It would make sense to review and document the state of the art in PEM electrochemical hardware quality control. Certainly, the auto manufacturers in, for example, Japan or Korea are not going to waste platinum by building faulty hardware. It would be useful to have this team do a review—maybe one week of travel and one week to document—of global quality control technology, both physical instrumentation and software, now being utilized in the commercial sector. (Decades ago, the primary Nafion™ fabricator would lay sheets

of polymer on a light table and look for “fish eyes” in the material. These came from Teflon™-like regions that resulted during the polymer synthesis, zones where the primary product was Teflon. Defective polymer was discarded. Therefore, optical scanning for PEM quality control was around in the 1980s.)

Project strengths:

- Overall, this is an interesting project that has a chance to provide a large benefit to the industry. There is great work done in defining defects; capturing real-time data, including thickness and catalyst loading; and setting up training documentation. This is a critical area that is needed for next-generation, large-scale production manufacturing.
- This task has been under way for years now. The NREL team provides insight and direction; the existing team is clearly a strength. The task seems essential as PEM technology progresses. An expensive system, such as a PEM fuel cell stack, involves considerable costs, materials, and labor. It really makes a huge difference, when you consider cost/mile driven, if the hardware has a lifetime of 50,000 miles or 5,000,000 miles. The team should scheme on “onboard diagnostics” that monitor degradation during testing.
- The team has the required capabilities. There is great technical progress.
- Improvements in accuracy and the breadth of parameters create additional value of the instrument for commercial use.
- Technology has been transferred out of the laboratory. The project has an industrial partner with interest in commercializing developments.

Project weaknesses:

- The task is rather well-defined. Once people are convinced that fuel cell systems will be deployed and many systems will be manufactured, quality control becomes critical. Some “tests” were meaningful but simple. For example, when stainless steel was used for bipolar plates, nickel dissolved and increased membrane electrical resistance. However, it was also possible to actually see that the membranes developed a pink color—clear as it can be. One weakness is that the project seems tightly focused on one instrument. Many other tools could provide additional information. Some efforts are needed to develop a larger scale. The challenge is to be able to identify isolated problem locations within a working stack.
- It is unclear how much market pull there is for the technology. Upfront data showing scrap rates, downstream failures, etc. and costs would be the best justification for the original developments transferred under this project.
- The industry collaboration is lacking and could be improved with the addition of new industry partners. The conceptual system is promising but does not have the flexibility required for softer materials or production-sized rolls.
- The project is limited in funds to be able to partner across multiple original equipment manufacturers.
- The project lacks engagement with potential customers.

Recommendations for additions/deletions to project scope:

- It would be beneficial to the industry as a whole if the defect definitions, vision parameters, and training documentation could be provided to the industry after the system is proven out over the next year. The project team should conceptualize next-generation designs, looking at increasing web width, using different roller diameters, and allowing excess space for longer production rolls (e.g., roll diameters ≥ 1 m). There needs to be more clarity on the cost–benefit analysis of system design and implementation versus labor costs associated with manual inspection and the potential cost of defects making it into final products. It would be beneficial to have at least one volume-producing industry partner consulted for each critical component associated with this vision system to make the design more versatile for the industry.
- DOE should help Mainstream find potential customers for this new product. This should obviously include the Hydrogen and Fuel Cell Technologies Office introducing the team to CCM, membrane electrode assembly, GDL, and membrane producers, but the project should also engage with other DOE offices (e.g., the Advanced Manufacturing Office and Vehicle Technologies Office) to try to identify other potential end users.
- Other scanning tests may be useful. This team should explore possibilities. Clearly, the roll-to-roll status is the last part of the stack build procedure where defects can be identified and managed (perhaps discarded). As the stack is assembled, the task is far more complex. Thermal imaging should be explored. Acoustic testing might be useful.

Project #TA-007: Roll-to-Roll Advanced Materials Manufacturing Lab Collaboration

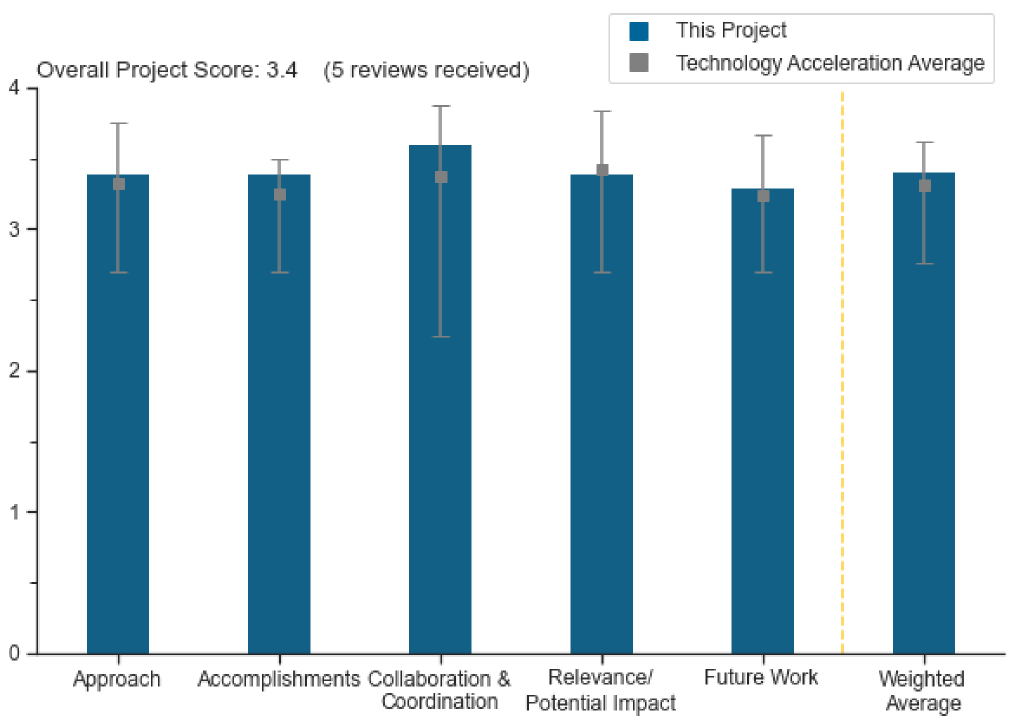
Yarom Polsky, Oak Ridge National Laboratory

DOE Contract #	WBS 10.2.0.604
Start and End Dates	4/1/2016
Partners/Collaborators	Nel Hydrogen, General Motors, Plug Power Inc.
Barriers Addressed	• Lack of high-volume membrane electrode assembly processes • Low levels of quality control

Project Goal and Brief Summary

All U.S. Department of Energy (DOE)-sponsored cost analyses for high-volume production of membrane electrode assemblies (MEAs)/cells assume roll-to-roll (R2R) processing will be used. The project objective is to develop R2R manufacturing techniques to reduce the cost of automotive fuel cell stacks at high volume (500,000 units/year) from the 2008 value of \$38/kW to \$20/kW by 2025. The project goals (depending on technology area) are to (1) increase throughput by 5 times and reduce production footprint, (2) reduce energy consumption by 2 times, (3) increase production yield by 2 times, and (4) enable a substantial shift of manufacturing to the United States by assisting in the development of a domestic supply chain.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The task is to pioneer R2R manufacturing techniques for electrochemical devices, especially for polymer electrolyte membrane devices. This activity integrates a DOE-based team that is carefully coupled to several quality U.S. firms in a focused, detailed study of the manufacturing of electrochemical hardware. Various specific steps are required, and the identification of new processes is assigned to various participants so that one effort can support others. The planning is excellent. The National Renewable Energy Laboratory (NREL) is the lead lab. The project has a large distributed team. There are many tasks. There are many variables for each task. It is a multiyear project. There are many challenges. It is apparent that the approach has proven successful. The project is well-managed and -integrated. It is well-done.
- The approach across all tasks is coordinated for maximum efficiency. The project covers several different approaches (anode, cathode, catalyst-coated membrane [CCM], gas diffusion layer [GDL], etc.), which is appropriate, given the uncertainty as to which approach will be optimal for commercialization.
- The overall approach is good for developing CCMs. The coordination between the two different projects (Advanced Manufacturing Office [AMO] and Hydrogen and Fuel Cell Technologies Office [HFTO]) is good, and the fact that the team presented both during the peer review is greatly appreciated. However, there is no focus on the ultimate component that most fuel cell and electrolyzer developers would like, which is a five- or seven-layer MEA (sometimes called a unitized electrode assembly [UEA]). This is the CCM integrated with the GDLs and often includes a perimeter feature for interfacial sealing. The principal investigator did not seem to be familiar with this component, which is not good. It is not clear how engaged NREL is with industry.
- Developing R2R manufacturing is needed for fuel cell commercialization, and the team is studying various processing approaches for MEA-making.
- The approach discusses two national laboratories working on the project but is not totally clear about how they coordinate their efforts. It appears they are working independently, with one laboratory (AMO) reporting the results.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- R2R manufacturing is critical for meeting the hydrogen production cost targets. The project shows good progress in understanding factors for achieving uniform coatings and the impact of ink rheology.
- Considerable progress is apparent. In some ways, it looks like the results were “harder than we thought,” but much has been accomplished. Clearly, on the globe, this team is as good as any.
- Accomplishments include the rheology model and slot die and experiments-validated model. Slide flow studies are very informative, and the concept of lower surface tension for the top layer should be directly applied to multilayer coating. Spectrometry-based metrology is making great progress. An in-line method for simultaneously measuring thickness and loading will be very useful. Active thermal scanning for half-MEA roll materials is reported to be successful, but a statement of what was needed was not presented. Plug Power inputs on high-shear mixing are very applicable, but overnight low-velocity mixing is reported mostly defect-free, and it is unclear what “mostly” indicates. It would be helpful to know how many defects can be tolerated. For the wrapping of the microporous layer, the target diameter roller is unclear. Nel Hydrogen (Nel) developed a methodology for direct gravure coating onto a membrane. Work at AMO reports slot-die modeling. It is unclear if the difference in coating techniques is important. It is unclear whether the AMO slot-die effort will help Nel.
- The project has demonstrated reproducible R2R deposition of anode and cathode layers on membranes.
- There are some good accomplishments here, although the project could reasonably be expected to be further advanced than it is, considering the AMO work started in 2016 and the project’s annual budget is large.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- The management is just about collaboration and coordination. The cast is large and distributed. There are federal people, academics, and industrial folks. The project has made considerable progress. As the United States develops its industrial base in electrochemical devices, this team knows the territory. Nobody knows the end results, but it is apparent that the results are good enough to begin performance, then cost, then durability. The results are not in yet, but the work has started well.
- This is a well-integrated and comprehensive effort of five national laboratories: Oak Ridge National Laboratory, Argonne National Laboratory, NREL, Lawrence Berkeley National Laboratory, and Sandia National Laboratories.
- Five national laboratories are working together, and an industrial cooperative research and development agreement complements the efforts.
- This is good with the HFTO work, since collaboration with fuel cell and electrolyzer developers seems to be the primary focus of this newer project. It is not evident that much engagement is done in the AMO project, either with potential customers for this work or with R2R experts in industry.
- There is good collaboration with industrial partners, with real-world components analyzed using developed techniques. In the short time allotted for the presentation, it was difficult to tell what the major contributions of the laboratories besides NREL are.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Electrochemical devices are high-volume products. Fuel cells and electrolyzers will be made in high volumes and made throughout the globe. This project was designed to pioneer techniques and processes for that high-volume manufacturing. Unlike batteries, these newer devices are meant to be long-duration hardware. It is critical to have excellent manufacturing engineering. This project is how that happens.
- R2R manufacturing is recognized as a process to meet DOE cost and volume targets for MEAs. It is important to have this effort going forward and working with (U.S.) industrial partners. This effort should be a valuable assist to U.S. manufacturers' competitiveness.
- Critical mass for R2R processing within the U.S. community is needed to advance these methods to commercialization. Having significant laboratory effort in this area, in conjunction with key U.S. industries, provides a good mix of applied trials with fundamental understanding of the underlying physics for accelerated development.
- R2R methods are important. A way to make a seven-layer membrane, anode layer, cathode layer, anode GDL, and cathode GDL is most relevant to manufacturers.
- The project is well-aligned with key DOE objectives, but the results are disappointing, and the lack of attention to (or even knowledge of) what components are ultimately needed/desired here is quite disappointing.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Heavy emphasis on industrial engagement and technology transfer is appropriate for this area. Coordination with Hydrogen from Next-generation Electrolyzers of Water (H2NEW) partners and industry is extremely important, especially as H2NEW gains momentum.
- The team is continuing to improve the quality of deposited layers in R2Rs being made.
- The team is working on the last year of an extended project. There is still much to do. Platinum management is an example. Platinum is a rare element, and it remains expensive, perhaps in part because of the existing global cartel that manages demand and supply. It makes sense for future work to consider the platinum supply, budget, and management. If the MEA has an endurance issue, after that duration, the platinum needs to be recovered. That technology needs consideration. There are environmental concerns with the perfluorosulfonic acids, and the management of those materials needs to be done carefully. It

might make sense for the electrochemical hardware, “fuel cell,” to be leased to the owner; and at the end of its useful life, it gets returned to the “owner,” who manages recycle and disposal.

- Proposed future work for the AMO core laboratory activity includes the following statement: “Leverage application agnostic process for development of fuel cell and electrolysis MEA challenge.” This statement is unclear. “Study novel structures to address durability.” It would be helpful to supply an example of a novel structure and an explanation of why the structure would improve durability. The proposed future work for the HFTO R2R activity includes the following statement: “Complete key deliverable projects and transfer to industry partners.” It is unclear what the key deliverables are. “Pursue continued funding with HFTO.” It is unclear what that funding would be for. It is unclear whether pursuit of funding is a project or a need.
- The major focus of the proposed future work is seeking “continued funding” (both with AMO and HFTO). There is not much here with respect to specific goals. What is obviously lacking is to focus on making five- and seven-layer MEAs.

Project strengths:

- The team is strong. The management plan and execution appear to be first-rate. The project created a credible technology base, which needs to be the basis of a successful commercialization.
- Strengths include the laboratory capabilities, from characterization to pilot-scale manufacturing of MEAs and gas diffusion electrodes, as well as strengthened relationships with key industrial partners.
- The project has a very strong team of researchers. The project is leading in manufacturing R2R understanding for industry quality control.
- The project is using the experience of all team members.
- The project has five national laboratories with many capabilities.

Project weaknesses:

- In general, not much weakness is evident. There is absolutely no mention about competition, and what the competition is doing, e.g., Toyota. There is a global activity for different electrochemical systems, such as lead acid. That technology has a very admirable recycling arrangement, and much of the Pb in the global lead acid batteries is recycled, not mined. This is a good example to build in.
- No major weaknesses were noted.
- The R2R processing developed to date is too limited in that limited numbers of layers do not translate into a commercial fuel cell. Only the seven-layer reel-to-reel synthesis gives a fuel cell process useful for practical manufacturing.
- There is poor engagement with industry, both with respect to understanding what manufacturers actually want and to obtaining R2R knowledge that exists in industry.

Recommendations for additions/deletions to project scope:

- There are many established capabilities in industry that NREL could leverage here, which include R2R coatings of polymers for non-fuel-cell components as well as CCM processes developed by W.L. Gore and 3M (who, having now exited the CCM business, may now be more willing to share some know-how). It is not clear whether NREL has tried to engage and learn from the R2R experts in industry. There is no evidence of that here. If there is interest in integrating CCMs and GDLs, the project should consider starting with making UEAs for redox flow batteries (RFBs), which consist simply of bare membranes and C papers (without polytetrafluoroethylene). Ideally, these should include some polymer picture frame on the perimeter, which is desirable for all types of cells for sealing purposes. Researchers could work on this in parallel with making CCMs that are acceptable since CCMs are not required in RFBs.
- The project needs to focus on a way to make a seven-layer membrane, anode layer, cathode layer, anode GDL, and cathode GDL, which is most relevant to manufacturers. The team should consider novel ways to deposit good, complete seven-layer structures using reel-to-reel methods.
- The project should accelerate the R2R effort and quality control effort and bring in additional industrial partners.
- The project is close, in this phase, to completion.

Project #TA-009: Maritime (Pierside Power) Fuel Cell Generator Project

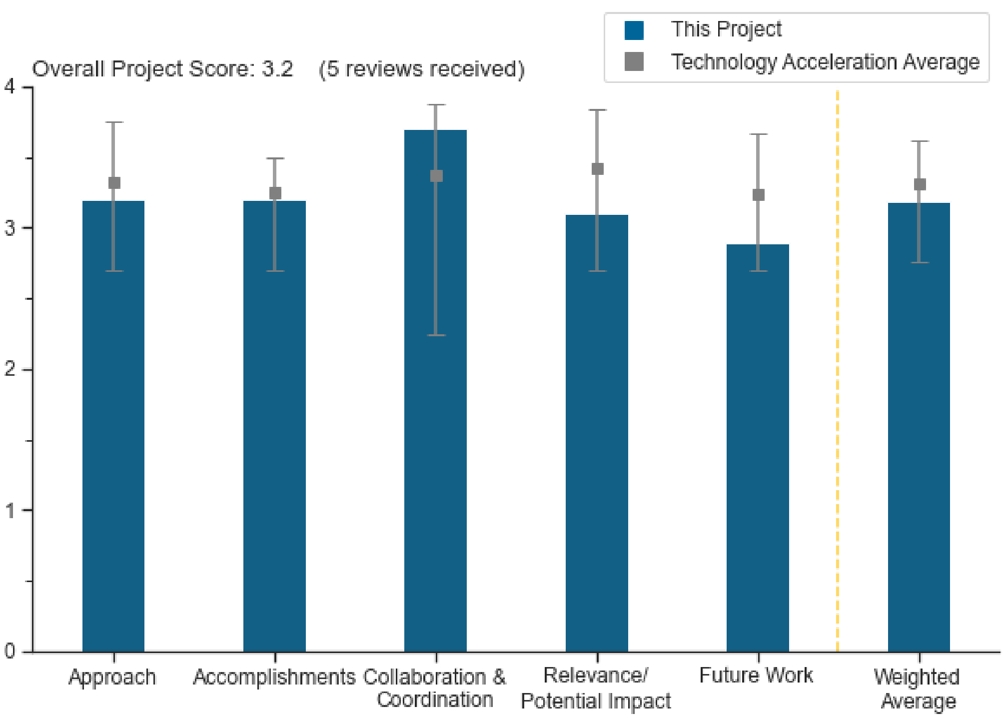
Lennie Klebanoff, Sandia National Laboratories

DOE Contract #	WBS 9.2.0.2
Start and End Dates	7/1/2016
Partners/Collaborators	Scripps Institution of Oceanography, Hydrogenics
Barriers Addressed	• Inadequate standards • Financing mechanisms • Inadequate user experience

Project Goal and Brief Summary

The overall objectives of this project are to (1) lower the technology risk of future maritime fuel cell deployments by providing performance data on hydrogen polymer electrolyte membrane fuel cell technology in this environment, (2) lower the investment risk by providing a validated business case assessment for this and future potential projects, (3) enable easier permitting and acceptance of hydrogen fuel cell technology in maritime applications by assisting the U.S. Coast Guard (USCG) and the American Bureau of Shipping (ABS) with developing hydrogen and fuel cell codes and standards, (4) act as a stepping stone for more widespread shipboard fuel cell auxiliary power unit deployments, and (5) reduce port emissions with this and future deployments.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project concept is concise, with clear objectives and goals and a path to complete the required work to meet the goals. The partnerships leveraged the necessary skillsets by letting the partner with the most experience complete the work. This ranges from sourcing the hydrogen for the quayside power system to servicing the power system after the pandemic isolation subsided.
- One of the goals of the U.S. Department of Energy (DOE) Hydrogen Program is to enable market introduction of fuel cell technology. This project is relevant to that effort and could help to reduce barriers to further deployment of fuel cells.
- The project demonstrates that a stationary fuel cell system can operate in the demanding maritime environment and demonstrates that fuel cells and hydrogen can meet performance challenges. The project also provides experience with fuel cells, visibility to fuel cells and hydrogen, and use of hydrogen in a new market that could potentially help increase demand and market pull. The project has addressed issues with standards and siting. The original involvement of ABS and USCG has promoted the development of hydrogen and fuel cell codes and standards within these organizations. The gathering of performance data will further promote the development of standards based on real-world experience. The use of renewable/green hydrogen shows the potential of green hydrogen for distributed power production. The project could be improved by tying more closely to technoeconomic analysis studies, looking at the cost to provide clean electricity with this system and projected future systems and comparing these costs to those of other dispatchable options (potentially swapping truckloads or shipping containers full of batteries, or diesel generators with biodiesel, or standard diesel and a carbon tax). It is not enough that hydrogen and fuel cells can do the job; they have to be able to do it while being economically competitive with alternatives or providing significant other advantages. At the cost of hydrogen for this project (>$45/kg), it makes it look like the hydrogen fuel cell solution cannot be competitive, as a rough estimate suggests the resulting cost for electricity would be over $2/kWhe. However, this hydrogen cost seems excessive, and a projected cost of electricity at more reasonable hydrogen costs and at hydrogen costs that meet DOE targets would be helpful.
- The general goals of the project are sound, and the team and project have shown considerable flexibility with recovering from the various issues along the way (permitting at various sites, COVID-19, power quality, etc.). From a clean energy perspective, some element of shipboard use for powering reefer containers would have been nice to see.
- The project objectives of building and deploying a containerized hydrogen fuel cell generator for portable power in land or sea applications for replacing diesel generators, aimed at reducing fuel costs and greenhouse gas (GHG) emissions, are clearly articulated. Major barriers being addressed are clearly identified.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- COVID-19 restrictions have essentially put the project on hold for the past year. The principal investigator has made as much progress under those circumstances as could be expected. The unexpected long shutdown, while unfortunate, has provided a useful test and demonstrated that the system can be shut down for extended periods and apparently suffer no ill consequences. This also suggests the system would have a reasonable shelf life.
- The project was hindered by and benefited from the pandemic in that the site realities changed during the pause and provided the opportunity to demonstrate the portability and flexibility of the technology concept. Working with actual customer loads and discovering issues, such as the electrical grounding issue, that will not appear during laboratory testing reveal the value of demonstrations for maturing technology. The electrical grounding issue should still be monitored closely, as this can be a non-trivial issue plaguing electrical systems.

- The project seems to be doing a reasonably good job of demonstrating that fuel cells can be used for power on land and at sea at ports. There was little progress in the last year because of COVID-19. The team seems to be making progress toward getting the fuel cell system running again after the prolonged shutdown.
- The project was delayed because of COVID-19 pandemic restrictions. Team members kept in contact with periodic phone calls to keep the team together. Equipment was confirmed operational despite the long, unanticipated shutdown. The project began using renewable hydrogen in July 2020 to further reduce lifecycle GHG emissions. Deployment of the Scripps Institution of Oceanography (Scripps) vessel has been delayed until June 15, 2021.
- It is unclear whether enough hours have been run to validate any model of the economics. It is to be hoped that this will improve during the remaining six months in the project. Also, it would be helpful to see a little more data on the hydrogen usage and duration between refuelings.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- Partners cover all critical aspects of the project, from Cummins (Hydrogenics), which manufactures the fuel cell system, to IGX Group Inc. (IGX), which manufactures equipment for and supports hydrogen fueling, to Scripps, which will deploy the technology, to Sandia National Laboratories (SNL), which covers project safety in addition to leading the project. There appears to be excellent collaboration between all team members. Funding provided by the U.S. Department of Transportation's Maritime Administration from fiscal year (FY) 2017 through FY 2020 shows that the federal Maritime Administration is interested in and supports the potential of this DOE technology for addressing GHG emissions in the industry. The project demonstrates cooperation and collaboration between two different federal agencies.
- This project incorporates the full spectrum of participants in the energy chain, from supplier to end user. The California State University, Los Angeles, solar (photovoltaic) supplier feeds IGX water electrolyzers for converting sunlight into hydrogen gas. Cummins (Hydrogenics) converts that hydrogen into electrical power for a research vessel at Scripps. SNL orchestrates the music and dancers.
- Collaborations with Scripps, IGX, and Cummins appear to be effective, and earlier collaborations with USCG have been beneficial for the maritime and fuel cell communities.
- There is excellent collaboration between SNL, Cummins, and Scripps.
- Obviously, there were initial struggles in the project with attempting to support reefer containers; these issues occurred because of a disconnect on permitting. That may not have been a collaboration issue, per se, but it seems like there may have been a disconnect in planning that caused some of those problems. Technically, it seems like the project has proceeded well, with the partners working together successfully since the shore power model was put in place.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project began in 2013. The unit has been demonstrated on land and over the ocean in Hawaii for a portside refrigeration demonstration. The unit has since been upgraded to provide shore power for a Scripps vessel. The two demonstrations should provide cost data and performance data to help define standards, and they provide users with experience in using fuel cell power systems. The project addresses the DOE Hydrogen Program goal of developing hydrogen/fuel cell technologies for replacing diesel generators to reduce GHG emissions, as well as conducting a demonstration of the technology. Reducing high hydrogen infrastructure cost was identified as a DOE target. The cost of renewable hydrogen is high. Addressing the high cost of renewable hydrogen or the hydrogen infrastructure as a technical target seems beyond the scope of this project. Demonstration activities provide the performance and user experience to address the identified market transformation barriers of inadequate standards, market uncertainty, and inadequate user experience.
- The project is helping to demonstrate the relevance of fuel cells for power in ports and other stationary/portable applications. There is a need for more analysis demonstrating that fuel cells are competitive or evaluating what improvements are needed to make them competitive.

- As outlined in the feasibility report, this demonstration could be the energy storage portion of the hybrid power and propulsion system of maritime vessels. It also could provide shore power to piers in remote or compromised marinas.
- The experience gained from demonstrating the technology with potential customers is very valuable and essential to getting a successful product to market. The potential impact will be tied to the economics and to how this product compares with the competition. This project does not address the economics or how hydrogen and fuel cells compare with the competition.
- The technical demonstration is generally satisfactory, including capability, robustness (during the COVID-19 delay), and portability. The quoted price of hydrogen ($45/kg) is concerning. The reasons behind that were not well-explained, and it seems that the economics are not going to work at that level. It is unclear whether the team has explored any other alternatives for hydrogen supply at a lower price.

Question 5: Proposed future work

This project was rated **2.9** for effective and logical planning.

- The future work focuses on upgrading and modifying the unit for a third demonstration: providing power on the hydrogen barge at the San Francisco waterfront. Demonstrating the unit in a number of different maritime applications provides a range of performance and cost data that enable one to better evaluate whether the technology can compete with incumbent diesel technology in these applications.
- The project is drawing to a close with a clearly identified series of tests to complete. The electrical grounding issue is appropriately at the forefront of the discussion, as it could be a non-trivial complication. It will be interesting to see what the processed data and testing reveal for utilizing hydrogen as an energy storage medium in this application.
- Given the remaining life of the project (six months, until December 31, 2021), it makes sense that the team is focused on running as much as possible and getting as many operational and economic data as possible. This project has the opportunity to inform a broader array of stationary power applications for fuel cells, so the team is encouraged to consider other applications in reporting the experience and data.
- The project is nearing its end, and the proposed remaining work for the dockside deployment for Scripps and data collection should provide useful information. Plans for an additional deployment in San Francisco could be beneficial, but more information is needed regarding that deployment and, in particular, what the fuel cell unit would power.
- The future work is vague. More information should be provided about what upgrades are planned, what work is required, and what benefits are expected from the new deployment on the hydrogen barge.

Project strengths:

- Multiple demonstrations for different applications provide a wide range of performance and cost data to inform portside operators of the potential benefits of hydrogen/fuel cell technology. The ability to modify and upgrade the unit for the various applications is a major benefit.
- Clearly, the leading strength to this project is the collaboration partners. The correct partners are collaborating with the appropriate equipment at the precisely controlled venue to illustrate the feasibility of the stated project objective.
- The team has shown much perseverance and flexibility over the whole (eight-year) life of the project.
- The project is helping to demonstrate that fuel cells can be used for land and sea power in ports.
- The project provides hands-on experience with hydrogen and fuel cells for people in the maritime arena and provides fuel cell developers with experience in the marine environment.

Project weaknesses:

- There are no major weaknesses. The cost of hydrogen for demonstration projects such as this will be high, even unreasonably high, especially if the goal is to use completely “green” hydrogen. The expectation is that the cost of “green” hydrogen will come down as demand increases. The project needs to understand that using “green” hydrogen at $45/kg could strain the budget.
- This project is still recovering from pandemic complications. Reality ties it to a singular, specific vessel. The project technical data are moderately challenging to find, as the listed website contains reports from 2017.

- The use case has ended up being quite narrow, and the extremely high cost of the hydrogen ($45/kg reported) undermines the usefulness of any economic data that come out of the project.
- The project does not sufficiently address the economics or competitiveness.
- There is little science or analysis in this project. There is no indication that the fuel cell is providing a significant value proposition.

Recommendations for additions/deletions to project scope:

- If feasible, it would be beneficial to illustrate the capability to power a remote marina or a primary shore-power bus for multiple smaller vessels. This would illustrate the capability of not only addressing the shore-power needs of a major vessel but also addressing shore-power needs of smaller venues. The second recommendation would be to demonstrate the maritime fuel cell system powering the *R/V Robert Gordon Sproul* electrical loads while the research vessel is at anchor away from the pier. This would demonstrate both the versatility of the power source and its minimal environmental signature as to not impede ongoing research activities.
- Technoeconomic analysis and comparisons to alternative green power sources should be a part of future demonstrations related to this project.
- As noted in the presentation, it is important to make sure that all data are available to the public. It was mentioned that the unit's initial location was at a dock that was close to a private home and that noise coming from the unit could be an issue. It would be good to know much noise was coming from the unit and whether the noise can be further reduced.
- It is likely too late for much change at this point in the project, but it is recommended that the team take a look at alternative means of hydrogen delivery/on-site storage to get the cost down. It would be helpful in the final analysis to determine what cost level for the hydrogen fuel would be required to make the unit competitive with other stationary power alternatives.
- Analysis is needed that would support the relevance and applicability of fuel cells in port applications, and that would assess the competitiveness with alternative technologies.

Project #TA-016: Fuel Cell Hybrid Electric Delivery Van

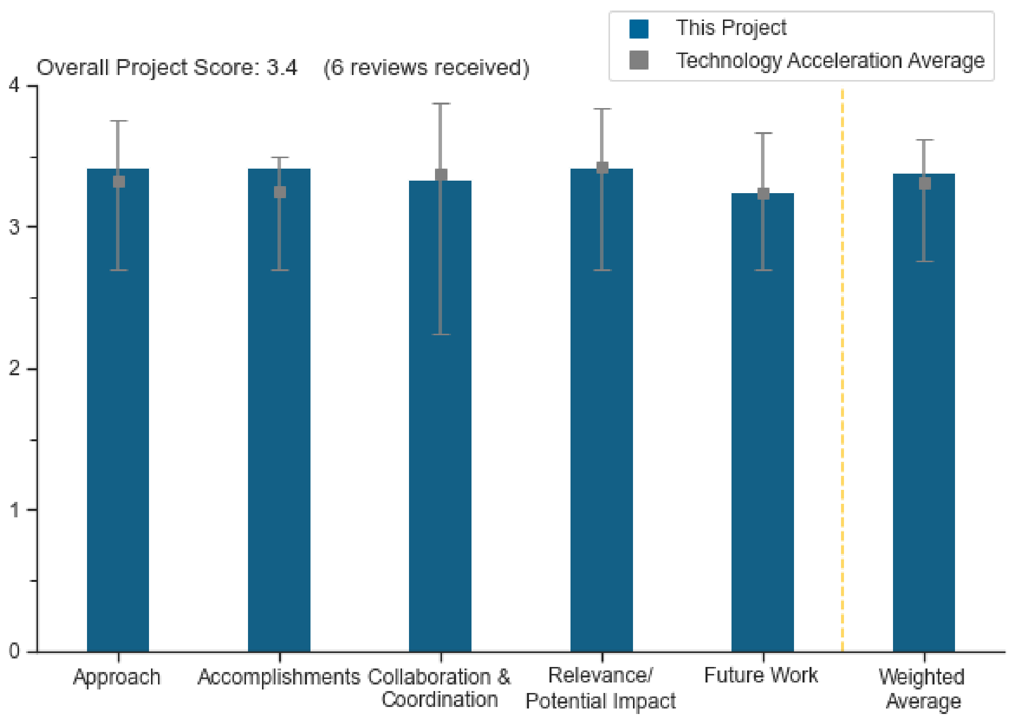
Jason Hanlin, Center for Transportation and the Environment

DOE Contract #	DE-EE0006523
Start and End Dates	7/15/2014 to 7/31/2022
Partners/Collaborators	California Air Resources Board, South Coast Air Quality Management District, California Energy Commission, United Parcel Service, Center for Transportation and the Environment, Hydrogenics, Unique Electric Solutions, Center for Electromechanics – University of Texas at Austin
Barriers Addressed	• Lack of fuel cell electric vehicle performance and durability data • Market uncertainty around the need for hydrogen infrastructure versus timeframe and volume of commercial fuel cell applications • Inadequate user experience for many hydrogen and fuel cell applications

Project Goal and Brief Summary

This project aims to increase substantially the zero-emissions driving range and commercial viability of electric-drive medium-duty (MD) trucks by integrating a hydrogen fuel cell into the powertrain. Investigators will develop and validate a demonstration vehicle to prove its viability and then build and deploy up to 16 vehicles, which will perform at least 5,000 hours of in-service operation. The project will also develop an economic and market opportunity assessment of MD fuel cell hybrid electric trucks.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The Center for Transportation and the Environment (CTE) showed a good approach to the work for demonstrating fuel cell hybrid delivery vans. The team is flexible in adjusting the scope as needed, such as choosing to stay with 350 bar tanks instead of going to 700 bar tanks. In large fleet applications, this lower pressure can save significant money on the cost of fuel delivery and the capital cost of building out a new fueling depot. The project also had to work around long delays in infrastructure availability and station reliability outside of the researchers' control. It is amazing they will complete the project after 10 years; most partners would have stopped by now. Phase II is a big step forward in going from one vehicle validation to 15 new vehicles.
- It seems much progress has been made since the last Hydrogen Program Annual Merit Review. It is great to see the fuel cell van well received by United Parcel Service (UPS) drivers. Most issues have been addressed, except for the life/durability issues, which will require extended study and testing to evaluate to end-of-life conditions.
- Development of a vehicle to which the operator is accustomed and that works for the operator is a good plan. The choice of a progressive and large partner in delivery is also good. The location is suitable. It is wise to start with one vehicle and then build the fleet with any lessons learned in hand.
- The project approach is greatly aligned with technical barriers, and the scope is clear on how each will be addressed. The economic and market opportunity work are well-suited to addressing the market uncertainty challenge.
- The project demonstrates a sound approach to accomplishing tasks. The project objectives are clearly identified, and the project addresses barriers in hydrogen fuel cell MD vehicle commercialization.
- The project used a large commercial van fleet user, UPS, to collect feedback, as delivery services will be the ultimate users of this vehicle. The project used a reputable fuel cell supplier, Hydrogenics, to source the system, and well-known integrators.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Good progress has been made toward DOE goals. It is unfortunate that the project experienced early delays from 2014 in component integration (inverter). Then, as soon as the researchers started meeting build deadlines in 2019, there were issues with infrastructure, and then there was the COVID-19 delay. That being said, the project is making good progress with UPS to demonstrate the availability and long range of a fuel cell delivery van for zero emissions. The team went above and beyond by nearly doubling the demonstrated time from 6 months to 11 months in total. The project has also hit major cost hurdles by completing the UPS Ontario maintenance bay hydrogen safety audit. The online dashboard will be critical to optimizing the driver experience and showcasing economics of the hydrogen delivery vans. This will allow DOE to better track fleet performance and give UPS confidence to deploy additional vehicles after this pilot Phase II is complete. Procurement of all parts required for the 15 Phase II vehicles shows the researchers are good at planning and are making good progress on high-level goals, i.e., deploying multiple zero-emissions delivery vans to lower greenhouse gas (GHG) emissions and creating learnings for hydrogen infrastructure choices to enable broad deployments. This project should be critical in supporting DOE's economic and market opportunity assessment. The 169-mile range validation is the most impressive metric in proving overall project success.
- The project has accomplished much during the preceding 12+ months (especially during the COVID-19 timeframe). Extending the duration of the demonstration enabled the team to gain more data, as well as gain understanding of how well certain design changes will perform in the new phase of vehicle builds. The team has active project participation and has solved fueling issues along the way. The project began the rollout of the Phase II vehicles, which will provide more data from more vehicles over time.
- Over the last year in a build phase, one vehicle was completed and is in extended service. The project demonstrated a range suited to the application so refill would not be needed during the day very often. There is much better progress than indicated in the slides, as five more vehicles are finished and five more

nearly so. The project has achieved much improved idle fuel consumption and a 170-mile range, which covers virtually all delivery routes for a day (so no refuel is needed en route). The project also found some "soft" selling points. Drivers liked showing off a socially responsible vehicle. The fact that UPS went for double the time to which the company originally agreed indicates UPS liked the project.
- The project completed multiple phases, and managing a small fleet of 10+ vehicles in multiple locations is a substantial effort.
- This project is very well-aligned with DOE goals of demonstrating fuel cell MD trucks in the real world.
- The project demonstrates good progress towards meeting overall project and DOE goals. While total cost of ownership (TCO) is one of the project's end goals, it would be nice to see some initial costing information (e.g., available from Phase I of the project) to get the interim performance indicators.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- CTE has done an outstanding job of coordinating all the partners. There is significant unseen overhead when managing multiple sponsors and ensuring all funding organization needs are met. This is even before the difficult coordination of integrating non-commercial technologies across UPS operations, which must not disrupt the company's revenue service. It is difficult to interface between service needs and technical specifications with the multiple component integrators and suppliers: the Center for Electromechanics at the University of Texas at Austin, Unique Electric Solutions, and Hydrogenics. The fact the project met the long range, exceeding fleet requirements, with only 9 kg, and met 15 mi/kg efficiency is very impressive proof of the excellent coordination. Other organizations such as the Hydrogen Safety Panel and the National Renewable Energy Laboratory can both detract from and add to a pilot project such as this. Data collection can add additional hurdles in formatting and user fatigue. The second review of safety may result in constructive support but brings additional project risk and possible cost.
- Collaborating with UPS is about as good as it gets as far as end customers for these types of vehicles. It would be interesting to see how smaller fleet owners would respond to a fuel cell electric vehicle (FCEV) van, given the difficulties with infrastructure (UPS can probably afford to install infrastructure). The majority of van fleets are smaller (<20) vehicle fleets; infrastructure affordability will be an issue.
- The project has extensive partners and participation from the appropriate members. The members give this project a best chance at success.
- There is a good choice of partners; they can place orders at large scale if the pilot succeeds. It looks like there are appropriate levels of coordination.
- The project demonstrates satisfactory collaboration and coordination with project partners. To capture the most honest feedback, the team should gather feedback from the operator/user/maintenance crew through a formal, anonymous survey instead of just informal conversation.
- The collaboration between all the partners seems good. Clearly, the project has been delayed somewhat, and it is unclear whether there were collaboration issues in the past, but based on the presentation, all parties are currently involved and contributing to the success of the project.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is a perfect project to showcase the pivot from passenger cars to medium- and heavy-duty vehicles. The on-road results are critical to proving the technical capability of the fuel cells and hydrogen storage, while helping to highlight hurdles of hydrogen cost and infrastructure deployments. The fact that the target range was exceeded with 350 bar onboard storage rather than with 700 bar is an important signal for where cost reductions should be focused across the DOE Hydrogen and Fuel Cell Technologies Office. The detailed route maps, fuel consumption modeling, and real-world driving results are invaluable to showing Hydrogen Program progress.
- This project captures what needs to be done, especially as it moves into Phase II. Starting with one vehicle and learning about its use and performance, then building many more vehicles, is a great plan and is providing essential information to the technology community, as well as the municipal

community. Assuming a successful conclusion, the impact could be huge for delivery providers in terms of reducing carbon emissions and maintenance.
- Understanding reliability and maintenance in MD FCEVs is important, especially as a partner has the ability to have great impact on the penetration of the technology. The project aligns well with reducing criteria pollutants and GHG emissions. There could also be a broader supply chain impact if the project does induce early adoption of this technology in delivery vans.
- Collecting strong customer fleet feedback on these range-extended electric vehicle vans is crucial to understanding powertrain sizing and customer needs.
- The project aligns well with the Hydrogen Program and DOE research, development, and demonstration (RD&D) objectives and has the potential to advance progress toward DOE RD&D goals and objectives.
- A technoeconomic analysis (TEA) should be done at the end of the project to see how close the technology is to meeting Hydrogen Program goals and targets. No indication was provided in this presentation regarding the hydrogen targets.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The project has a strong future work proposal that will continue to answer questions about the challenges associated with fuel cell mass adoption. Market opportunity assessment is one of those essential pieces of work that needs to be completed along with the data collection on the additional vehicle fleet.
- The project demonstrates a sound approach to the future work plan. It sounds like vehicle certification remains a challenge in certain states. Recommendations on how to address this barrier need to be addressed.
- It was good that CTE and UPS were able to use public infrastructure as a stopgap, but it clearly shows how difficult it is when the infrastructure is unreliable, and the fuel is very costly. Because of the ongoing delays in infrastructure build-out and the multiple delays in delivering fuel to California over the last three years, low-cost, reliable delivery of fuel will likely be the biggest hurdle for a positive Phase II test and evaluation. Extra care should be taken with ongoing coordination regarding the Shell hydrogen station.
- It will be very interesting to see all the trucks on the road.
- The project will finish the creation of vehicles and gather operation data. Maintenance is part of the future work, but there are no data now.
- The project is nearing completion.

Project strengths:

- It is good to see a fleet of 15 trucks built and demonstrated. This will provide the industry with performance, reliability, and cost metrics that will be the basis of future hydrogen-focused projects. It was great to see Phase I completed successfully after all the initial hurdles. This project seemed to uncover some shortcomings in the hydrogen distribution network.
- The project uses a vehicle body with which the customer is familiar and that the customer values. The project aims for a range that will minimize fueling issues so long as hydrogen is available at the base of operations. The project has a nearly perfect customer partner and test area.
- For CTE and the project partners, the biggest strength is perseverance, which is required to see this project through from start to finish. This strength is followed closely by execution and coordination required to reach the outstanding technical results of range, fuel economy, and meeting all routes requested from UPS.
- The project has a strong plan to gather real-world usage data on a fleet of fuel cell delivery vehicles. The phased approach with a go/no-go decision is excellent. The project has a great, experienced team.
- This demonstration project addresses barriers in fuel cell MD vehicle commercialization. There is effective engagement and coordination with UPS and local hydrogen station operations.
- The project has deployed real-world demonstration vehicles with a large fleet customer.

Project weaknesses:

- It would be good to know what the “fueling station issues” were and how they were addressed. This can help the industry improve infrastructure for future easier adoption.

- Retrofitting the old chassis vehicles may be an impediment because of certification issues and not being able to take advantage of the latest developments in safety, functionality, weight savings, connectivity, etc.
- There is no formal feedback (e.g., survey) nor initial TCO data presented from Phase I to determine interim cost outlook. Some barriers in vehicle certifications have yet to be addressed.
- There is no ability to scale up production nor to develop a certified vehicle where sales could be scaled to any level desired.
- The most significant weaknesses were likely past failures from component suppliers for smooth integration and the uncertainty of hydrogen infrastructure due to the unreliable California hydrogen market delivery performance to date.

Recommendations for additions/deletions to project scope:

- As it stands, this project will show this conversion can be done and give some data on how well it works. That might catch the eye of someone who could take it further, but the odds are it will not. To have real value to the country and to the company, this work needs to scale up in a very large way, and since the researchers cannot do that, they need to be very actively courting people who can. Certification is a problem, so lining up a partner who can build the hybrid vans from scratch at appropriate scale is critically needed. The project should consider looking for a large partner that could do the extensive engineering and validation/test work needed for vehicle certification by the government and that could accomplish production on any scale.
- The project should prioritize Task 8 to ensure hydrogen fuel is available as the new vehicle batches are commissioned and delivered in Task 5. Task 6 will also be critical in operations training relating to driver acceptance and a smooth integration for UPS. Given the previous project experience, it is important to highlight the importance of a reliable fuel supply. If possible, priority should be increased for coordinating logistics and fuel delivery in the event of unexpected outages from Ontario regarding the supply of hydrogen, as well as the potential for such outages. It may be helpful to consider a contingency plan if the station goes down without notice and a backup supply of hydrogen is needed on short notice.
- It would be good to add a TEA task to determine all the costs associated with the trucks, maintenance, and fueling. This can form a baseline to see how much costs need to improve if FCEV trucks are to be successfully adopted.
- The project could perhaps conduct a small demonstration with smaller fleet owners to get a different perspective on willingness to use hydrogen as a fuel.

Project #TA-017: Innovative Advanced Hydrogen Mobile Fueler

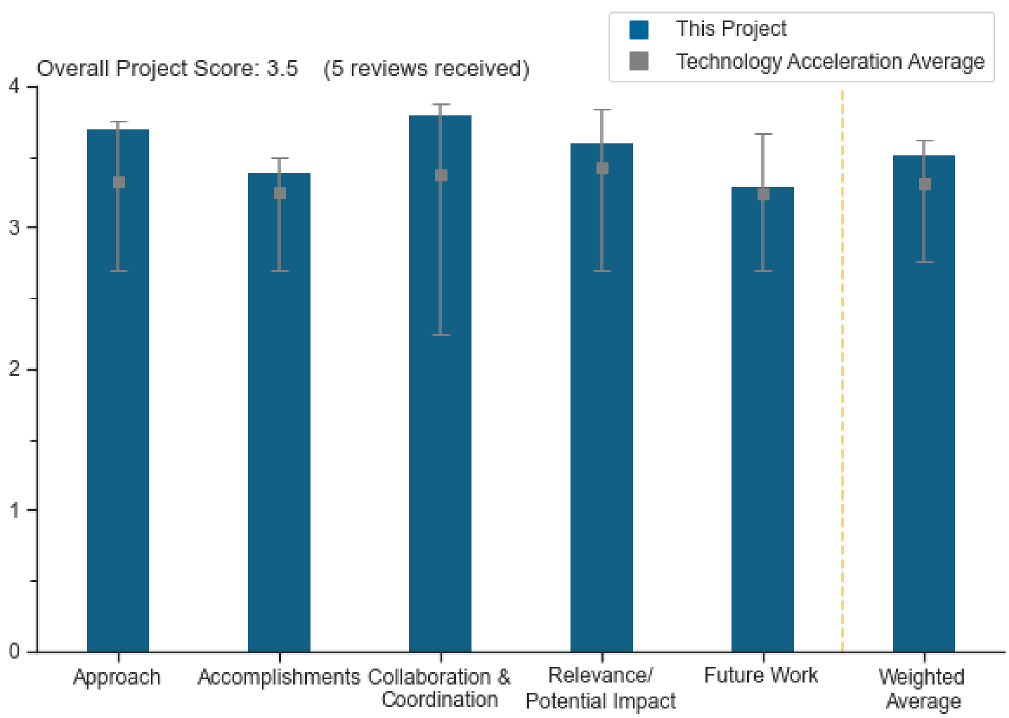
Sara Odom, Electricore Inc.

DOE Contract #	DE-EE0007275
Start and End Dates	7/1/2016 to 6/30/2021
Partners/Collaborators	Air Liquide, HTEC, QAI Laboratories, Manta Consulting
Barriers Addressed	• Hydrogen codes and standards • Hydrogen storage • Lack of hydrogen refueling infrastructure performance and availability data

Project Goal and Brief Summary

The objective of this project is to design and build an advanced hydrogen mobile fueler (AHMF). The developed mobile fueler will be deployed to support a network of hydrogen stations and vehicles; fueling data will be gathered for analysis by the National Renewable Energy Laboratory's Technology Validation Team. To reduce risk, the mobile fueler is based on an existing conventional station design, and project efforts are coordinated with station providers and automotive manufacturers.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project has a strong approach to meeting the challenges specified. The design and demonstration of the mobile refueling station that is able to accomplish point-of-sale hydrogen sales will provide excellent usage and performance data to follow-on efforts. Demonstration at three sites provides a more robust use case with more varying data for any design improvements.

- This project has been under way for several years now, and the most challenging objectives and barriers have been identified (Tasks 4 and 5) and addressed. It appears previous input from reviewers and project stakeholders has been considered and included where there are needed improvements to the project.
- The staged approach with design and development, followed by demonstration and validation, was good. It is nice to see concept-to-hardware all the way through. It is good that the performer received a special waiver to carry 950 bar and that this can be used in other projects. This is a small thing, but bar seems to be the standard unit for hydrogen, so it would make sense to report as bar *vice* MPa.
- The approach is sound and reasonable. The compact design is applicable to most potential sites and expected to be user-friendly.
- The connection to U.S. Department of Energy goals and the benefits to the industry are clear.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made great progress toward its goals. The liquid nitrogen (LN2) cooling validation was a big step and important to validating the station performance and the ability to meet commercial filling requirements. Site selection was also an important accomplishment toward getting the project completed.
- Carrying 95 MPa, without purging for system transportation, requires a special permit—a valuable achievement for the overall industry. LN2 appears to work as anticipated (to be fully proven through Hydrogen Station Equipment Performance [HyStEP] device testing). It has been system-integrated, and it passed quality testing. The self-contained system for H70 fueling from the mobile fueler is a very positive achievement and sets the bar for the United States for future mobile fueling solutions with similar fueling capacity. The anticipated first demonstration site has been selected.
- This project is on track to demonstrate the mobile fueler, although timing was delayed. The delays are understandable, considering the issues during the pandemic.
- Progress has been made. It is understood that COVID-19 and permitting processes tend to take a toll on the schedule. Perhaps selecting a location with permitting under industrial or commercial zoning would help, at least for initial qualification refueling, in order to begin demonstration use as light-duty-relevant locations are permitted.
- It would have been preferable to see more actual hardware by now, but the design looks good.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project appears to be successful in collaboration with partners and with initial demonstration site providers. The city of Ontario is expected to come through with a temporary permit after the paperwork is submitted, in part because of previous experiences in that region.
- This project is well-connected with major hydrogen suppliers, as well as DOE national laboratories and other partners. It appears to be a well-balanced and strong team.
- The team looks like a good mix of industrial experts. Teaming with the national laboratories for economic analysis seems like a good approach.
- This is a well-coordinated project, with multiple specialist partners that span industry and government.
- There is excellent collaboration between all project partners.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The information from projects like this will help municipal governments expand hydrogen filling access as new stations get planned. If usage is below or above the planned use case, that could help save funding in the long run. The U.S. Department of Transportation's (DOT's) approving 95 MPa hydrogen tanks is huge for the industry and has already been trickling down to other projects and efforts. This effort is also helping with the permitting work, which can be a huge obstacle in many places. This also has a huge potential impact.

- The project is highly relevant to DOE goals because it will facilitate build-out of hydrogen infrastructure. The mobility and quick set-up are important. This type of system could be used to fill in the gaps of a network or to help test out locations for permanent future stations. The lessons learned during this project could be used to help improve other stations and potentially lower station footprint, which is a challenge for some sites. Approvals from DOT could aid other mobile fueler development.
- Mobile refuelers that are more than just a cascade fill are going to be critical in building demand and consumer confidence in new markets. Building fixed infrastructure has too long of a lead time and cost for early, low-demand markets.
- This is the first project under DOE funding to achieve a fully self-contained H70 mobile fueler at this fuel pressure and with this capacity.
- Mobile refuelers are a nice demonstration project to help achieve hydrogen at scale because they can be moved to various demonstration sites.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The future work planned is in line with the needs and objectives. The project is working on an extension to allow full time for demonstration and data collection, and it is very important to analyze these data and eventually share results.
- Future work falls in line with completing the efforts as proposed: finishing the demonstration sites and getting the required data to mark the project as a success and contribute to progress on the DOE barriers.
- Some contingency planning concerning alternate siting or siting philosophies, in case permitting continues to be drawn out, could help.
- There is a high degree of effective planning, even through delays. Successful continuation of the project based on the proposed future work is anticipated.
- It is good to see that Air Liquide plans to use the AHMF beyond 2022.

Project strengths:

- This project has a strong approach in developing and demonstrating a mobile filling solution that can help bring down hydrogen filling barriers. There is a strong team working together to learn as much as possible about the system to help enable future iterations for specific needs.
- AHMF is a first in the United States, and it has strong potential for replication to accelerate the rollout of infrastructure and provide infrastructure where needed (because of a new market, delayed planned infrastructure, temporary infrastructure where existing infrastructure is down, or emergency fueling infrastructure). Another strength is the 95 MPa special permit and the simultaneous education of DOT. There is potential for the use of lessons learned from the “station equipment footprint reduction” exercise to fit on the semi-trailer for future new approaches toward footprint reduction of permanent hydrogen stations.
- The compact mobile design is easily set up and user-friendly. The mobile fueler could be used to test out viability of sites for future permanent stations and also to fill in gaps in the overall hydrogen station network. The lessons learned can aid other DOE projects and mobile fueler development.
- This project provides a well-thought-out design for a mobile refueler, with a demonstration plan and validation. The innovative LN2 cooling technology will be interesting to compare side by side with the incumbent cooling technology from other projects.
- This is a well-engineered system from a team with the right strengths.

Project weaknesses:

- LN2 as a consumable is a little concerning. Maybe it would be good to include some economic analysis showing the low cost of LN2 relative to the cost of other cooling technologies.
- It is strongly suggested that the project look at high-density fuel cell power packs (bus powerplants, perhaps) instead of a diesel genset.

- The cost reduction potential and outcomes of the economic modeling are unclear. The timeline of execution is also a weakness.

Recommendations for additions/deletions to project scope:

- It is recommended that the project conduct a follow-up project to build two to five additional units. The team should apply the lessons learned to a future version that can be used for fueling medium-duty and heavy-duty vehicles. Removal of the fueling data collection requirement should be considered, as the majority of equipment components exist elsewhere or apply significantly to only specific components of the system.
- The project needs an analysis of the LN2 cost as a consumable, along with user feedback on it.
- The project is well-planned, and no additions or deletions are suggested.

Project #TA-018: High-Temperature Electrolysis Test Stand

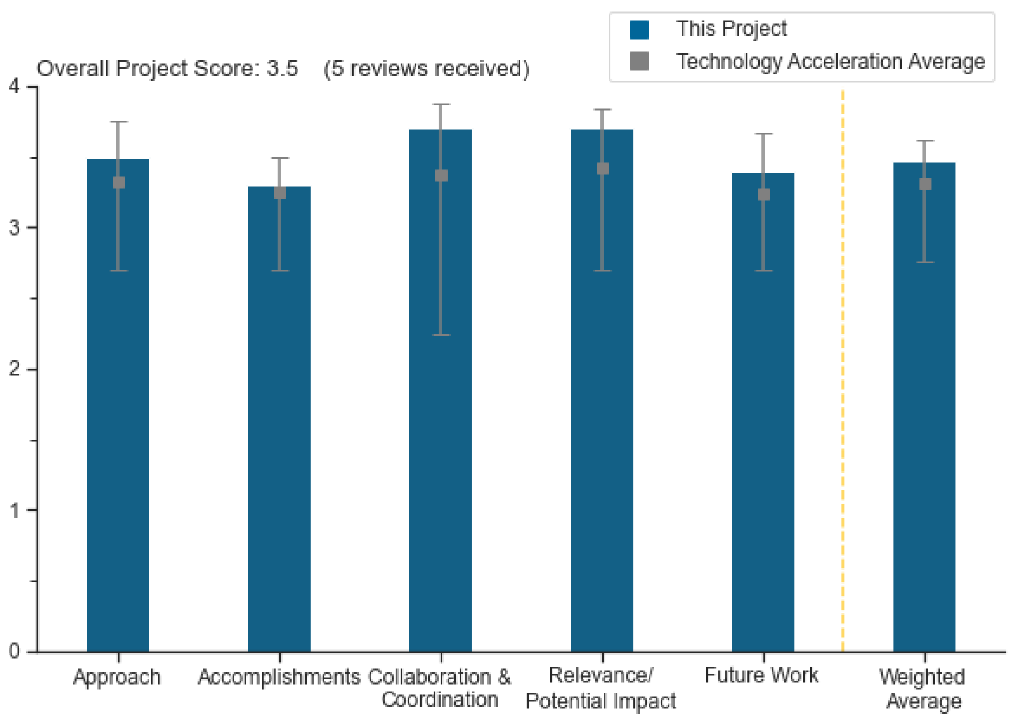
Micah Casteel, Idaho National Laboratory

DOE Contract #	WBS 7.2.9.1
Start and End Dates	9/30/2020
Partners/Collaborators	Idaho National Laboratory, Strategic Analysis, Inc., Bloom Energy, FuelCell Energy, Nexceris, Energy, Xcel Energy, OxEon
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Controls and safety

Project Goal and Brief Summary

The project objective is to advance the state of the art of high-temperature electrolysis (HTE) technology by discovering, developing, improving, and testing thermal–electrical–control interfaces for highly responsive operations. The project will (1) develop an infrastructure to integrate support systems for 25–250 kW HTE testing units, (2) support HTE research and system integration studies, (3) measure cell stacks, performance, and materials health under transient and reversible operation, (4) characterize dynamic system behavior to validate transient process control models, (5) demonstrate integrated operation with co-located dynamic thermal energy distribution/ storage systems, and (6) operate the system with co-located digital real-time simulators for dynamic performance evaluation and hardware-in-the-loop simulations.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is an outstanding project. Idaho National Laboratory (INL) is supporting several solid oxide electrolysis stack developers with performance and durability testing while providing the U.S. Department of Energy with data to assess the status of solid oxide electrolysis cell (SOEC) stack technology. As the project goes forward, INL will develop the capability to test larger stacks (and multiples of larger stacks). This capability will enable system-level assessments of SOEC technology.
- The approach to evaluate stacks from multiple customers to further compare the technologies and to further advance stack/system technologies (in terms of technology readiness level [TRL]) is highly valuable. The major solid oxide cell (SOC) players will be participating in the project, which will encourage collaboration toward a mutual goal of reduced hydrogen production cost. The attempt to provide open-access benchmark information on various tests for different customers, along with their supply chain options and costs, may be easier said than done, and what information is shared will depend greatly on the willingness of the customers. Another potential challenge is that the operating conditions for different customers may be different. This will create a challenge in data comparison if, for example, all stacks are operated at different current density.
- It is very important to provide an independent testing platform for manufacturers that also functions as external validation for end customers and applications that require a high degree of reliability. The list of companies that collaborate in this project is impressive.
- Objectives are clearly defined, but additional detail would be helpful. Barriers are listed as capital cost, system efficiency/electricity cost, and controls/safety. Controls and safety seem to have been addressed in the slides and talk, with perhaps some information on system efficiency and electricity cost, but it would be better if there were more discussion on how capital cost, system efficiency, and electricity cost are being addressed. The project approach in general seems sound; however, when a stack test stand is used to evaluate multiple technologies, it is advised that caution be taken since certain aspects of the test stand may yield bias toward one stack technology versus another and skew interpretation of results. As long as analysis of data and reporting of results take this into account, the bias can likely be minimized. It was mentioned that input to the cost modeling would come from participating companies. However, past cost studies sponsored by the U.S. Department of Energy have not always done as good a job as they could clearly describing the limitations in their assumptions and the impact that uncertainties may have on the results. Sensitivity analyses are not always going to uncover the impact of unknowns if the unknowns are greater in scope than assumed. It is advised that the approach to the cost study probe the participating companies to acknowledge whether they are omitting certain sensitive information, which can then be acknowledged in cost study reports and addressed as a potential risk.
- The project approach is excellent in setting up a test station appropriate for evaluation of multicell stacks provided by various manufacturers. However, the team should identify, discuss, and document issues, if any, in operating such a system.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The new larger test stand is a primary focus of this project, but that progress has been impeded by procurement delays resulting from the COVID-19 pandemic. Given that, the performer has wisely shifted to using its smaller test to test additional stacks and get data on smaller-scale stacks, which can be useful in comparison to the larger-size stacks that will be tested eventually, once the larger test stand build is completed. The performer has added many more companies to the list of those who will provide stacks for testing, which will increase the available data for comparison to achieve DOE goals and project objectives. The performer acknowledges that the increased number of companies that will be involved presents a challenge, especially since assembly of the larger test stand has been delayed. It is advised that the performer think about prioritization of stacks to test that will provide more useful data sooner, considering the delays and limitations in the number of simultaneous tests that may proceed for long periods of time.

- The project has made excellent progress in setting up the test station and demonstrating operation and performance of stacks provided by several manufacturers.
- INL has established a state-of-the-art SOEC stack testing capability and is working toward extending this capability to larger stack sizes and power levels. Testing results will provide inputs to a number of SOEC-stack-related system design decisions, such as optimum stack sizing, current density, and thermal management.
- The INL team has already demonstrated a flexible electrolysis stack test platform with multiple stacks from different vendors. Promising durability and degradation of ~0.5%/1 kh have been achieved with some stacks, meeting the go/no-go decision. What is not clear is the current density at which these tests are conducted (on a stack) or how operation at different current density affects durability and lifetime. Because of COVID-19, significant delays have been experienced on the equipment side, which will make completion of system validation challenging. However, the team is doing everything it can to catch up.
- This project has clearly shown progress with external manufacturers, but the boundary between troubleshooting testing hardware and customizing for stack/hotbox integration is vague. Typically, it is not acceptable for a test station to suffer from steam instabilities or blackouts if the aim of the testing is to show trouble-free operation for 3,000 hours. Therefore, the system maturity should increase with the next partners coming to test.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- The performer appears to have recruited a great number of organizations with whom the project team will collaborate through testing of those organizations' stacks. This has the potential to increase the usefulness of the project but presents a coordination challenge, as acknowledged by the performer.
- The project structure requires excellent communication and collaboration with customers, vendors, national laboratories, and academia. The team has strong relationships with partners.
- INL is working with and has established testing agreements with all of the major HTE stack developers in the United States.
- Collaboration is clearly industry-focused, one-on-one and sequential testing, but it would be good to see that the test results also feed back to a wider consortium directly (not just a paper) so that the entire SOEC community can be engaged to increase TRL levels collectively and bring closer nuclear applications.
- The project has collaboration with many major manufacturers of high-temperature electrolyzers.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project has potential to accelerate HTE stack development work by collaborating with HTE stack developers, both by providing independent testing results and by testing HTE stacks for longer durations than feasible for some HTE stack developers. This provides valuable data that HTE stack developer needs to prioritize improvements in performance and durability. The HTE stack testing and system design capabilities being established will make INL an excellent partner as HTE systems are developed and implemented.
- Demonstrating the reliability and efficiency potential by an independent party on a trusted test system is needed to increase the trust in and maturity of SOECs.
- This project provides one way to benchmark current stack TRLs and evaluate the amount of research that DOE should provide (and in what areas of focus) to achieve DOE Hydrogen Program (Program) goals of $2/kg (and now $1/kg with the Hydrogen Shot initiative). Given the potential for bias, as outlined in Question 2, additional testing by stack developers and other independent testing organizations is advised.
- Data validation (stack, system testing) at INL provides significant value to customers and DOE. This project will strengthen relationships with industry and national laboratories to accelerate technology advancement and achieve the overall Program objectives.
- The test station provides a common platform for evaluating high-temperature electrolyzers from different manufacturers.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The proposed future work is reasonable and will include testing of various stacks and completion of an HTE system.
- INL plans to expand the scope and size of HTE stack tests, expanding the lab's solid collaborations with industry.
- The proposed future work is consistent with its work scope and timeline.
- The plan forward is clear, but it would be good to see the test station improvements being quantified in the roadmap, not just when new stacks will be tested. This project should provide a quality standard for third-party testing, in which the quantity of stacks tested is not a key performance indicator unless they meet target performance expectations (test station and stacks are all technically sound and qualified for application).
- Plans for dealing with delays and possible unknowns when the missing equipment is received could benefit from additional details. The project plans to build a second HTE system, which will address the increased number of participants, but it is unclear what delays will exist in building the second system.

Project strengths:

- The approach to evaluate stacks from multiple customers to further compare the technologies and to further advance stack/system technologies (in terms of TRL) is highly valuable. The major SOC players will be participating in the project, which will encourage collaboration toward a mutual goal of reduced hydrogen production cost.
- There is key expertise, as well as high-end facilities, and these capabilities are key for manufacturers to bring their products to market (nuclear). The technical skills presented are impressive.
- The project seems well-thought-out, and the approach for widespread participation will generally help provide more data that can be useful in the pursuit of DOE's hydrogen production goals.
- The main strength of the project is the development and demonstration of a common platform for evaluating high-temperature electrolyzers from various manufacturers.
- State-of-the-art HTE stack testing capabilities have been established. Collaboration with industry is the strongest attribute of this project.

Project weaknesses:

- A good deal of time and many resources could be needed to adjust to each manufacturer, as there is no standardization and there are probably many proprietary system solutions (hotbox) that would not allow mutual comparison of test results. Therefore, it seems questionable whether the objective of the test to demonstrate TRL 7 from manufacturers can actually be validated on a common denominator if the stacks are all different in nature. It feels like the testing service provided aids individual product development rather than being a stage gate for proving technical maturity.
- The information shared from an open-access system will depend greatly on the willingness of the customers. Also, the operating conditions for different customers may be different. This will create a challenge in data comparison if, for example, all stacks are operated at different current density.
- The project seems focused on large-scale implementations (likely because of Programmatic focus) but would eventually benefit from investigating smaller-scale, distributed generation applications.
- The project needs to put some work into collecting and documenting "lessons learned" in operating the test station with different stacks (having different materials and architectures) from different manufacturers.
- INL will probably want to improve uniformity of steam delivery to their test stands.

Recommendations for additions/deletions to project scope:

- Rather than check TRL 7, a wider range of customer-specific development support could be offered to reach the overarching goal faster, such as application of SOECs with nuclear. Shorter test timeframes or specific accumulated accelerated stress test protocols could prove very valuable, bringing experience from other partner test experiences to fruition.

- The project should seek to establish a meaningful matrix in which stacks from different vendors can be quantitatively compared at the same level (similar conditions) and to identify which stacks (technologies) have the best potential for scaling and for hitting the cost metrics. For instance, durability at 0.1 A/cm^2 is rather different from at 1.0 A/cm^2, which is a minimal DOE target to get anywhere near the target hydrogen costs.
- There are no recommendations for additions or deletions to project scope.

Project #TA-024: Analysis of Fuel Cells for Trucks: Real-World Benefits

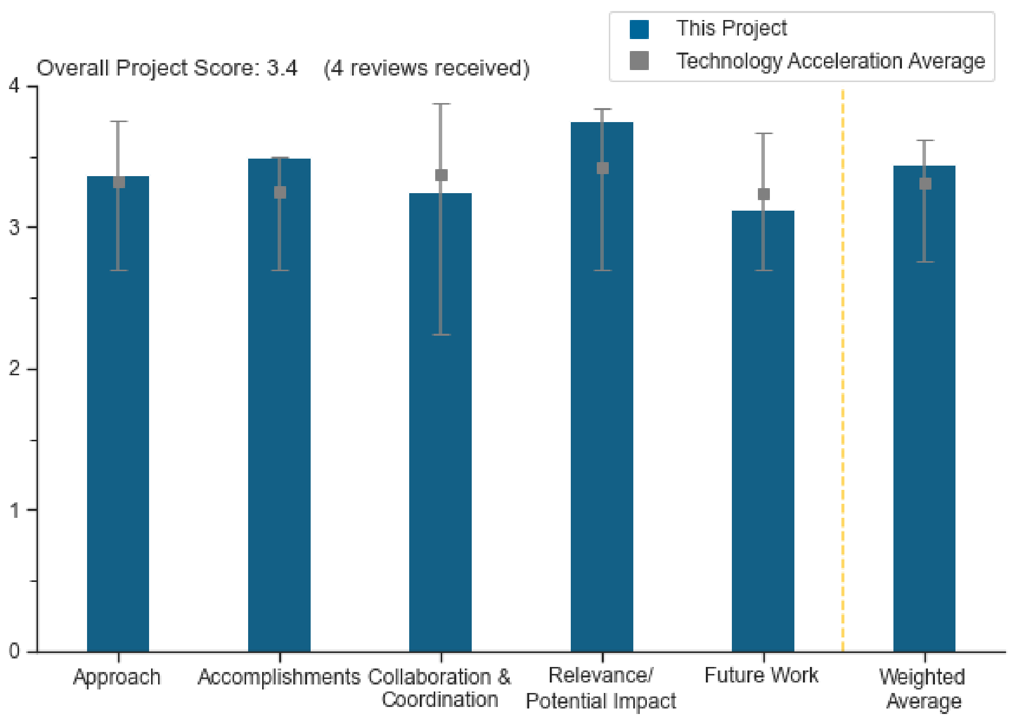
Ram Vijayagopal, Argonne National Laboratory

DOE Contract #	WBS 7.3.8.1
Start and End Dates	9/1/2020
Partners/Collaborators	National Renewable Energy Laboratory, 21st Century Truck Partnership (21CTP)
Barriers Addressed	• Future market behavior • Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools

Project Goal and Brief Summary

The primary objective of this project is to reduce the ownership cost of a fuel-cell-powered truck by finding optimal component sizes for the onboard hydrogen tank and battery pack energy storage system. The Argonne National Laboratory Fuel Cell Team will support the U.S. Department of Energy by creating a design solution that will meet or exceed the baseline performance and cargo capacity of a conventional vehicle.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project has a good approach, and Autonomie is a respected tool for this sort of work. The baseline chosen makes good sense, and as the two test cases bracket vehicle duty cycles likely to be seen on the road, the test plan also makes sense. As maintenance expenses will differ from those associated with conventional vehicles, maintenance should be included in a simple cost of ownership (SCO) estimate (rather than just fuel and purchase costs), even though maintenance does have a smaller influence on total cost of ownership (TCO). Leaving out insurance and wages is a good plan.

- The approach is sound and provides comparisons to multiple conventional architectures.
- The project has a clear description of the methodology, with focus on a couple key vehicle types.
- The vehicle powertrain sizing approach is practical and based on worst-case gradeability scenarios of Davis Dam.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- This is good progress. Fuel cell hybrid electric vehicles (FCHEVs) using battery energy and reducing fuel cell usage save up to $15,000. The fuel cell allows the battery to run at a maximum charge rate, so the researchers went with energy. They size the battery by ensuring proper speed for 11 miles at 6% grade. The project should use DOE Vehicle Technologies Office cost targets for battery cost. The project predicts 50% energy savings using hydrogen priced at $6.00 to $7.00 per kilogram and $2.60 per gallon for diesel, but the prediction is relative to conventional trucks, not a hybrid with an advanced engine. The idea that the slope of the SCO plot shows the justifiable cost increase for improved fuel cell efficiency is a valuable biproduct of this study.
- Many good insights can be drawn from this work, and the accomplishments, to date, should be appreciated. The following are a few suggested improvements:
    - For meeting baseline performance, more context for the vehicle's design would be appreciated (i.e., whether the vehicle is designed for the average representative cycle or the most difficult cycle). Also, it would be interesting to know whether the powertrain can achieve a one-to-one replacement of the difficult duty cycles or whether there are challenges to consider other than costs.
    - With the addition of battery electric vehicles (BEVs), insight could be greatly improved with a BEV comparison to understand both performance differences and cost differences.
    - Helping to set technology targets does not appear to be a prime part of the scope, but this was mentioned a few times. More clarity about whether target-setting is an end goal would be appreciated—as would information as to whether the focus will be on Class 4 and Class 6 delivery trucks only.
- The project has made excellent progress and accomplishments on defining the baseline sizing and TCO; many extra use cases and scenarios can be built off these results.
- The project is on track with the team's plans. The completed simulations predict cost curves and estimate the timeline of cost parity with conventional vehicles.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- There is an appropriate mix of industry through the 21st Century Truck Project (21CTP) and government organizations. Until recently, 21CTP was not well-represented with original equipment manufacturers (OEMs) in the lower weight classes. It is to be hoped that in the coming years, coordination and data in these lower weight classes will continue to improve.
- The project has great collaboration with industry and other laboratory partners. Participation in 21CTP enables input from OEMs and other technical teams for specific parameters.
- The project obtained information from OEMs on technical specifications and information from the National Renewable Energy Laboratory on drive cycles. This is a good choice of partners.
- Both internal and external collaborations are good, as the team leverages other projects within DOE and obtains industry input. The project could benefit from more input on a "representative" cycle that would actually meet the needs of most customers. There is also an opportunity for more collaboration related to TCO. The addition of a simple TCO is actually a bit confusing when there is another referenced DOE

project that dives deeper into TCO; perhaps better coordination is more appropriate than trying to make a simplified and separate calculation.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- These projects are needed to establish reasonable baselines on vehicle sizing and duty cycles from which infrastructure, cost of ownership, and other considerations can be deduced.
- It is important to estimate, in a rigorous way, the cost of ownership for medium-duty (MD) fuel cell electric vehicles and to explore methods to reduce that cost in simulations rather than much more expensive hardware. This points out where research is needed and eventually acts to give early adopters confidence that they understand the costs they will incur.
- The project aligns well with DOE objectives and contributes to target-setting for Class 4 and Class 6 trucks. Typical use for these truck classes is significantly different from long-haul trucking, which necessitates targets specific to this use.
- This is a very valuable project. There is room for further value add and more clarity in informing DOE.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The mention of both near-term expansion and future ideas is welcome. It is recommended that the project include a focus on near-term opportunities, such as other priority vehicle classes/vocations (Class 8 trucks, transit, MD vans, etc.) and a refinement representative cycle. Access to synthetic drive cycle data would certainly provide more opportunities to explore.
- Including system cooling capacity in the analysis would be valuable. Difficulties in this area for Class 4 pickup trucks and max trailer tow gross combined vehicle weight (GCVW) ratings are seen in other analyses. The analysis should include additional vehicle-to-load function (V2L) loads up to 20 kW, as this is an increasingly important feature in the truck space. It would also be good to add grid service balancing and fueling time versus fleet hourly shift requirements.
- The project's plan to study potential future traffic situations and systems is useful work, but it is somewhat more speculative in nature.
- Proposed future work presents the next logical step to current work.

Project strengths:

- This project has a strong focus on fuel cell vehicle design that will meet the needs of operators. This is then coupled with real driving data to understand how the vehicles are used. This combination is a powerful tool.
- There is a highly validated tool chain. This is a good simulation team with good data sources. The author's call for MD standards is correct; heavy-duty standards are likely to be too easy or too hard for the MD case.
- The project has an excellent methodical approach to vehicle sizing and ownership costs. Logical assumptions are made in most cases.
- This project provides valuable insight into estimated timing for cost parity with current technology.

Project weaknesses:

- The project is well-done overall. The smallest gripe is that OEMs typically like to size for Davis Dam at 65 mph, not 40 mph. This will increase the total powertrain sizing and energy demand.
- Using real-world data to validate the model results (once fuel cell electric trucks get into service) is recommended.
- It is not clear the project is looking at similar levels of progress in batteries or gasoline engine–battery hybrids, or expected levels of progress in the diesel hybrids.
- It is a bit unclear whether the final goal and output are target-setting, TCO, or performance comparisons. It is hoped that all three will be expanded on, but they are currently only partially addressed.

Recommendations for additions/deletions to project scope:

- The project team should consider the following:
    - Including system cooling capacity in the analysis would be valuable.
    - The project should focus on designing to the most difficult duty cycle since the trucks must be capable of that.
    - The project team should collaborate for TCO insight rather than create a simplified version.
    - The project should expand to other vehicles, such as Class 8 trucks, transit, and vans.
    - The project team should recommend new targets if appropriate.

  The principal investigator and team have done a great job.
- Including a system cooling capacity analysis is recommended, as difficulties in this area for Class 4 pickup trucks and max trailer tow GCVW ratings are seen in other analyses. Additional V2L loads up to 20 kW are also recommended for inclusion in the analysis, as this is an increasingly important feature in the truck space. The project might also add grid service balancing and fueling time versus fleet hourly shift requirements.
- The project should search for a non-fuel-cell case that would exceed the performance the team calculates for the fuel cell or FCHEV to identify whether there is any true competition in future years.

Project #TA-025: Laser Three-Dimensional Printing of Highly Compacted Protonic Ceramic Electrolyzer Stack

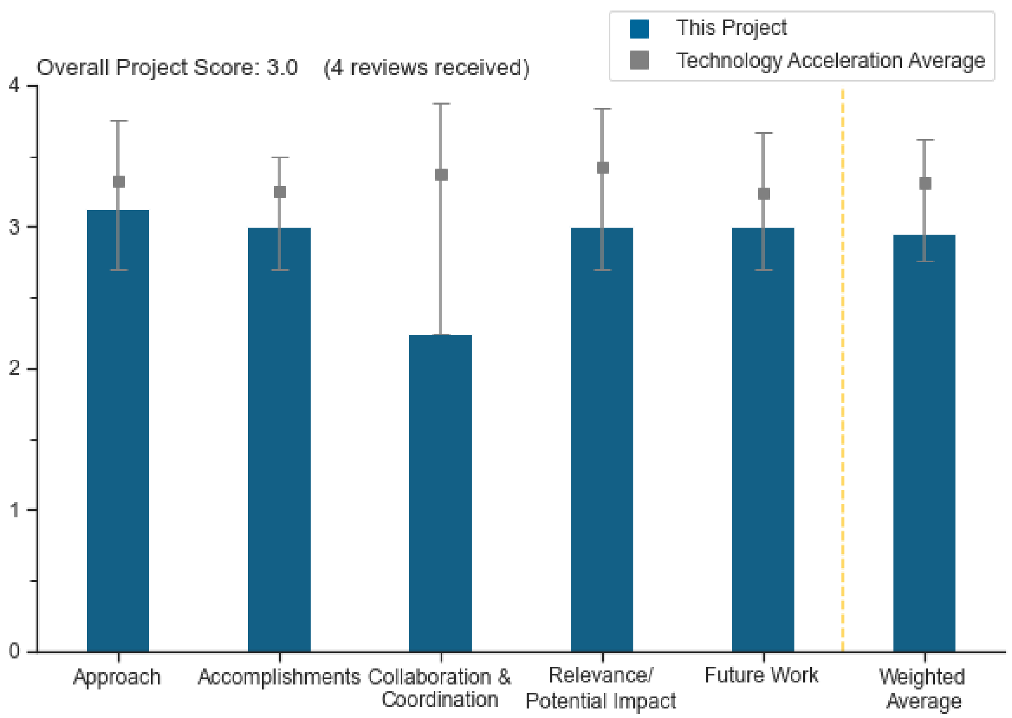
Jianhua Tong, Clemson University

DOE Contract #	DE-EE0008428
Start and End Dates	11/6/2018 to 4/30/2022
Partners/Collaborators	N/A
Barriers Addressed	• Capital cost: Capital cost of water electrolysis system is prohibitive to widespread adoption • System efficiency and electricity cost: Low-cost cell stacks addressing efficiency are needed • Manufacturing: Electrolysis units are produced in low volume; fabrication technology is capital-intensive

Project Goal and Brief Summary

This project aims to reduce the cost of manufacturing state-of-the-art electrolyzers by designing, developing, and demonstrating a laser three-dimensional (3D) printing technology. This innovation will enable cost-effective, rapid, and flexible manufacturing of high-performance, intermediate-temperature protonic ceramic electrolyzer stacks (PCESs) for hydrogen production at various scales. The target PCES will have a total effective area of over 100 cm^2, a current density of over 1.0 A/cm^2, and a stable operation time of over 1,000 hours at 600°C.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The application of 3D layer construction and reactive laser sintering opens up a wealth of possibilities in design and implementation.
- The approach lays out a logical path toward the exploration of laser 3D printing as a laboratory-scale fabrication pathway for solid oxide electrolyzer cells (SOECs) and stacks. Different aspects of deposition and sintering are evaluated, and different material compositions are of interest. Testing of fabricated cells and stacks is necessary and is being pursued. An economic assessment is certainly needed and is being pursued as well. This being said, the potential outcomes of the project do not seem to be a good match to the perceived scope of a Technology Acceleration project. In particular, the fabrication technologies under study do not seem to be relevant to addressing near-term manufacturing goals or targets or, thus, to addressing cost targets.
- This project is a novel laser processing of ceramics into water electrolyzers.
- Generally, the description of objectives and barriers is fairly clear. However, it is difficult to understand the extent to which the project will be able to assess the impact of developments on manufacturing costs. The project would benefit greatly if Clemson University (Clemson) worked with, or at least spoke with, other organizations with manufacturing experience. The project would also likely benefit if Clemson spoke with, for instance, an appropriate national laboratory to truly understand how the process being developed will compare with standard processes.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The technical accomplishments demonstrated, from a materials and structures perspective, are good, and the effort appears to be on track relative to project milestones. The materials, fabrication, and cell testing work are of value for an exploratory effort. The progress toward achieving conductivity and performance targets is good, though it would be useful to have comparison data for cells fabricated via standard/typical fabrication techniques, e.g., tape casting and firing. Appropriate characterization methods appear to be in use. The use of the cylindrical lens with the laser sintering appears to have been a success, with target morphologies achieved. It is stated that laser scanning could significantly decrease manufacturing energy consumption, assumedly in comparison to high-temperature air sintering. On an instantaneous basis, this would seem to be the case; however, a rate needs to be assessed to validate this on a cell-area-per-time-unit basis. While sintering ovens can use a lot of energy, per-unit energy usage can be offset by the high throughput of material (in a batch oven) or the use of continuous sintering kilns.
- The presentation shows clear interactions toward scaling up the active area, while dealing with identified issues along the way. The technical solutions seem effective.
- The project demonstrated a 5 x 5 cm water electrolyzer with good performance (1 A/cm^2 and 1.3 V) at 600°C with non-platinum catalysts.
- The project seems to have yielded good results so far. Additional detail and clarity around certain aspects of the project would be useful (e.g., given all the various configurations, laser types, etc. that have been explored). The team should either describe each in very clear detail and/or do the same for the one that has the greatest potential for achieving the most project goals. Also, that best combination structure and process should be clearly compared to standard ceramics manufacturing processes in large-scale production, such as pusher kilns. There are clear energy efficiency and flexibility advantages that may potentially win over standard processes, but the Clemson team seems not to fully understand that in large-scale manufacturing, pusher kilns can lead to relatively large batches of parts being made relatively quickly once the process has been started (e.g., one batch every minute, or even hour, can lead to an effective rate of more than one part per minute). Being clear about the comparison of the laser sintering approach to conventional approaches will help in the evaluation of cost and implementation of the technique in large-scale manufacturing.

Question 3: Collaboration and coordination

This project was rated **2.3** for its engagement with and coordination of project partners and interaction with other entities.

- Currently, it does not appear that Clemson is collaborating with other organizations. However, Clemson has indicated interest in collaboration with national laboratories and industry.
- All work is done at Clemson, but the team is looking for national laboratory partners.
- Clearly, little collaboration outside of Clemson has been established to date. The principal investigator indicates that national laboratory collaborators are sought, but he did not provide much about what the objective or intent of the collaboration would be. He also indicates that industry collaborators are being sought but does not indicate which companies. It may be that non-disclosure prohibits this, but some indication of industrial interest would be of value to DOE, especially for a Technology Acceleration project.
- The project's wish to collaborate was expressed, but no evidence of concrete implementation was presented.

Question 4: Relevance/potential impact

This project was rated **3.0** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Electrolyzers are a good way to store renewable energy, and this electrolyzer had fairly good performance and low materials cost.
- The technology readiness level of this project is still low, and the level of control of the final outcome and performance is in question. The number of creative options available compensates for these concerns.
- The project could technically reduce the cost of manufacturing, but it is unclear how this will scale. The flexibility to do small and potentially large quantities is attractive, but it is unknown exactly how this approach competes with conventional high-volume sintering methods. Furthermore, it is unclear how well this technique will transfer to larger-size cells and whether the stresses experienced in the cell during rastering of the sintering laser will be exacerbated at the larger cell size. While the project has merit, Clemson would benefit greatly from discussing such matters with national laboratories and industry to gauge the types of issues that may arise in attempting to transition the methods being developed to a scaled-up implementation.
- SOEC, as a high-efficiency hydrogen production technology, is definitely highly relevant and is of high value that merits DOE support of its development. However, it is not at all clear how the fabrication methodologies currently under study, from a throughput perspective, will really contribute to reducing hydrogen production costs via reducing manufacturing costs. In particular, the rates shown in the accomplishments are extremely slow. It is very hard to understand how these technologies, unless future improvements can provide very large rate increases, could reduce manufacturing costs compared to current methods that are known to be relevant for high-volume production. This is an open question that, relative to the goals in the Technology Acceleration subprogram area, should be addressed by the project, at least from a cost analysis perspective. Relevant industry input should be used to validate any cost model.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The proposed future work appears to show a logical progression forward. Industry participation seems critical, particularly input to a validated cost analysis. Some level of comparison to cells made from standard methods would be of value to the project.
- The need to demonstrate the capability at larger scale is understood, and the plans continue on the current path. There are some doubts as to whether inherent material properties, such as thermal expansion, will inherently limit the production size with the current design.
- Additional detail would be desirable to clarify what the remaining focus of the project is intended to be and why. While a focus on estimating the manufacturing cost is important, Clemson would benefit greatly from talking with the appropriate parties at national laboratories and/or industry to ensure inputs to the cost model are valid. A better comparison is needed between the laser sintering approach and conventional

(continuous process) sintering at scale. Ideally, such an analysis will also lead to a clearer vision of how the laser sintering approach will realistically scale for high-throughput manufacturing.
- The project needs to expand its area and possibly raise the current density at 1.3 V.

Project strengths:

- The team is in command of a novel new process for improved ceramic electrolyzers. It has a straightforward approach, good characterization, and low materials costs. Thin films are being made, which are more robust than thicker films. Stacking is demonstrated using this fabrication method.
- Clemson has a strong knowledge of protonic ceramic electrolyzers. The team has made good progress in developing the laser sintering method for small-scale cells.
- The team has strong capabilities and facilities related to laser-based fabrication. There is a good team at Clemson to accomplish most of the stated goals of the project.
- A clear expertise has been demonstrated, and there is awareness of the resulting composition (gradients), ultimately translating to performance results.

Project weaknesses:

- More attention should be placed on how the laser sintering method is scaled to larger-area cells in a way that keeps it competitive with conventional sintering methods. As in conventional sintering, the larger the cell size, the harder it is to sinter the cells using the laser sintering approach. More attention needs to be placed on a clear comparison of the laser sintering method with conventional sintering in larger-scale manufacturing (e.g., continuous pusher kilns). Clemson should make sure to determine how the laser sintering method will scale and compete versus the conventional methods.
- There is no industrial participation, specifically as related to the relevance of manufacturing methods and cost analysis—this should be a focus in the next year. The team may want to reach out to the high-temperature electrolysis part of the new Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium, led by Idaho National Laboratory, to discuss cost analyses and how H2NEW is going to evaluate manufacturing costs. Ideally, the team's cost analysis would be comparable with and/or using the same methodology as is used in H2NEW. Quite frankly, it seems that this would be a much better HydroGEN project than a Technology Acceleration subprogram project.
- It appears that this project is not grasping the true 3D nature of laser sintering and tries to mimic traditional coating/annealing technology. Considering the background of 3D printing, more design solutions to interweave weak interfaces and counterbalance thermal tensions would be expected.
- The processing costs are not clear. The path to improved scalability to larger-area cells is not clear. This is a very interesting project, but it may be a "flash in the pan," dead-ended project if these scaling and process cost issues are not successfully addressed to help get past possible limitations.

Recommendations for additions/deletions to project scope:

- This project should consider alternative options to achieve larger active surface area by designing cells in parallel, as well as in series; this way, the uniformity of a single 1 cm^2 cell can be guaranteed, and a complete pack of cells can be designed to best practices. This stays within the strengths of a small beam and a controlled outcome.
- The project should work on increasing its cell area. Nickle metal support may help prevent failure from mechanical shock. The project also needs to work on steel interconnect to minimize failure due to thermal shock. The team should address reliability when cycling (turn-on and turn-off cycles) this high-temperature device.
- Clemson should work with a national laboratory and/or industry organization to help think through the realistic barriers that will be faced in trying to scale the laser sintering approach to large-scale manufacturing. This is best done by comparison with a conventional sintering process, and such an analysis will also benefit the technoeconomic analysis work that is planned.
- No additions or deletions are suggested for this project, but one point should be reinforced: a validated cost analysis (with industry input and review), showing how these fabrication techniques can reduce manufacturing cost relative to standard methods, should be a strong focus. Observing the H2NEW cost analysis would be beneficial.

Project #TA-026: Low-Cost, High-Performance Catalyst-Coated Membranes for Polymer Electrolyte Membrane Water Electrolyzers

Andrew Steinbach, 3M Company

DOE Contract #	DE-EE0008425
Start and End Dates	10/1/2018 to 3/30/2021
Partners/Collaborators	National Renewable Energy Laboratory, Giner, Inc.
Barriers Addressed	• Capital cost • Manufacturing

Project Goal and Brief Summary

This project aims to reduce the manufacturing cost of polymer electrolyte membrane (PEM) water electrolysis catalyst-coated membranes by developing scalable roll-to-roll fabrication processes capable of producing reproducible and uniform state-of-the-art PEM water electrolysis components. These advanced processes will convert input raw materials into high-performance, roll-good components while reducing process time six-fold. If successful, this project will enable cost-effective, high-volume production processes that can meet the needs of gigawatt-scale electrolysis infrastructure.

Project Scoring

The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- It seems like the participants are well-drilled in moving toward targets. The goals are clear. Sensible tasks are under way. The activities are appropriate and correct.

- With the wide range of potential parameters and objectives, the project clearly identified concise objectives and a clear plan to achieve them. These approaches were successful in that the project exceeded most of these objectives, with identified paths forward for the two metrics not met, had the project continued.
- The project provides a Gantt chart for the approach. That is good for those active in the project, but for a reviewer from outside, a discussion would have been helpful.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There is a very impressive list of successes given in chart 6. Subsequent charts are very helpful in understanding how these successes were achieved, and there is a good explanation of what the next steps should be. Roll-to-roll optical inspection is very successful. Process development of the catalyst powder rate improvement is reported, but how it was achieved was not explained. Scaling of the production process is impressive. Successful catalyst-coated membranes yield high and uniform performance—another success. NREL development of direct electrode dispersion coating appears to be moving the manufacturing process for fuel cell stack components forward, and, combined with 3M's approach, it may be time to cost the processes again. Giner, Inc., test results suggest these concepts are solving many of the problems of the industry. Cost may be an issue.
- The project exceeded four of the six project objectives and arguably met a fifth. The sixth objective was not met likely as a result of overly succeeding on the platinum group metal (PGM) loading. The results of this project will have impacts on not only the stated partners but also any of the customers of this membrane electrode assembly (MEA) supplier.
- PEM electrolyzers are on DOE's plate. There is ongoing foreign competition, both in the European Union and in Asia. It is good to have America's best on the trail as well. It is hard to understand the status of the global competition. There is positive progress evident. Making hydrogen is a DOE goal.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- This activity included a supplier, an end user, and an independent evaluator, which captured representatives of the key commercial entities for this product. Over the course of this project, each organization completed its assignments to deliver on the contract requirements.
- It is hard to understand who does what. It seems like those participants in this activity are well-focused and supportive. Collaboration with participants seems appropriate and good.
- There is a great combination of industry and national laboratory collaboration.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Clearly, electrolyzers are a hot item right now. The age-old debate of acid/alkaline rages on. It seems like with electricity "too cheap to meter," the emphasis on efficiency (voltage) is less critical. Probably, the competition will depend more on endurance and cost. Very similar to photovoltaics, when electricity gets cheaper and cheaper, say, a few U.S. cents/kWh, many things change. Cheap electricity results in cheap hydrogen. The engineering constraints change.
- With the large range of customers for this electrolyzer MEA supplier, this activity has the potential for significant impacts on multiple customers across a range of applications, achieved by reducing both the capital and operating costs of generating hydrogen on a per-unit basis.
- The project addresses needs for high-volume production processes for PEM electrolysis at scale. This is a needed project.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Future work is not clear. In the present global push, new players seem likely, so even if this project had achieved outstanding performance, such an accomplishment will have others with similar success. The project needs to team with people who have a compelling need for hydrogen, perhaps a fuel cell auto manufacturer. 3M certainly knows the “get to market” drill. There needs to be some discussion about “which market.” Certainly, should anyone be thinking about infiltration into urban environments, there need to be amendments in codes and standards. It would make sense that the regulatory regimen is documented before products hit the marketplace. A device with a 50-year lifetime needs to get it “right” quickly.
- The project discusses remaining challenges and gives potential solutions. This is very good; not many projects do this. The project is complete.
- Proposed future work is not applicable. This activity concluded on March 30, 2021.

Project strengths:

- This activity delivers an improved industrial-scale manufacturing process using very low-PGM catalyst loading, demonstrating equivalent or superior performance to the current state of the art.
- The project has good people, good organization, and supportive federal aid. The project has just who is needed for success.
- The team working on this project is exceptionally strong, as demonstrated by the success of the effort.

Project weaknesses:

- This report is rather positive. If there is weakness, it is well-hidden. The electrolyzer technology is moving rapidly. Some review of who is doing what, and how well, would have been welcome. It is hard to grade a company when this involves an analysis of its performance contrasted to others. The document provided is sort of cocky, in a good way. It shows good people doing their thing.
- Testing protocols are not as consistent as would be appropriate for this sort of activity. In particular, the location of the thermal measurement can significantly influence the accuracy and precision of the likely MEA surface temperature.

Recommendations for additions/deletions to project scope:

- It seems like the project has been successful (almost, but the targets are all arbitrary). The project needs to get a fleet of electrolyzers machining hydrogen and see just how long they last and what sort of technical problems show up. With electrochemical stuff, “accelerated” testing can never be useful, because it takes just one “hot spot,” if testing conditions are not controlled well enough, to wreck the device. Ten years of evaluation needs to take ten years.
- DOE should meet with the researchers and ask them what the next steps should be to move the manufacturing technology forward.
- This question is not applicable, as the project has concluded.

Project #TA-027: Catalyst Layer Design, Manufacturing, and In-Line Quality Control

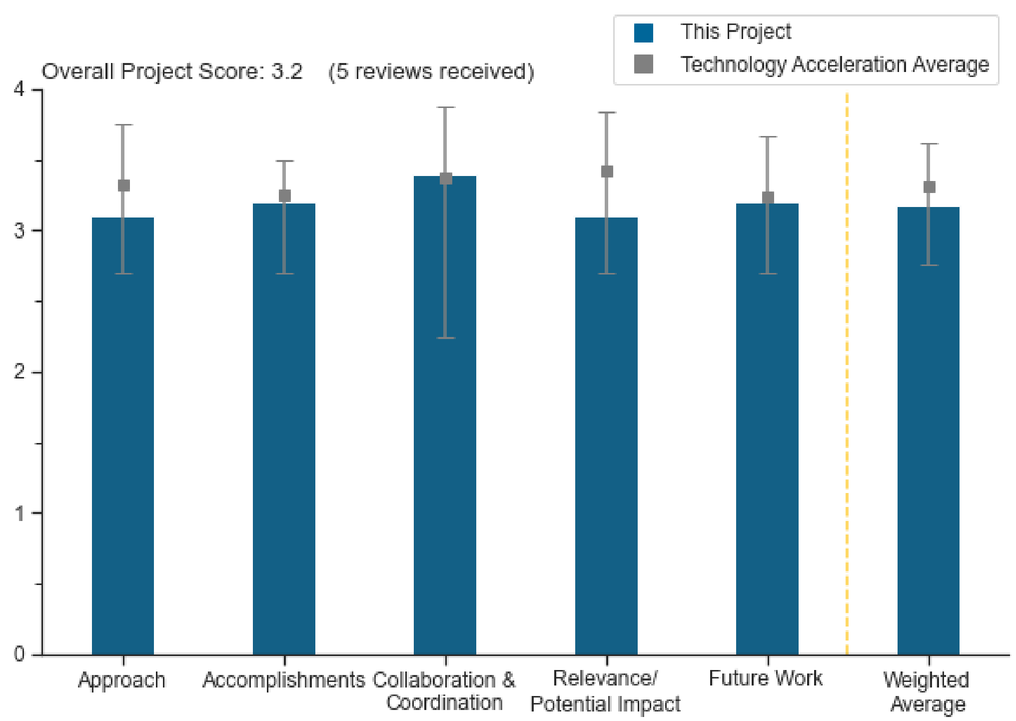
Radenka Maric, University of Connecticut

DOE Contract #	DE-EE0008427
Start and End Dates	10/1/2018 to 11/30/2021
Partners/Collaborators	Nel Hydrogen, Mainstream Engineering
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Manufacturing

Project Goal and Brief Summary

This project will demonstrate the capabilities of reactive spray deposition technology (RSDT)for direct catalyst deposition and fabrication of large-scale membrane electrode assemblies (MEAs). The project aims to produce MEAs with 10% of the catalyst loading of commercially available MEAs and stability for over 1,000 hours of use, greatly reducing the cost of hydrogen electrolysis.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach appears to lay out a logical plan toward validation of a novel fabrication technique for catalyst-coated membranes. Scaling the technique from active areas of less than a hundred to hundreds of square centimeters is an important aspect for the Technology Acceleration subprogram area. Also, exploration of using the technique to fabricate a recombination layer is important, as this is an open question for electrolysis MEAs. Including a commercial polymer electrolyte membrane (PEM) water electrolysis supplier enables strong inputs as to the technique's viability, and including quality inspection is appropriate to help ensure high yield, should the technology be adopted by industry. Overall, the work is appropriate for a laboratory fabrication technique that may have some MEA formation advantages. The technique's viability as a true high-volume production technique is a large question, and it should be addressed in the future to truly assess the usefulness of the method. The principal investigator stated that unit fabrication time was on the order of two hours, potentially reducing to 15 minutes with higher jet speeds. Depending on the other potential benefits of the technique to create a high-performing cell, this may not be enough benefit for the cost. The industry participant can presumably give guidance on the needed rates for high-volume production.

- The reactive spray method is meant to enable achieving the target loadings and meeting durability targets, but it is hard to see how this method ever leads to a manufactured product or meets overall manufacturing cost targets, as the reactive spray deposition process is slow compared to continuous roll-to-roll (R2R) coating methods. In terms of developing an MEA manufacturing process that could translate to industrial production, this project misses the mark, and it is not clear how a stack produced with reactive spray deposition would be able to produce $2/kg hydrogen. It is a shame that so much emphasis and so many milestones focus on developing the spray deposition process for large-scale coatings, as this does not seem to leverage the capabilities of reactive spray deposition. Overall, there are some good parts to this project in terms of catalyst materials development, but the focus on large-scale MEA production is misplaced and detracts from what is the most compelling aspect of the project, which is the ability of reactive spray deposition to tailor IrO_2 particle size. This should be more of a focus.
- Clearly, the task is challenging. The "game" has become more intense now that the well-documented federal goal is to create hydrogen at the price of $1/kg or less. The materials—perfluorosulfonic acids (PFSAs), platinum, and solubilized PFSAs fabricated by a flame spray process—are in no way novel. One would think the first task is to examine existing PEM electrolyzers, perform a global search, and understand what others have and how that hardware deals with technical issues. The technical approach might be designed well for a pioneering situation. There are other devices, and it would be appropriate, one would think, to learn their tricks. There is a general theme of discovery rather than a theme of understanding. One interesting issue is that there is no discussion about repeatability, i.e., whether all MEAs perform at the same level, and if not, why not. The flame spraying also seems difficult to control. It is unclear whether the spray is actually homogeneous.
- The project uses a straightforward approach. It is not clear as to what porous transport layers are being used in the electrolyzer. The approach toward optimizing the process, although Edisonian, is sufficient.
- The approach was a series of Gantt charts, which gave the project status but not much explanation. A discussion of why the approach is taken would be most helpful.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There is good progress toward objectives, given delays and laboratory restrictions associated with COVID-19. Stability of performance over time of the 86 cm^2 cells looks promising so far. Further exploration of causes of the observed degradation should be pursued, as the structural stability of the electrodes fabricated with the new technique must be understood. The ability to coat the thin Nafion™ layer is interesting, as this tends not to be easy to do with standard spray methods. From a performance perspective, the polarization data shown on slides 9 and 13 do not seem to be that great, though not all the details of the cell build and testing conditions are provided. Using the same test, the project should perform a comparison of the flame-sprayed electrode performance to that of a standard electrode (e.g., one fabricated by the industry partner's current methods, not just the large flame-sprayed electrode to the small flame-sprayed electrode). The progress on the optical loading quality diagnostic is good to see and is consistent with other electrode loading studies using the same method.
- The project goals are clearly stated. There is mention that project results will be compared with a "commercial" specimen. The goal of more than 1,000 hours is described. Importantly, the Pt loading is just 10% of something not stated. The DOE target recently redone is one of cost, not performance. As the cost

of electricity continues to plummet, the economics necessarily shift. There are certainly signs of progress, as the Period 1 milestones document. The performance data over 5,000 hours shows performance loss, and there is no indication that the rate of loss with time is decreasing. Fifty microvolts/hour seems rather "non-commercial." The precious metals, including Ir, tend to be moving around, which is not unexpected.

- Stable performance for 5,000 hours was outstanding. Polarization data are very impressive. It is unclear whether hydrogen crossover after 5,000 hours will be a problem. There is anode and cathode degradation in post-mortem, with particles in the membrane and cracks in the recombination layer. It seems like these are problems that may need resolution, but this was not discussed. Fabrication via RSDT looks very promising; perhaps it is ready for a detailed cost analysis by a third party. In situ Raman spectroscopy looks promising for quality control (QC). It would be good to know if RSDT can be used in R2R processing or if the batch is limited.
- The work is appropriate toward meeting the outlined milestones/goals of the project. However, the results do not make much progress toward DOE goals for technology acceleration because reactive spray deposition seems poorly suited to large-scale manufacturing. Results clearly demonstrate the ability to achieve target loadings of Ir and Pt with good uniformity. Stability targets have been achieved. It is hard to critically evaluate the MEA performance. Generally, the MEA performance seems low, but there are no higher-load baselines presented to make comparisons. Therefore, it cannot be determined whether these lower loadings actually lead to acceptable performance. Additionally, Alia et. al. (https://iopscience.iop.org/article/10.1149/2.0231915jes/meta) were able to achieve less than 1.9 V at 2 A/cm^2 with 0.1 mgIr/cm^2 loadings, whereas MEAs in this presentation on slide 13 are above 1.9 V at less than 1.5 A/cm^2. Given that there is an extra 25 µm of membrane due to the added N211 membrane, it would have been beneficial to show high-frequency-resistance-corrected polarization curves to make comparisons to other published results easier. At the next DOE Hydrogen Program Annual Merit Review, there should be polarization curves comparing the low-loaded MEAs prepared in this project and a higher-loaded baseline.
- There is good performance, stability, and scale-up, although not quite as high of performance as in some of the work coming from the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium and other techniques. The recombination layer is good for crossover, but it is unclear whether it is stable or whether it gets Pt migration or enhanced membrane degradation. It is unclear what causes the cracks in the recombination layer. The use of underlayers and mitigation shows promise. It is not clear how the porosity of the layers is controlled.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- Teaming with industry is very appropriate for the Technology Acceleration subprogram, which is good to see. Inclusion of the PEM water electrolysis manufacturer is very important. However, the level of guidance that the electrolysis manufacturer is providing is not clear. This should be indicated in more detail in the next reporting period, especially regarding the veracity of the method for high-volume production, as well as acceptability of performance. Including the QC technology, the provider demonstrates that the team is looking ahead to implementation of the technique.
- Collaboration between UConn and Nel Hydrogen seems good, with materials generated at UConn being transferred to NEL Hydrogen for in situ testing. Mainstream Engineering seems similarly well-engaged. There have been numerous site visits.
- Industry and the university are working together for successful research and development.
- There is a good team and seemingly good communication between the partners.
- The management is hard to understand. It seems that most of the scientific work is done at UConn. Testing is done at Nel Hydrogen and Mainstream Engineering. Flame spraying is a commercial endeavor and has seen extensive use in other DOE projects. Most likely the management is just fine, but the presentation certainly was not convincing that was so.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Hydrogen production from electricity will be a major business globally. Any significant advance will be adopted in the marketplace. Yes, the goals are fully aligned with DOE research, development, and demonstration goals. There is potential here. However, the game is still just on, and “significant progress” may be difficult to achieve.
- This project addresses the key issues of capital cost (but needs third-party analysis), system efficiency, and manufacturing.
- The need for demonstration of scalable electrode fabrication methods for PEM water electrolysis MEAs is high, so the work certainly addresses strong DOE and industry needs. The applicability of the specific fabrication method to rates actually needed for high-volume production must be validated in some way. Also, the team should think about trying a thinner membrane, as the trend is certainly away from N117 toward 90–120 µm membranes (in the near term).
- Lower Ir and Pt loadings have been achieved. It is not clear that these lower loadings result in acceptable MEA performance, as they were not compared to the higher-load baseline. Results demonstrate a successful hydrogen crossover mitigation strategy to ensure safe electrolyzer operation. The MEA production speed of the reactive spray deposition process is too slow for high-volume production, so this technology might never be capable of meeting the economies of scale needed for low hydrogen production costs. If this project had been designed as a materials development project and scoped accordingly, it would have been rated it higher. It just seems poorly aligned with the objectives of the Technology Acceleration subprogram.
- The technique is interesting but needs to demonstrate it can go to lower loadings, as the state of the art is to move to much lower loadings. The project is not clear as to the throughput rate or cost of the process.

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- There is emphasis on deposition of Nafion materials on the surface of the electrodes, and that is of interest. However, Nafion solubility has much to do with molecular weight and tends to move around. This technology is challenged by expectations of durability, perhaps unreasonable ones. The current status resulted in complex architecture, which is thought to be useful and stable. There need to be efforts to investigate polymers moving. It would be interesting to utilize segmented cells and check to see if the current density is uniform across the device surface. There needs to be some closure on the environmental implications of using Nafion polymers when those toxic compounds ooze into the environment. There needs to be some real care in knowing exactly where the Nafion is. The crossover issue is also a concern. There is a tradeoff with pressure (across the membrane) and hydrogen loss. Some modeling on crossover and operating pressure might be informative.
- The remaining challenges and barriers are clearly identified. Future work addresses most issues. The project should have a task that addresses formation of catalyst particles in membrane.
- Future work is fine, as the project is winding down, although seeing the feasibility of lower loadings would be interesting.
- Two tasks need to be performed: (1) comparison of the flame-sprayed electrodes to the industry partner’s standard electrodes under the same test in terms of polarization performance and (2) some kind of assessment of the fabrication technique’s viability for high volume, based on DOE’s, H2NEW’s, or an industry partner’s volume manufacturing analysis or estimates.
- How to rate and comment on the future work presents a conflict. Based on the milestones, the future work seems reasonable, given the design of the project, and is consistent with meeting upcoming milestones. However, as has been previously stated, there is not much value to the community for this project to focus on making 680 cm^2 MEAs, given the slow coating speeds. There should be more future work studying impacts of IrO_2 particle size on performance and durability. This seems like it would provide more value to the low-temperature electrolysis community and catalyst manufacturers.

Project strengths:

- The most compelling results of this project are the results related to IrO_2 particle size that were not presented in the slides but were discussed during the question-and-answer session. More studies related to decreasing particle size to increase electrochemically active surface area and catalyst utilization would be very beneficial to enabling reductions in precious metal loading in electrolyzers. More emphasis on this for the remainder of the project would be good to see. These studies could be very useful to the community in guiding improvements in catalyst design to enable high performance at low loadings.
- There is a certain optimism in the presentation. Good people are making progress working on, all things considered, necessary technology for the global community. There are good concepts. This is a work in progress.
- There are strong capabilities for flame spray development and advanced characterization at UConn. There is a good team, including important industry partners.
- The reactive spay technique is promising. The scale-up is being realized, and there is a good team.

Project weaknesses:

- This project is poorly categorized as Technology Acceleration, and the work is not focused on the strengths of this coating technology. The strength of this reactive spray is in materials development (catalyst particle size optimization, Ir/IrO_2 ratio, and MEA design), not manufacturing or technology acceleration. The presenter commented that reactive spray deposition could achieve one 680 cm^2 electrode in 15 minutes. That equates to about 45 cm^2/min. Continuous R2R coating methods are easily capable of square meters per minute and even square meters in a matter of seconds, in some cases. Some old work from 3M (http://www.nature.com/doifinder/10.1038/nature11115) indicated that production rates of tens of square meters per minute are needed for modest production of fuel cell vehicles, and presumably similar rates are needed for gigawatt-scale electrolyzer production. Therefore, it is not clear how this reactive spray method will ever be able to achieve the rates needed for mass production. This project should have focused on more closely exploring IrO_2 catalyst particle size and its effects on materials utilization, performance, and durability. This seems like very interesting work, and there would be much value here. Ultimately, this project suffers because it was funded as a Technology Acceleration project. It would have been a much better HydroGEN consortium seedling project focused on catalyst development. Had this been a materials development project, it would have been given higher ratings because the researchers are doing good work toward meeting their milestones.
- It seems like there is good progress, but perhaps there need to be some other experiments that will be useful for understanding.
- The project possibly needs to have a discussion with NREL about integrating RSDT into R2R processes.
- The team needs to compare the method under development to standard methods capable of high-volume production.
- The practicality for high throughput and lower loadings is not clear.

Recommendations for additions/deletions to project scope:

- The project should focus more on materials development and optimization. The presenter mentioned that the team is observing higher materials utilization at low loadings, thanks to the particle sizes, which are smaller than those in standard catalyst materials. It seems like, with reactive spray deposition, the UConn team could make MEAs with a variety of IrO_2 particle sizes without having to do a great deal of lengthy wet chemical IrO_2 particle synthesis to get catalysts of different sizes. If this work can show that a certain particle size is optimum for material utilization and durability, then this could be translated to mass-scale materials synthesis efforts and could be integrated into MEAs using higher throughput coating methodologies. This is where there could be some technology acceleration. This is where this project would provide much value. It is recommended that some MEAs containing these novel catalysts be tested by H2NEW to compare to that consortium's baseline MEAs. Alternatively, UConn should ensure that the project's control sample can match the performance of the H2NEW baseline, once that information is published. Because of the low coating speeds of the reactive spray deposition process, there is no value in making such large MEAs. Making one 680 cm^2 electrode in two hours does not add much value when screening different catalyst particle sizes. It seems like optimization of Ir particle size could be done at 25 cm^2 or below and not require such lengthy coating times.

- There are probably enough positive results to think of stacks at about the 25 kW sort of scale. Ten cells are sufficient. There is much literature about Ir anodes. The project should pay attention to the environmental issues and have answers ready when they are raised.
- The team should compare performance and potential throughput to standard methods shown to be able to fabricate PEM water electrolysis electrodes at high rates.

Project #TA-028: Demonstration of Electrolyzer Operation at a Nuclear Plant to Allow for Dynamic Participation in an Organized Electricity Market and In-House Hydrogen Supply

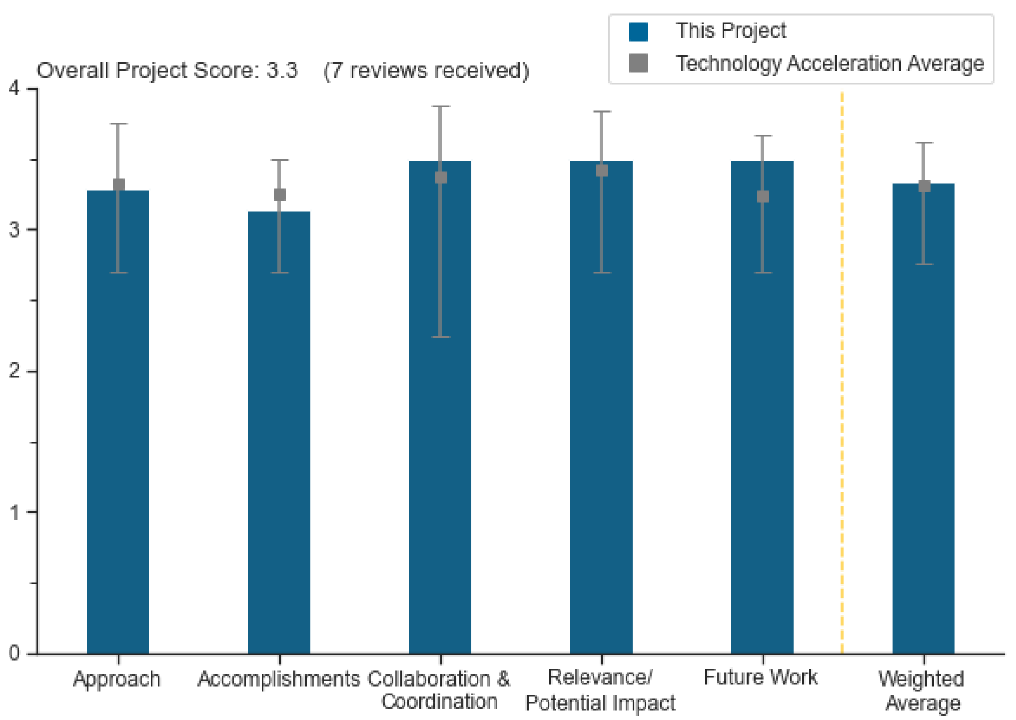
Uuganbayar Otgonbaatar, Exelon Corporation

DOE Contract #	DE-EE0008849
Start and End Dates	10/1/2019 to 4/1/2023
Partners/Collaborators	Idaho National Laboratory, National Renewable Energy Laboratory, Argonne National Laboratory, Nel Hydrogen
Barriers Addressed	• Site selection: What are the criteria for site selection? • Regulatory: What are the relevant regulations that affect nuclear hydrogen production? • Market-related: What is the effective electricity price that the electrolyzer pays?

Project Goal and Brief Summary

This project aims to demonstrate cost-effective supply of in-house hydrogen consumption at an Exelon nuclear power plant. A 1 MW polymer electrolyte membrane (PEM) electrolyzer and supporting infrastructure will be installed at an Exelon plant, providing an in-house supply of hydrogen. Researchers will also simulate the scale-up of electrolyzer participation in power markets. The project will demonstrate the potential for hydrogen production to increase the value of nuclear power plants, both by supplying plants' onsite hydrogen needs and by providing hydrogen to regional markets.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The integration of an electrolyzer with a nuclear power plant for onsite demonstration is meaningful. The integration of hydrogen production with a regional hydrogen end user is also commendable.
- Project objectives are clearly identified as installing an electrolyzer, providing in-house hydrogen, and simulating operation of a larger system. Key barriers are identified as identifying criteria for site selection, regulations in play, and an effective electricity price that the system must pay. The approach uses a combination of research and demonstration to verify the dynamic operation of a 1 MW electrolyzer at a nuclear power plant, review aspects of regulation and safety, and perform an evaluation of scale-up. The approach for the economic feasibility assessment is not described well. Argonne National Laboratory (ANL) estimated local demand for hydrogen for one site (presumably prior to the New York site being identified), but it is unclear what approach will be taken for estimating cost and performance targets (before transportation costs are even considered).
- The project has clearly articulated goals, objectives, and challenges. Progress toward these objectives is on or ahead of schedule and is well-presented in the material. The project is also well-defined and appears to be feasible on the timescale established. However, the presentation does not demonstrate how achieving these objectives will address critical barriers for the U.S. Department of Energy Hydrogen Program (the Program). This information may be available but could have been brought out more clearly in the presentation.
- The approach is clearly identified and seems likely to address the needs and barriers toward which the project is targeted. As the presenter noted, the approach could be improved by exploring the potential to supply hydrogen for different onsite and offsite use cases. However, the project, as scoped, makes sense as a first step in this line of empirical demonstration and research.
- This approach seems to address many of the barriers to integrating hydrogen production at a nuclear plant, at least in terms of small-scale initial barriers.
- A methodical, thoughtful approach was used. The research element is not clear, though the presenter claimed it to be. This is a demonstration project, and as such, the presenters need to be transparent on lessons learned and best practices. There is no task or milestone that includes lessons learned, best practices, or other dissemination of information.
- The project addresses the need to explore issues around siting an electrolyzer at a nuclear facility. However, no clear plans to demonstrate how electrolyzers could interact dynamically with nuclear operations are shown.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made excellent progress with the identification of a site with hydrogen and switch gear infrastructure. The Exelon partner agreed to move forward with the pilot, an identified source of hydrogen. National Renewable Energy Laboratory (NREL) and Idaho National Laboratory (INL) partners have made excellent progress conducting simulations of electrolyzer operation and dispatch, including developing the front-end controller (INL) and completing the factory acceptance task (NREL). ANL has made good progress toward addressing market-related questions prior to starting its economic analysis task. The analysis progress (slide 7) was not clearly linked to the question presented on slide 2, "What is the effective electricity price that the electrolyzer pays?", for the base case of power generation.
- Goals and milestones for this project are well-articulated, and progress toward these goals seems strong. There is little to criticize here.
- Progress toward project objectives has been made and measured against go/no-go milestones. In some areas, specific performance indicators (e.g., factory acceptance tests and voltage degradation thresholds shown on slide 8) are included in addition to these more qualitative measures. As noted in question 2, the linkage of these efforts to critical barriers for the Program could be more clearly articulated.
- The progress seems fairly on track, especially given the COVID-19 pandemic.

- It is confusing that the 750 kW stack was installed in NREL, which is far from Exelon's nuclear plant (slide 8). Major progress has not been seen in the past year for such a high budget ($13.8 million). The project spending should be reported on slide 2.
- There is a concern that there is still substantial regulatory uncertainty so close to the go/no-go decision.
- The reported progress seems modest for the team and budget. It is not clear whether the market demand analysis took into consideration the hydrogen price or what the hydrogen selling point would need to be for the market to materialize. There is no analysis on the quantity of greenhouse gas emissions that would be displaced by the hydrogen. It is unclear whether the front-end controller will be useful for other installations or whether a new controller will need to be designed and calibrated for each site. The balance-of-plant considerations are not reported. For example, it is unclear how hydrogen will be stored or whether a compressor will be used.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- Outstanding coordination is described across multiple portions of the large Exelon Corporation (Exelon) as well as well-defined research and pilot teams (as shown on slide 12). The project's focus on coordination with partners and outreach to other interested groups (also on slide 12) is extensive and notable.
- There is excellent collaboration with partners contributing to the project. Better alignment of the ANL task with NREL's and INL's work may be necessary to ensure the economic analysis and electrolyzer simulations are assuming the same operation cycles.
- There is excellent collaboration with national laboratories and an electrolyzer company.
- It is encouraging to see the Exelon team actively engaged with multiple national laboratories and the electrolyzer vendor.
- Collaboration seems good overall. It might be worthwhile, though, to explore collaborations with potential hydrogen end users who might procure the hydrogen produced by this demonstration project.
- There is good cross-laboratory coordination, but it would be good to collaborate with the U.S. Nuclear Regulatory Commission (NRC). (This might already be happening, but it would be good to report on that next year.)
- There is good collaboration between the entities. It is not clear whether the project has engaged the Center for Hydrogen Safety in its work. If the researchers have not done so, they should use this important resource.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is highly relevant and supports and advances Program goals. It investigates potentially impactful methods of hydrogen production and use. Further, it does so with real empirical demonstration of the technology, from which much will be learned about the feasibility of this production strategy. This will be critical to determining whether hydrogen production at nuclear plants is a strategy that may be viable at commercial scale.
- The project plays a critical role in demonstrating the use of nuclear power for generating carbon-free hydrogen and using that hydrogen for peak power generation and other end uses.
- This is highly relevant and is the vision of H2@Scale. The relevance can be increased with intentional efforts on lessons learned and best practices. These could easily be reported on the H2Tools.org website that the DOE supports. The relevance can be increased by identification of codes and standards that are particularly onerous or in need of updating.
- The potential impact is great and definitely supports the H2@Scale vision.
- This project is very relevant to the Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.
- As with other nuclear-related projects, this effort to develop both supply and demand modeling for a new source of hydrogen has the potential to advance progress toward Program goals (though, as noted above,

linkage to critical barriers could be clearer). It is at an early stage, so it is challenging to characterize the impact as advancing or significantly advancing.
- This is an important early-stage nuclear–electrolyzer integration project. However, since the electrolyzer operation will be largely disconnected from nuclear operations, the impact on demonstrating the nuclear-to-hydrogen pathway will be limited.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- Planned future work seems likely to lead to project success. As the presenter noted, the approach could be improved by exploring the potential to supply hydrogen for different onsite and offsite use cases. However, the project, as scoped, makes sense as a first step in this line of empirical demonstration and research.
- Progress and future work are very well-defined (e.g., slide 13). Given the recent initiation of the project, the future work presented in the main portion of the slides is within the scope of this project. Additional materials (slide 16) provide thoughts on future scale-up and fleet hydrogen use that were not discussed in detail but could advance the Program.
- This is an obviously involved plan. With respect to nuclear regulations, it appears to be on target.
- This is outside the scope of this project, but it would be good to see future work leverage the learnings here and work on larger (and high-temperature) electrolyzer integration.
- Future work is mostly clearly described. Some future work, such as DOE reporting and attending conferences, is quite trivial. The original plan is to install a 1 MW electrolyzer next to nuclear power, but slide 13 changed it to a simulated nuclear power plant.
- The future work details how to demonstrate the 1 MW system. It is not clear whether the future work would include identification of how a 100 MW or 500 MW system could be integrated into a nuclear site.
- Project milestones and future work are well-aligned. Risks associated with the project are not clearly stated, and a risk mitigation plan is not clearly discussed.

Project strengths:

- The project has strong project management, dedicated staff at Exelon for both research and pilot project scopes, and strong external communication with state and local governments, as well as presentations to nuclear societies. There is strong collaboration and participation by partners and progress with a site toward demonstration, and a dedicated hydrogen supplier has been identified.
- The project includes clear understanding of the many interfaces (internal and external to the project) to make it successful. The engineering detail completed to date is significant and reflects progress on or ahead of milestones. The presentation slides themselves are very clear and laid out well.
- The learnings regarding compliance with regulations and safety, codes and standards will be important to enabling larger-scale production of hydrogen at nuclear power plants.
- There is strong relevance to Program goals. There are well-articulated goals and milestones.
- The project uses the combined capabilities of the team of two industry leaders and three national laboratories.
- This is a meaningful electrolyzer–nuclear power plant demonstration project, if it succeeds. The team is very strong, with complementary expertise.
- This is a well-funded project with a solid team. It has the potential to have a significant impact.

Project weaknesses:

- The project could benefit from a more detailed consideration of end uses. The market demand analysis is a strong start, but a good next step would be to conduct outreach with potential users to define what might be needed to establish these relationships.
- Given the strong progress articulated in the presentation, additional information of any risks to completion could help the project sponsors understand the remaining work.
- There should be a formal and public report detailing some of the learnings, especially with regard to safety, codes, and regulations.

- The electrolyzer is being tested with dynamic signals to see how it can handle ramping, but it is not clear what the real-world cases are on which this work is based. It is unclear what onsite hydrogen consumption is or where decision points are for onsite versus offsite use of the hydrogen. It is unclear what approach will be taken for estimating break-even costs or how the economic analysis will be coordinated with the information and knowledge developed in other tasks.
- There is no plan to explore dynamic operation of the electrolyzer based on local market demands and nuclear plant supply. The project should identify specific hurdles for a large-scale electrolyzer system (e.g., 100 MW) at a nuclear facility and make recommendations for how to address those hurdles.
- The project's milestone table does not show quarterly milestones (it jumps from month 1 to month 9) or milestone numbers. Some major milestones have not been explained well enough (how and when they were completed). It is unclear what the go/no-go milestones due on July 30, 2021, are. It is not clear where the 1 MW electrolyzer is supposed to be installed, whether at NREL or Exelon. It is not clear why a simulated nuclear plant, instead of real power plant, will be used.
- There are no lessons learned or best practices in the scope of milestones. The project may benefit from engaging the Hydrogen Safety Panel and some of the safety, codes and standards experts who have designed filling stations and/or modeled releases of large volumes of hydrogen.

Recommendations for additions/deletions to project scope:

- To the extent possible in future cycles, the project participants and DOE are highly encouraged to pursue the onsite and offsite hydrogen use cases identified as 4, 5, and 6 on slide 4 of the presentation. This would both be a logical extension of the current work and highly valuable as a collaborative demonstration of the potential for nuclear plants to supply hydrogen to other users.
- If it is not already included within the scope, the project may benefit from identifying what information or technologies are needed before "scale-up" (as described in slide 16) that are not covered by this work. Specifically, the response to multiple audience questions on regulatory challenges was fairly general (this is a first-of-a-kind project, so there is some uncertainty), and this may need further attention. As a note, these thoughts provide this reviewer's personal perspective on the presentation provided at the Program Annual Merit Review and do not represent any endorsement or approval by the NRC on this or any future project.
- Lessons learned or best practices should be included in the scope of milestones. There may be a benefit to engaging the Hydrogen Safety Panel and some of the safety, codes and standards experts who have designed filling stations and/or modeled releases of large volumes of hydrogen. A design for a 100 MW or 500 MW electrolysis capability could be done to better understand what it would take to implement at that scale.
- The project should evaluate the need for onsite hydrogen storage and possibly a compressor beyond the existing storage tank. The team should size the storage system and look at its operation based on the electrolyzer operation and market analysis.
- Additional tasks likely are not feasible within this project budget and scope, but it would be good to see larger projects with high-temperature electrolyzers funded in the future.
- With the help of a partner, the project should test pump capabilities against performance needs under different heavy-duty refueling station scenarios.
- The project can have more executable milestones to ensure good progress quarterly.

Project #TA-030: Demonstration of Integrated Hydrogen Production and Consumption for Improved Utility Operations

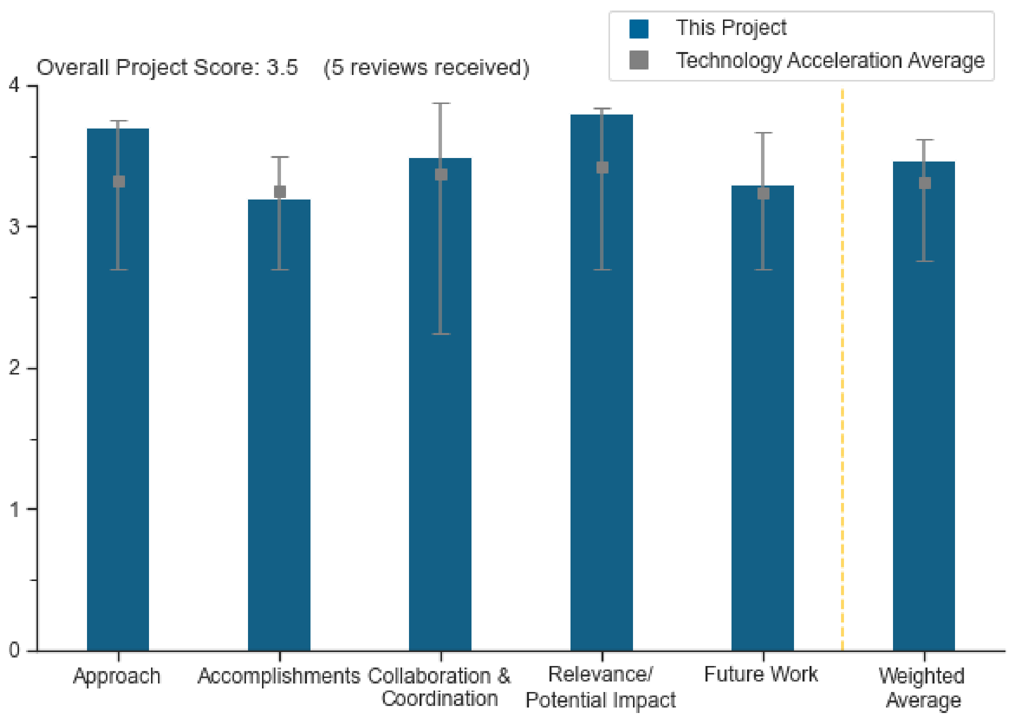
Monjid Hamdan, Plug Power Inc.

DOE Contract #	DE-EE0008851
Start and End Dates	5/1/2020 to 4/30/2023
Partners/Collaborators	Orlando Utilities Commission, OneH2, Inc., University of Central Florida, National Renewable Energy Laboratory
Barriers Addressed	• Systems integration • Reliability • Cost • Performance • Efficiency

Project Goal and Brief Summary

The project goal is to demonstrate grid-level hydrogen assets to bolster the hydrogen economy across sectors. Using grid-integrated hydrogen assets, a system operator can leverage variable renewable sources to produce hydrogen, which can then be stored or deployed for use in fuel cell electric vehicles (FCEVs), emergency back-up power, or grid operations. The project will manufacture and assemble an integrated system that incorporates polymer electrolyte membrane electrolysis for hydrogen production, compressed hydrogen storage, hydrogen dispensing for FCEV refueling, and stationary fuel cells for electricity generation.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project team provided an excellent presentation of its approach and the way in which task leads will get the work done. The approach has a strong focus on optimization of electrolyzer units with storage, the grid, and FCEVs, as well as stationary end uses. The approach addresses key technical barriers including systems integration, cost, performance, reliability, and efficiency. The approach for taking data from the Orlando Utilities Commission and elsewhere to model dispatch and grid-scale services for electrolyzer operation was compelling.
- The approach represents demonstration of an integrated solution from generation to end use, which is important for providing confidence to the market for commercial projects. Another interesting component of the project is cybersecurity analysis, which is likely to be an important consideration, based on recent ransomware attacks in other industries.
- The approach speaks to Plug Power Inc.'s experience in carrying out projects, and the equipment is off-the-shelf. The description of the project has a number of moving parts, but they seem well-connected.
- Overall, the project approach seems effective. The project goals and barriers to address seem clear. The project appears well-suited to address the barriers identified. One area that could be improved is to articulate how the project will capture and report challenges to achieving the $2/kg hydrogen cost target. While project participants clearly articulated a modeled path to sub-$2/kg hydrogen, uncertainties and potential roadblocks were also articulated during the presentation. It is not clear how the project will benchmark real-world results against these modeled conditions or how the project will analyze performance against these benchmarks and articulate lessons learned. Developing and articulating a clear plan for doing so would improve the project's likelihood of success and ultimate value to DOE.
- The approach seems solid, although it would be good to hear a bit more about how the team is going to catch up on their Year 1 milestones and keep the project on track.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Excellent progress has been made toward completing the technoeconomic analysis (TEA) and developing a path to <$2/kg. There is a very clear presentation of bottlenecks and the way in which the TEA task identifies bottlenecks to a <$2/kg hydrogen target. Good progress is being completed toward developing economic dispatch models.
- The team and partners are motivated to see this through, even with the delays due to the acquisition of Giner ELX. Equipment has been delivered, procurement has started, and design specifications/details are well on their way. Some of the barriers may be out of the team's control, but the remaining project partners have the capabilities and are motivated to complete this work, contingent on funding.
- The project progress against the identified performance indicators seems to be strong. The participants have proven themselves flexible, for example, when pivoting from fueling light-duty vehicles to medium-duty bucket trucks. One area for improvement would be a more detailed description of cost modeling methods. An explanation of what it is about these methods that gives the participants confidence that they have demonstrated a feasible and realistic path to sub-$2/kg hydrogen could have been articulated better in the presentation and subsequent question-and-answer period.
- The project seems somewhat behind schedule as an understandable result of the Giner ELX acquisition.
- The project has just started, so it is difficult to assess accomplishments this early.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The team is making good progress on Year 1 milestones, and each requires close collaboration and coordination with project partners.
- The team covers a good range of disciplines, from research to hardware to analysis to utility expertise.

- The use of partnerships in this project appears to be strong. There are no criticisms here.
- This portion of the project seems very good; there is a nice team of partners with complementary strengths.
- The flow of work between partners in the three years of the project is clear and logical. More integration of industrial partners into the TEA modeling would be important.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is very necessary, as it is demonstrating the role of electrolyzers in hydrogen production for grid energy storage and load management. Initial analyses of production and storage needs that are linked to the sizing of equipment illustrate the potential to use a similar approach to design and implement such an application at a larger scale.
- The project supports H2@Scale concepts and is an important part of showing the feasibility of this vision.
- The development of a utility control architecture to dispatch the system for both power and hydrogen sales is critical for achieving <$2/kg hydrogen.
- This is a well-targeted project to work toward integrated renewable and hydrogen systems for reduced hydrogen costs—a key goal of the DOE Hydrogen and Fuel Cell Technologies Office.
- The project could benefit from some clearer articulation of uncertainties regarding hydrogen costs. Identifying these potential barriers up front and then tracking progress against them would be valuable to DOE as the Department considers future projects of this type. The participants may have a plan to do exactly this, but if so, it was not well-described in the presentation. This minor criticism aside, the relevance and impact of this project are clear. This is a highly valuable demonstration project for the DOE Hydrogen Program.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The next steps for Year 2 are clearly laid out and, once implemented, should enable a robust demonstration and analysis.
- The proposed future work is well-thought-out and addresses the key identified barriers.
- The future work identified in the presentation seems logical and well-planned. The key risk to success seems to be whether the project can deliver hydrogen at the target cost. The project could benefit from scenario planning around the greatest potential barriers to achieving this target. Otherwise, the project seems well-positioned.
- It seems like a logical set of next steps. Other than the potential difficulty in obtaining an FCEV to test, it would have been effective to present a little more about other potential barriers/issues, such as integration of the various systems.
- Cybersecurity analysis is listed as part of the project as "in process" with 0% complete but is not listed in future work. Other aspects build on the project start and specifically call out showing a pathway to $2/kg in the analysis.

Project strengths:

- This is an ambitious project to test an interesting concept for integrating hydrogen systems with high penetration of renewables. The prime has a proven track record of real-world deployments. Overall, the project team looks fairly strong.
- Despite setbacks, the redistribution of the project's scope and progress made are impressive.
- There is good use of partnerships and flexibility in the face of project challenges.
- The project lead and partners are experienced and motivated. Additionally, the project is located in the sunshine state, Florida.
- The strengths include overall team and project scope, which seems to be off to a good start after novation delays.

Project weaknesses:

- The preliminary design may not be scalable to other locations or fuel cell and storage architectures. The presentation did not discuss adequate critical analysis of assumptions and inputs in modeling the path to <$2/kg hydrogen. It would be important to understand the limitations of the models and cost forecasts.
- This project is lacking a sufficient off-take vehicle for hydrogen fuel. It is suggested that the team look for a transit agency or college campus nearby that may be interested in a bus pilot.
- The project is somewhat behind on Year 1 milestones. A clearer plan for catching up on those milestones and expectations for Year 2 work would be useful.
- The project could benefit from more thorough uncertainty analysis and planning.

Recommendations for additions/deletions to project scope:

- The project should conduct further analysis of institutional, utility, policy, regional, economic, and regulatory impacts on optimization of system integration. Also, more integration of the TEA with the individual system units and site architecture is needed, specifically with how the select site design is representative and scalable.
- For market analysis, the team should extrapolate findings from this project to model economics and feasibility of larger-scale deployments.
- Uncertainty analysis should be incorporated explicitly into TEA and planning for future work.

Project #TA-032: Electrolyzer Integrated Modular Nano-Array Monolithic Catalytic Reactors

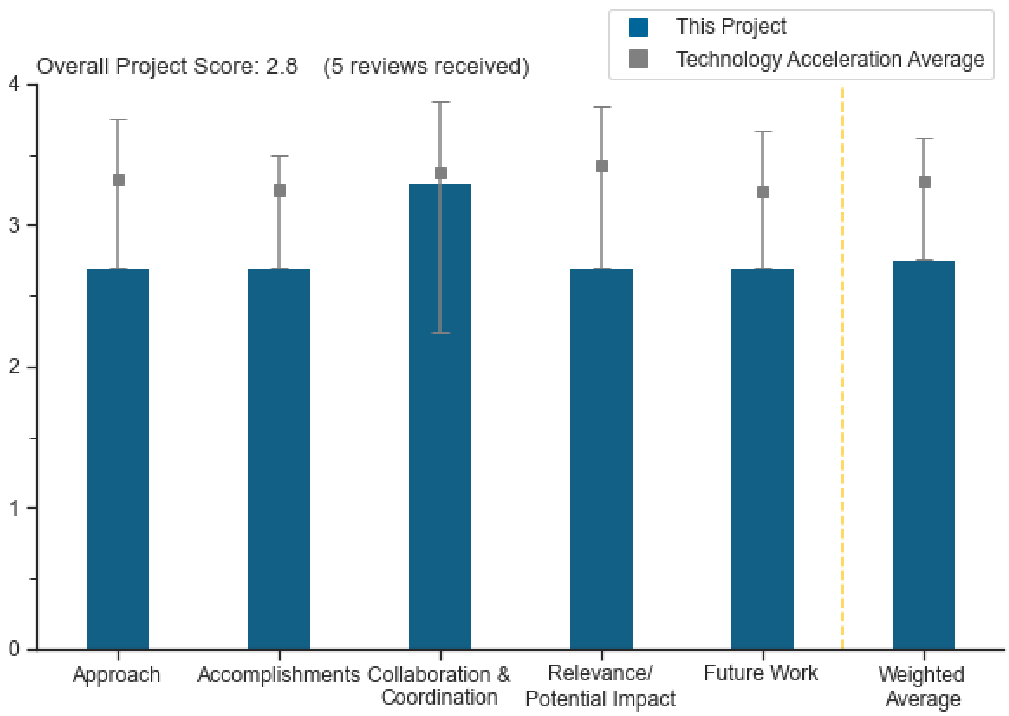
Trent Molter, Skyre, Inc.

DOE Contract #	DE-EE0008423
Start and End Dates	10/1/2018 to 12/31/2021
Partners/Collaborators	University of Connecticut, Connecticut Center for Advanced Technology, Advanced Manufacturing LLC, University of Tennessee, Knoxville, Stony Brook University, Brookhaven National Laboratory
Barriers Addressed	• High cost of hydrogen and fuels due to reactor expense/efficiency—particularly relevant when integrated with renewables • High cost and low reliability of gaseous and liquid hydrogen fueling infrastructure • High cost to convert CO_2 to chemicals and fuels using intermittent renewable power • Hydrogen fueling safety

Project Goal and Brief Summary

The project aims to demonstrate methanol synthesis with cost-effective hydrogenation reactions under low-temperature (<200°C) and low-pressure (<10 atm) conditions, which will significantly reduce the energy demand for the entire process. If successful, the project will provide a method to produce a widely used chemical and fuel with renewable energy and minimal greenhouse gas emissions.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **2.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is a good approach to demonstrating the production of a liquid fuel from an intermittent renewable energy source. This project can help to promote the H2@Scale concept.
- Renewable hydrogen production combined with utilization of CO_2 to make synthetic fuels provides an alternative to CO_2 sequestration and an energy storage medium that may be easier to store and transport than hydrogen. The approach to combine electrolysis to provide green hydrogen with more traditional thermal conversion of H_2 and CO/CO_2 to methanol may provide some benefits and should reduce CO_2 emissions compared to traditional synthesis from natural gas and may improve on the current low selectivity of direct electrochemical conversion to methanol. A large focus of the project appears to be on developing nano-array catalysts for the reaction of H_2 with CO/CO_2 for methanol production. It would have been beneficial to do a comparison of the results from modeling the flow and mass transport in the nano-array catalysts to a commercial methanol synthesis catalyst as a baseline, showing where the nano-array catalysts have benefits. The presentation suggested improved transport properties could be achieved with the nano-array catalysts. It is not clear how mass transport limitations affect the current commercial catalysts, and modeling results or experimental data showing reaction and transport properties were not provided. The project work directed toward electrolyzer electrode development lacks a baseline using a current commercial state-of-the-art electrode for comparison.
- The critical barriers for converting CO_2 to value-added chemicals have been clearly identified, including the high cost of hydrogen and the high cost of converting CO_2 to chemicals or fuels. It is unclear whether the project has identified the actual cost drivers that contribute to the high cost of hydrogen production and CO_2 conversion technology and, consequently, focused its research to address those issues. While the high cost and low reliability of gaseous and liquid hydrogen fueling infrastructure are major issues, it is not clear that this is a critical issue for this project. Hydrogen safety is always an issue, particularly regarding deployment in new technologies that employ hydrogen, but it is unclear how this project is addressing hydrogen safety.
- The project approach is defined fairly clearly and integrates with other relevant efforts. The core "integrated systems" approach is not well-supported. The "integration" is not evident, as the project approach seems to be an independent electrolyzer followed by an independent methanol reactor. There appears to be no linkage between the two unit operations. The diagram on the "Approach" slide is particularly helpful in explaining the system.
- The project claims to be targeting the barrier of high-cost, low-carbon e-fuels at scale. However, it is not clear how the technology being developed will lower costs, nor what the carbon footprint of the resulting e-methanol will be, nor the scale at which it will be produced. It feels more like an early-stage proof of concept than a technology acceleration effort. The key should be the design and demonstration of a scalable, high-performance methanol reactor. There is not a clear reason for diluting the effort by also developing a novel electrolyzer technology.

Question 2: Accomplishments and progress

This project was rated **2.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has exceeded the go/no-go criteria established for the methanol production rate and selectivity. The project has demonstrated methanol synthesis with high selectivity at low temperature. The principal investigator (PI) has demonstrated improved performance in the team's electrolyzer from utilizing a Pt nanowire (NW) array electrode through an improved three-phase boundary and enhanced interfacial contact between Pt NW array and polymer electrolyte membrane (PEM).
- Good progress has been made on fabricating the various structured materials for supporting the catalyst and for the heat exchanger and catalyst testing. It would be beneficial if the performance targets for these structured materials and catalysts were defined so that progress against expected quantified performance targets could be evaluated. For example, it would be helpful to know whether the observed methanol yield per kilogram and selectivity of the catalyst are sufficient to meet the required performance. Since some of these technologies, such as the methanol synthesis catalysts, are mature industrial technologies, it would be

beneficial to identify the shortcomings of the current technology and how the new technologies will address those shortcomings. A lack of defined performance targets for materials and technologies being developed makes it difficult to judge progress.

- The project has achieved significant results and shows focused activity and relevant testing. Fabrication of the aluminum scaffold for the methanol reactor is interesting, but it has not been compared to a conventional substrate. The testing appears to be on cordierite rather than the aluminum structures. Thus, the advantages of the novel structures are not demonstrated. The additively manufactured manifold–microchannel heat exchangers are, presumably, to remove the exotherm from the methanol reaction. However, the diagram on the "Approach" slide does not include a cooling system. Thus, it is not clear whether a cooled reactor or adiabatic reactor is envisioned. The PI's opinion on the implied/best operating point (to balance yield and selectivity) is not stated. The reactor size implications of operating at 200°C (low yield) are not discussed. Testing over 24 hours, although far short of ultimate system requirements, is of sufficient duration to demonstrate the performance degradation rate. The testing of Pt dopants appears to show advantageous effects. Using comparative test results between Pt NW arrays and assemblies is a very good approach. The use of an ultralow (2 micrograms/cm^2) Pt loading is a good development. However, this is for hydrogen evolution reaction (HER), which has already achieved competitively low Pt loadings (~0.05 mg_{Pt}/cm^2) with conventional electrodes. While "ultralow" is better than "low," there are diminishing returns. From an economic perspective, reduction of the oxygen evolution reaction (OER) catalyst would make more sense.
- The progress is good, especially taking into consideration the obvious COVID-19-related delays. There are many nice, but relatively modest, technical accomplishments. There are nine "Accomplishments" slides (which are all legitimately distinct items), yet due to some inexplicable repeated numbering system, they are shown only as slide 1 to slide 4. The revised completion date was not clearly communicated, and the reason for that was not clear. The only indication of the project schedule was the final slide, and the statement that the project is "currently progressing to meet all the milestones and no report submissions are due at this time" is not very informative.
- This is a technology acceleration project that, as of 2020, had spent 65% of its budget, yet the main accomplishments are still studies and lab-scale investigations. There is a good chance the project will not meet its goals. If this is a mischaracterization, a clearer description of the proximity to a working unit would be beneficial.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- Multiple organizations, including industry, national laboratories, and academia, are involved in this project. Each partner has a defined primary role, and from the results presented, it appears that the various partners are fulfilling their roles.
- There appears to be substantial and well-selected collaboration on this project.
- There is an impressive number of team members (six), and it is very clear what they are all contributing, both with respect to their roles (slide 5) and what they have delivered (with the appropriate logos on the "Accomplishment" slides). It is not clear how much collaboration has been done on the integrated system. It appears that the electrolysis folks and the catalytic reactor folks are acting independently. That should become clear when integration begins. The presenter did not seem to be very concerned about the integration task, but it was not clear whether that was because of his high confidence in the design and collaborations or because of his lack of familiarity with the overall project details.
- The engagement with four different university professors is encouraging. It would be good to see more commercial interactions that would facilitate confidence in scalability.
- The collaboration within the project appears to be working. The collaboration with external partners is not apparent. Collaboration with electrolyzer companies or DOE consortia involved with electrolysis would be beneficial.

Question 4: Relevance/potential impact

This project was rated **2.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project addresses developing new technology for producing methanol using CO_2 and green hydrogen, focusing on lowering the cost of production. CO_2 conversion using green hydrogen is one of the major opportunities identified in the Hydrogen and Fuel Cell Technologies Office (HFTO) H2@Scale initiative. For CO_2 conversion to be cost-competitive with current fossil-fuel-based technologies for producing methanol, the production costs for hydrogen and methanol need to be significantly reduced. While the project aligns well with the DOE Hydrogen Program's (the Program's) research, development, and demonstration objectives, the project is trying to develop new technologies for too many process steps/unit operations, and given the limited budget, the potential for making significant advances in all areas explored is lower than if the project focused on only one or two new technology advancements. There is a slide identifying progress toward DOE targets, but it is difficult to judge whether the project is actually making progress toward achieving those targets. Also, unless there is a plan to convert methanol into a transportation fuel, it is not clear that DOE targets for vehicle fuels are appropriate targets.
- This project has high relevance to overall DOE goals. However, the overall project goals are not linked well to the DOE goals. There is no consideration of how the approach would reduce overall methanol cost or enable greater system efficiency. The slide on progress toward DOE targets describes top-level DOE goals without stating how this specific project helps achieve them.
- The portion of the effort directed at improving catalysts for electrolysis is aligned with HFTO goals. The main focus of this project appears to be developing a better catalyst for methanol synthesis, and methanol synthesis is not a major HFTO focus. The impact of this project is not clear. It is not clear whether this process can compete with conventional methanol synthesis routes or what hydrogen cost from electrolysis would be needed to compete.
- This is good but could be more convincing by being more qualitative about the comparison with alternatives. Simply stating that the project is "significantly reducing the energy demand for the entire process" (slide 3) and "significantly reducing the energy demand" (slide 4) is repetitive and not very convincing. Some comparison of the alternative options should be shown, and better yet, some semi-quantitative estimate of the energy required should be provided. Qualitative statements about the project's robustness and its compatibility with intermittent energy sources are fine, but providing only "hand-waving" statements is not too compelling.
- The need for low-carbon methanol production options is recognized, but without the context of applicability (i.e., centralized or at-station), scalability, and relative economics, it is not clear what the impact of this project might be. It feels like an early-stage proof of concept that others may build on later, rather than a technology that could be put into the hands of even early adopters.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- The future work is well-defined and detailed.
- The proposed work is moving toward more integration of workstreams, which is good. It is suggested that the project focus more on demonstrating a working methanol reactor, even if just fed bottled hydrogen, and on evaluating economics. Leave "optimization" for later—unless the current status is unacceptable, making optimization required for viability.
- If this system is to be tied to renewable energy for electrolytic production of hydrogen, the electrolyzer, and then presumably the methanol synthesis reactor, will not be operating in a steady-state production mode but will be experiencing multiple start-ups/shutdowns. Methanol synthesis catalysts and supports should be tested over multiple start-up/shutdown cycles to ensure they can survive the pressure/temperature cycling. The economic analysis proposed is important. It will be important to know the hydrogen price at which the suggested process can compete with current methanol synthesis (in terms of the price of methanol) and how competitive it could be if carbon credits or a carbon tax is in place.
- There appears to be significant effort in the future work plan to evaluate new synthetic techniques to optimize the CO_2 conversion catalyst. The expected performance target at which the team is aiming is not clear, nor is the timeframe for identifying the optimal synthetic technique, given that the first task in the

future work plan is to evaluate the performance of the CO_2 reactor. If the current CO_2 conversion catalyst does not meet the performance target and the time to optimize the performance is long, it would be helpful to know what the benefit of the reactor optimization task is if the team uses a less-than-desired performing catalyst. It is not clear why the team is focusing on reducing the Pt loading on the HER catalyst and not addressing the precious metal content (particularly iridium) on the OER catalyst, when it is the OER catalyst that drives performance and hence cost.

- It is doubtful that all of the future work presented on slide 17 can be completed in just a couple of quarters, especially since some of this work needs to be done in series (i.e., all of the components must be done before the integration). However, perhaps the complete integration of both major subsystems is not even included, since this is not listed on this slide. Additionally, if one looks at the last slide (slide 22), it appears to show that everything is done except for milestones 9.2 and 9.3, which does not at all seem to match the status. Despite some questions on this topic, the reviewers were left a bit confused as to the actual current status and the future plans.

Project strengths:

- The development of CO_2 conversion technology addresses one of the major opportunities for utilizing green hydrogen, as well as addressing CO_2 emissions in the Program's H2@Scale initiative. There appears to be good collaboration between all the participants in the project. The project appears to be moving forward and to have met all defined milestones, despite having to deal with the COVID-19 pandemic.
- The project is mostly well-defined and -described. The project's strengths are its system diagram, the 24-hour reactor testing at different temperatures and pressures, and the concise yield versus selectivity graphs.
- The proposed process has shown good selectivity at the low operating temperature it is able to achieve.
- The project has a good approach and a good team, to which all team members seem to be adding value.
- This is a cross-functional group. There is faith in the scale-up potential for laboratory-based technology.

Project weaknesses:

- The weakness of this project is the poor communication of the project status, future plans, and end goals. Perhaps this could have been better if the project's PI had presented. However, the slides have many issues, so this was just part of the problem here.
- The project is proposing to develop Pt-based methanol synthesis catalysts. It is not clear whether the benefit from adding Pt to the methanol synthesis catalyst offsets the increased catalyst cost by reducing the cost of the overall process, assuming better overall process performance from the Pt-based catalyst than the non-Pt-based catalyst. The lack of performance targets for the various technologies being developed makes it very difficult to judge the progress.
- There is poor integration between the electrolyzer and the reactor. This could easily be two separate projects. There is a major lack of comparisons to the current status. Electrolyzer test results should be compared to current PEM stacks. Catalyst loadings should be compared to current statuses. There is no discussion of cooling the reactor and whether that is a key and necessary aspect of the overall concept.
- The weakness is the project's pace, if the objective is technology acceleration versus proof of concept for new laboratory-based ideas.
- The focus on methanol synthesis does not seem to be a good fit with HFTO.

Recommendations for additions/deletions to project scope:

- The project needs to complete a technoeconomic analysis (TEA) of its process technology. The TEA will serve numerous purposes, including the following: (1) letting the team know how its technology compares to alternative technologies for producing methanol, both from fossil fuels (as currently practiced in industry) and from renewable feedstocks; (2) identifying the cost drivers that may make the technology non-cost-competitive; and (3) identifying where to focus research and development to reduce costs, making the technology more cost-competitive. During the question-and-answer session, the presenter mentioned potentially pursuing Advanced Research Projects Agency–Energy (ARPA-E) funding in the future as follow-on funding for this technology. Based on the reviewer's experience participating in multiple ARPA-E projects, a TEA will be a critical aspect of any proposal and will be one of the first deliverables required by APRA-E if the proposal is funded. Given that the technology is essentially a "green" technology, the analysis should consider the additional cost of carbon capture and sequestration for current industrial fossil-fuel-based methanol synthesis processes for a fairer comparison. This project is working to develop several new technologies for both the electrolyzer and the CO_2 conversion process. It is suggested that the project team evaluate each of the technology development areas being targeted and rank them, from highest to lowest, on impact and potential for achieving success in moving the technology forward. Then the project should focus only on one or two of the areas that have the highest impact and are achievable.

- DOE needs to do more of these types of projects (i.e., making various products using renewable energy), if the Department really wants to promote the H2@Scale concept. These should be processes that can be highly distributed, such as renewables. However, DOE should seek more innovative projects than this one, which is primarily the integration of two known processes with some minor modifications (e.g., low-pressure hydrogen generation and different catalyst supports for methanol production).
- The project should add comparisons to current state-of-the-art or status systems in areas of electrolyzer polarization curves, Pt loading, methanol synthesis reactors, etc. The issue of the OER electrode and catalyst loading should be addressed. There needs to be a comparison to a system with a conventional PEM (or alkaline) electrolyzer. Economic estimates should be added to the analysis, both for the capital cost of the electrolyzer and reactor and for the product methanol.
- This project should drop the electrolyzer development and focus on the methanol reactor exclusively. The team should add information on the energy balance for the process, including heat and compression, and identify the origin of the claimed energy savings versus competitive processes. The team needs to address the implications of modest selectivity to methanol and explain what happens to the remaining CO_2 and what the by-products are.
- The project should add durability testing of the methanol synthesis reactor with on/off cycling to ensure it can be operated to match the cycling seen with renewable hydrogen production.

Project #TA-033: Developing Novel Electrodes with Ultralow Catalyst Loading for High-Efficiency Hydrogen Production in Proton Exchange Membrane Electrolyzer Cells

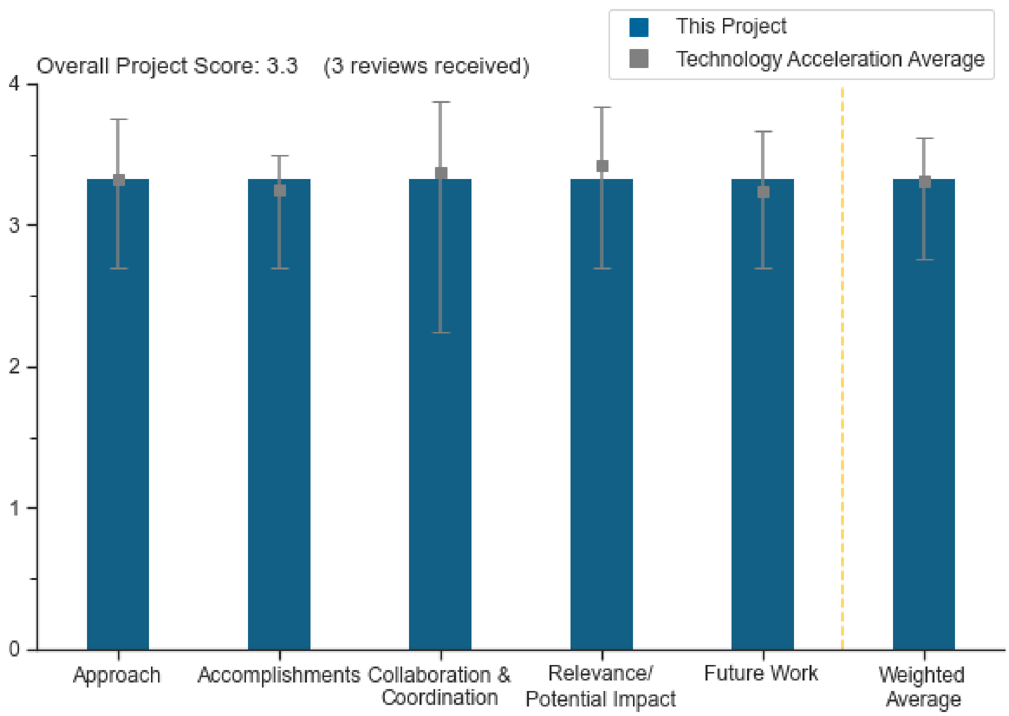
Feng-Yuan Zhang, University of Tennessee Space Institute

DOE Contract #	DE-EE0008426
Start and End Dates	10/1/2018 to 6/30/2021
Partners/Collaborators	University of Tennessee, Knoxville, Oak Ridge National Laboratory, National Renewable Energy Laboratory, Nel Hydrogen, University of Connecticut
Barriers Addressed	• Capital cost • Efficiency and durability

Project Goal and Brief Summary

This project aims to develop thin engineered liquid/gas diffusion layers (LGDLs) and catalyst-coated LGDLs for low-cost, high-efficiency hydrogen production in polymer electrolyte membrane (PEM) electrolysis cells. If successful, this work will reduce the cost of producing hydrogen in PEM electrolysis cells, supporting the U.S. Department of Energy goal to produce hydrogen for less than $2/kg.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Optimization of the electrode/transport media is emerging as a critical topic for PEM electrolysis cell membrane electrode assembly integration. The unique LGDL approaches pursued by the team appear to

have strong potential to provide significant contributions and knowledge. Controlling the macro-scale porosity and the thickness and other properties of the LGDL and incorporating a catalyst layer appear to be strong approaches, at least for learning about the dynamics of the gas evolution reactions. The optical imaging is a critical aspect of the approach. Cell modeling and cost analysis are strong elements.
- This is a very interesting approach to push toward generation of hydrogen for ≤$2/kg by increasing catalyst activity tenfold. The manufacturing cost of making these layers is unclear, but the assumption is that it would be less than savings associated with a 90% reduction in catalyst loading.
- Objectives and barriers have been identified.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The progress appears to be strong. Good understanding of the reduction in loading and improvement in mass activity has been achieved. Performance has been shown to be improved versus a baseline cell. There is very interesting work looking at the impact of the size and spacing of the LGDL pores. It would be interesting to understand the trends that were observed in more detail. Likewise, further understanding of the break-in requirement would be helpful. There are interesting results with the Ir catalyst application using the Ni template, where the Ni appeared to provide protection from the membrane without a separate protective coating on the Ti substrate. This should be verified in more detail, as the protective layer needed for the porous transport layer (PTL) is an open question for the community. It looks like there is good progress on the cell performance model, though it is not clear whether the model actually helped the project at all. It is unclear whether the model was used, e.g., to guide experimentation, in any cases.
- The technical accomplishments associated with this work are excellent, with clear progress in regard to catalyst activity and with further efficiency improvements related to flow enhancement, the addition of Nafion™ and TiN coatings, and parallel flow channels. It is unclear at this time whether the accomplishments will meet the goal of reducing the overall system cost, as there is no indication of the cost of manufacturing these parts in volume.
- It is unclear how much of the hydrogen production cost is allocated to the PTL + catalyst-coated-membrane production addressed by this project, as well as any corresponding over-voltage. It is unclear how much cost improvement is projected.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The project shows excellent collaboration between all of the institutions listed, with a clear delineation of work responsibilities.
- The team is well-formed and appears to be working well. There is a good combination of capabilities.
- The project team includes a broad array of laboratories, universities, and industry.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is highly relevant to providing information to the community about the critical electrode–PTL interface. This is very relevant to integration activities within Hydrogen from Next-generation Electrolyzers of Water (H2NEW).
- The work done is excellent and the achievements are remarkable; however, the impact of the project is difficult to assess. The technology is very promising, but there is no indication on manufacturability (maximum size, uniformity, continuous versus discrete processing, etc.), cost of materials, or construction. If these materials can be manufactured at high volume with good uniformity and reasonable pricing (accounting for the cost savings associated with efficiency and catalyst reduction), then the impact on the electrolyzer market could be very large.

- Improvements made by lower costs and improved performance through this project will have direct impacts on operating expertise and capital expenditures, thus reducing hydrogen cost. It is unclear how much impact is projected if the project is completely successful. The project has Ir loading and voltage improvements. It is unclear what this project does in terms of dollars per kilogram of hydrogen.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The proposed future work addresses the concerns related to the project and continues to push the boundaries of this cutting-edge technology.
- It was stated that all milestones were met, and according to the overview slide, the project ends in June 2021, and yet five activities were listed in proposed future work. That is confusing. It is not clear whether all of the future work had already been accomplished as of the DOE Hydrogen Program Annual Merit Review. Perhaps a no-cost extension will be pursued.
- This question is not applicable, as the project concludes this summer.

Project strengths:

- There is a great approach and a great combination of capabilities and activities within the project. The outcomes seem to be highly informative. The combination of bubble imaging, current density mapping, and performance modeling is really a great approach. The team is well-constructed.
- The strength of this project lies with the key developments in process efficiency and catalyst activity. If these results can be scaled easily and cost effectively, then the project could have a significant impact on next-generation electrolyzer production.
- Overall, this is impressive work. The focus on bubble evolution pre- and post-break-in is good. The project may consider ways to influence bubble evolution based on surface defects/pores in a similar manner to multiphase heat transfer optimization.

Project weaknesses:

- There is no weakness, just uncertainty about how the project is ending.
- The main weakness in this project is the lack of clarity on scale-up and cost associated with the technology. Additional work can and should be done to further understand the underlying reactions and push the boundaries of the technology.
- It is unclear whether durability testing was performed beyond the single 100-hour test presented on slide 10, e.g., start–stop, power cycle, and voltage cycle testing. The impact of the hole pattern on durability at differential pressure is also unclear. It seems like these tests would be performed by the industrial partner.

Recommendations for additions/deletions to project scope:

- The project appears to be complete, or nearly so. If there is an opportunity going forward, it would be interesting to assess the LGDL structures from a fabrication and manufacturing point of view in comparison to standard PTLs, which are generally available via some level of volume manufacturing.
- The group is addressing the key concerns and has a strong proposal for future work.
- This question is not applicable, as the project is concluding.

Project #TA-034: Rail, Aviation, and Maritime Metrics

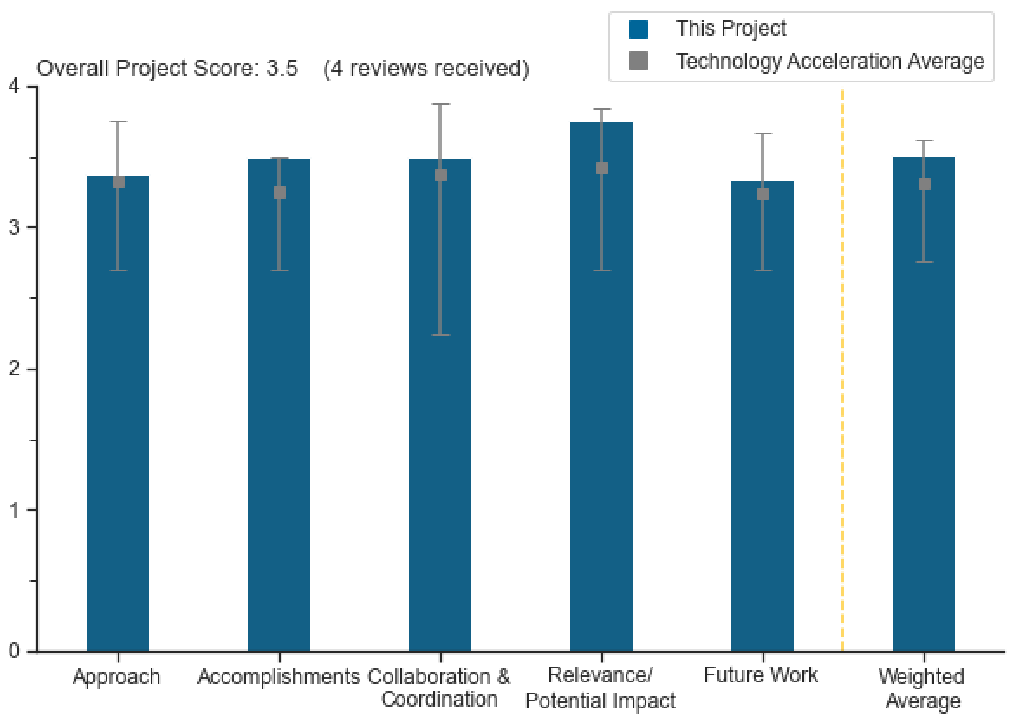
Rajesh Ahluwalia, Argonne National Laboratory

DOE Contract #	WBS 9.2.0.21, 9.2.0.22, 9.2.0.23
Start and End Dates	10/1/2020
Partners/Collaborators	Caterpillar, Cummins, Alstom, Stadler, North Country Transit District, San Bernadino County Transit Authority, CalTrain, Massachusetts Bay Transit Authority, Wabtec Corporation, Sandia National Laboratories, Chart Industries, Golden Gate Zero Emission, Swift Maritime, Universal Hydrogen, Ballard Unmanned Systems, Alaka'i Technologies
Barriers Addressed	• High hydrogen fuel infrastructure capital costs • Market uncertainty around the need for hydrogen infrastructure versus timeframe and volume of commercial fuel cell applications

Project Goal and Brief Summary

This project aims to determine how hydrogen and fuel cells compare with incumbent technologies in rail, maritime, and aviation applications, as well as what performance metrics are needed for hydrogen technologies to compete on a cost-of-ownership basis. Researchers will evaluate and identify opportunities for heavy-duty fuel cell adoption in rail, maritime, and aviation sectors, as well as opportunities for introduction of large-scale hydrogen into markets.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- By evaluating the total cost of ownership (TCO) and the potential economic and performance targets for each application, the project provides a holistic and robust perspective.
- The TCO analysis was comprehensive and systematic. The project team analyzed numerous important and interesting use cases in these sectors. If anything, the team tried to include too much in the presentation in such a short time. There were also too many acronyms to really follow all the assumptions.
- The analysis is conducted at a high level, and it is quite a logical plan. The baselines seem questionable, e.g., diesel trains are generally electric, yet batteries were put only on fuel cell trains; and use of the piston engine in aircraft is pretty much limited to very small planes, and the team did not explain why fuel cells are not usable in jet aircraft.
- The approach is unclear as to whether only liquid hydrogen (LH2) is being considered or gaseous hydrogen is being considered as well. The project team needs to say something more about the Hydrogen Delivery Scenario Analysis Model (HDSAM) that patently underlies all of this analysis. The methodology section is a bit weak, as the presentation states that the team started by choosing a “representative use case,” but it was not clear whether there was a selection for each main application or how many were to be selected. Further, the researchers wrote that they applied an internal rate of return (IRR), but IRRs are normally calculated rather than selected. The team might want to calculate an IRR and then compare it with a hurdle rate of X%.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made outstanding progress characterizing targets and TCO for all applications, as well as variations such as regenerative braking. The approach of developing representative cases for analysis allowed the team to make outstanding progress toward objectives. Several excellent variations were presented to show the influence on results; however, further discussion on the selection of variables and scenarios modeled in the analysis would be useful to get a sense of what barriers and uncertainties remain.
- This project has made good progress. This study did not look at regeneration on diesel, but fuel cell trains are the best choice even if regeneration were part of the base case. If hydrogen and fuel cell targets are met, fuel cell trains are predicted to be competitive. For private piston aircraft, fuel cells can be competitive at $8/kg LH2 and $430/kw for fuel cells. There is a clear advantage in fuel cells in unmanned aerial vehicles (UAVs), which should be followed up, as the use of UAVs is growing. Analysis of ferries suggests they are competitive at around $4/kg hydrogen.
- The results of this project were outstanding, and the TCO benefit of UAVs was particularly compelling. In future presentations, it would be helpful to rank the applications in terms of business case viability. It sounds like UAVs are economically viable today, while marine applications need better fuels and cheaper hydrogen.
- There is some very good progress here, but other aspects of the analysis need better explanation, especially around key baseline assumptions for fuel costs of hydrogen in different forms for the different applications. It seems they are being considered as “breakeven costs with conventional fuels” (hence higher for light aviation) rather than very much aligned with DOE costs and projections. Perhaps both could be considered in a somewhat more clear and nuanced analysis.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The project management and transfer of information among partners was not clearly described, but the project team is very strong, and the input of many industrial partners significantly improves the quality of the work.

- Collaboration seems very good. There is a good amount of industry engagement, and that is important for this project.
- The project got information from a large number of appropriate partners.
- It is good that there are numerous industrial collaborators contributing to the analysis.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Understanding what needs to be improved to get hydrogen into a wide range of transportation modes is essential to the DOE goal of a hydrogen economy. Figuring out where the barriers are likely to be surmounted first allows better use of resources by choosing to help those early modes of transport move to hydrogen and, thus, bring up the supply chain that will serve the entire economy. While these are hardly the most important vehicles to model, that is because they were covered earlier in the project.
- By conducting system analyses of hydrogen use in rail, maritime, and aviation transportation, the project addresses a critically understudied hydrogen market sector and provides technical targets that can help guide industry investments and research and development.
- It is very important to understand the economic potential of the different applications to promote H2@Scale. It would have been nice if more context had been provided about the differences between applications.
- This project is certainly well-targeted to define better metrics for these emerging hydrogen sectors.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Agriculture and construction are important applications for future work, and the project should consider adding mining equipment, as well.
- The proposed next steps for studying off-road vehicles are potentially impactful, but no sense of the market size was provided.
- Off-road trucks are a very good area to study.
- The project is seeming a bit rushed, as it is a one-year effort, so it is to be hoped that the project can be completed thoroughly, as there is significant scope left to accomplish.

Project strengths:

- The team took a challenging scope and completed it by selecting representative use cases and representative systems, both incumbent and hydrogen, for each form of transportation. The team chose reasonable options for all representative cases. The project presents a clear and consistent analysis and a comparison of systems. The project also calculated TCO using approaches consistent with Hydrogen and Fuel Cell Technologies Office research and economic assumptions.
- The overall strengths of this project are that it provides a comprehensive and quantitative analysis of the value proposition for fuel cells in rail, aviation, and marine applications. The project provides a clear comparison to the baseline incumbent technology.
- There is a good analysis of hydrogen for emerging transportation sectors that have generally been understudied in the past. The analysis generally seems sound and leverages previous work.
- This project references a deep base of other simulations, and a wide range of transport is covered.

Project weaknesses:

- In terms of weaknesses, some aspects of the analysis could be explained more clearly, such as the various hydrogen costs assumed, why they were assumed, and the impacts of those base case assumptions. In terms of the slide presentation, there was too much material for the presentation time allowed and the limited question-and-answer period. A bit less-dense information could have conveyed the project detail/complexity more effectively. There was some seemingly good work here nonetheless; this is more about the explanation of approach, methods, and presentation of results for future Annual Merit Reviews and general presentations.

- The overall weakness of this project is that there was just too much analysis to comprehend in too short of a time period and too many undefined acronyms. For example, it was not clear what FCD [fuel cell-powered drones] or FCH [fuel cell-powered helicopters] is. While it can be guessed that FC is fuel cell, the D and H were a mystery to the reviewer. The key takeaways need to be summarized more clearly.
- There was no presentation of the lifecycle analysis approach or results, nor was there integration with the technoeconomic analysis. There was also no guidance as to whether the proposed technical targets are contingent on a certain hydrogen production technology, its availability, or transportation market sector growth.
- Compared to other vehicle analyses, this analysis was not very deep.

Recommendations for additions/deletions to project scope:

- The project team should look for what level of hybridization in conventional systems is required to beat the best of the fuel cell hybrid electric vehicles (FCHEVs) (if indeed they can ever beat FCHEVs) to find the real competition for future markets.
- The team should include mining in the future analysis and maybe start considering the entire site development for a farm or a mine. Some of the TCO may be larger than the vehicles themselves.

Project #TA-035: Power Convertor for Electrolyzer Applications

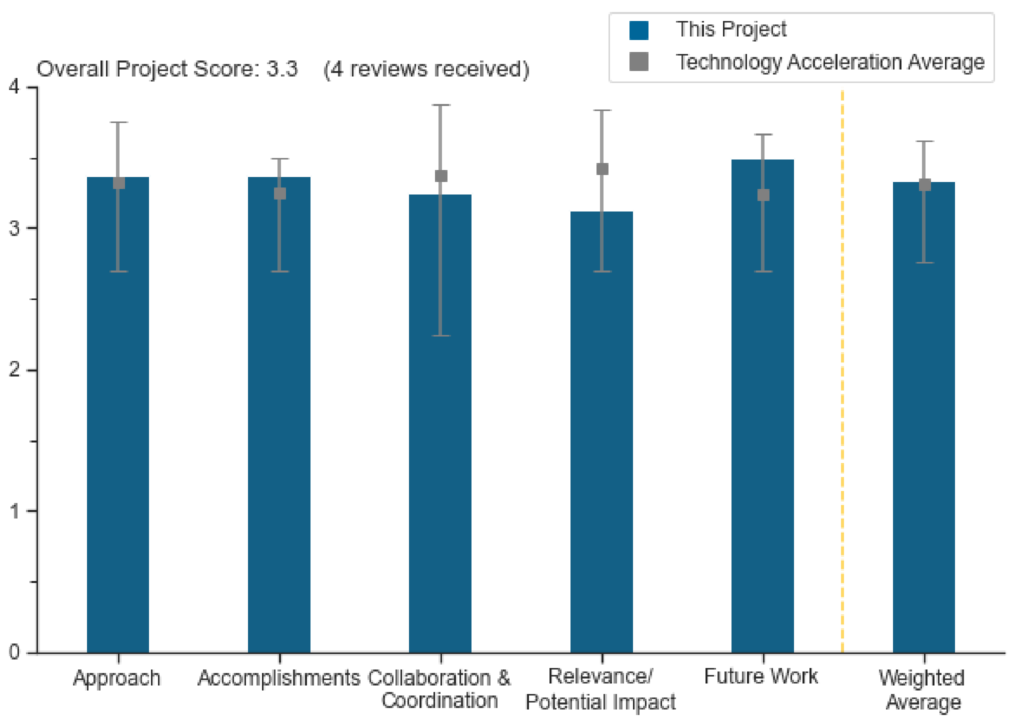
Robert Hovsapian, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.5
Start and End Dates	3/1/2020
Partners/Collaborators	EPC Power Corporation, NEL Hydrogen, Typhoon HIL, Dynapower
Barriers Addressed	• Lack of standardized controls interface for electrolyzer applications in real-world operation as per grid codes and interconnection, inter-operability standards • Coordinated control of multiple electrolyzers, including interaction with other power electronically interfaced distributed energy resource technologies • Optimized control for hydrogen and electricity co-production, including renewables

Project Goal and Brief Summary

The National Renewable Energy Laboratory (NREL) is developing a smart converter for dedicated electrolyzer applications. The converter will enable grid services by standardizing control interfaces between hydrogen electrolyzer system low-level controls and power converter controls. Project outcomes will improve the ease of adoption, maintainability, and reliability of electrolyzer systems.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is quite well-developed. The team is following the highly successful approach used by the solar photovoltaic power generation industry to develop power converter electronics for solar cell

applications. It is a bit early to tell in practice how universal the approach will be for the very different electrolyzer technologies on the market today.
- The project has a good approach to achieving the objective, which appears to be to develop a standardized power convertor for electrolyzers that are integrated with renewables, using off-the-shelf components as much as possible (i.e., standard power converter hardware).
- There is a clear need to standardize the communication between the situation on the grid and the control interface of the power electronics. The best practices are adopted from the solar field, and the partners represent strong players in the field.
- The approach is well-defined, with clear connection on how the work would be conducted to support the integration of low-temperature electrolysis and the grid.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team has made excellent progress despite the challenges of the COVID-19 pandemic. More progress is foreseen as the nation returns to work.
- There is excellent progress toward meeting the project's (modest) objectives.
- The project is off to a good start with a clear view on the design and its implementation. The project is focused on polymer electrolyte membrane electrolysis, and it is not clear whether the people involved have hands-on experience operating electrolyzers in the field already. This would help build a "feeling" of what the electrolyzer is/should be capable of.
- The project had quite a few lists of accomplishments, but it was difficult to tell whether these were associated with milestones or just reporting of tasks completed. No mention was made of Budget Period 1 milestones; there was only a slide at the end that had forward-looking milestones for upcoming quarters.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- It seems that the consortium was well-selected. It would be interesting to know whether there is an inside view or technical limitation of the maximum power level for the expressed modular approach. Considering the wide range of stack sizes (and number of stacks in a system), the partners will be able to anticipate a degree of flexibility.
- Collaboration with industry was very good, despite the challenges of 2020.
- The project has multiple collaborators but appears to be working with only one electrolyzer company. The project should also be working with more power converter manufacturers, which is the team's goal (but it is not clear why this has not already been done by this point).
- Collaborators appear to be well-suited for the project, but it would be nice to see a better breakout of their specific roles and what accomplishments they have made to date in support of the project.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project clearly shows the relevance, as it pertains to electrolysis deployment in a grid service application. Areas of impact are well-described, with numerous areas defined as being improved by this effort.
- The development of electrolyzer control electronics is essential to the integration of hydrogen generation into the grid. The transient nature of renewable energy dictates the need for sophisticated power conversion.
- The objective is sound, but there was no clear presentation of the economic drivers to adopt a new standardization over the status quo. Many stack suppliers argue that their proprietary solutions are the best and the power electronics should listen to their requirements (from low-level control), while everybody has learned the hard way how much influence the power supply control can have on the lifetime. Perhaps the

standardization demand comes from the regulations for guaranteeing grid stability, but again, this incentive could be clearer than just the vision "hydrogen stabilizes the grid."
- It is not really clear what DOE objectives this project addresses. Presumably, the objective is to reduce the cost of power electronics, but cost is not mentioned at all. The objective may also be to enable higher value for electrolyzers paired with renewables (e.g., fast response), but that is also not clearly shown.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The proposed future work represents a logical path forward toward the development of high-technology-readiness-level prototypes and pre-commercial testing of the control electronics in real-world environments.
- Actual demonstration with hardware at scale is proposed as future work. Description of testing, size, and location is well-defined, and there is a planned webinar to gather industry perspective on how best to integrate.
- The future work plans are clearly described, and the remaining milestones are also shown.
- Integrating the >1 MW electrolyzer system is a key part of the learning and validation of technology, and it remains to be seen how transferable this operational strategy could be to other electrolyzer makes, models, or types.

Project strengths:

- The project strengths lie in the ability to leverage hardware at scale to verify the concept. The use of power converter manufacturers for megawatt-scale implementation is good, and the development against existing grid codes and standards will show this end device and the testing results as having more validity. Using the webinar to engage industry and end users to solicit feedback for development and integration will gain more support from the grid/electrolyzer community.
- This project is strongly encouraged to continue the endeavor to achieve standardization and translate the grid status to a power control strategy for electrolyzer operation. If successful, there will likely be a similar strategy and architecture being applied for fuel cells (delivering to the grid) and other energy storage systems.
- There is excellent integration into the H2@Scale project goals. The highly capable teaming facilities and equipment are suitable for achieving project goals.
- The project plan includes demonstrations of real hardware. The results to date are promising.

Project weaknesses:

- There is strong focus on providing a technical solution, but there is a risk that this will become a one-off demonstrator if the technical, economic, and regulatory benefits are not made obvious through public dissemination in the near future. Overall, some elements seem to be missing: the feedback loop from the electrolyzer, the input from artificial intelligence, learning what the limitations are in (over)loading the electrolyzer, or anticipating the timing for stabilizing the grid (probably there is a pattern).
- The project appears to be using converters used for solar and batteries as a starting place, but the team is not looking at what has been done with convertors for fuel cells that have voltages and currents that are more similar to electrolyzers than batteries. Of course, fuel cells send power in the opposite direction from electrolyzers, but it is at least worth looking to see whether there are things that can be leveraged from that technology/hardware. The principal investigator should make much more of an effort in communicating the value of this work. For example, showing qualitatively how the value proposition for renewables and electrolyzers can be improved with a fast-response convertor would be great. It is likely that his colleagues at NREL have this already.
- The question of how "universal will the final product be" is yet to be answered.
- No weaknesses were identified.

Recommendations for additions/deletions to project scope:

- Designing in room for two-way optimization (grid to electrolyzer power control and also stack efficiency to power control to grid) could encourage all stakeholders to adopt the standardization while making room for artificial intelligence to anticipate patterns and parallel systems operating down the road. For example, perhaps battery electric vehicles could also contribute to grid stabilization simultaneously while already taking care of the worst dynamic grid irregularities.
- There does not seem to be any interest in seeking or identifying potential technology improvements. The goal of using off-the-shelf hardware as much as possible is understandable here, but the team should also strive to identify what technologies could enable even better future power convertors for this application. This should be a valuable additional output of this project but does not seem to be in the plan; namely, the project should communicate to power convertor hardware developers a “dream convertor module.” Then, the project should discuss with the convertor community what might be possible with some technology improvements.
- There are no recommendations for additions or deletions to scope.

Project #TA-036: Advanced Electrode Manufacture to Enable Low-Cost Polymer Electrolyte Membrane Electrolysis

Chris Capuano, Nel Hydrogen

DOE Contract #	DE-EE0008638
Start and End Dates	7/1/2019 to 6/30/2021
Partners/Collaborators	National Renewable Energy Laboratory, Oak Ridge National Laboratory, General Motors, Kodak
Barriers Addressed	• Capital cost • System efficiency and electricity cost

Project Goal and Brief Summary

This project aims to develop coating inks and roll-to-roll (R2R) coating process parameters specific to ultra-low-loaded catalysts used in polymer electrolyte membrane electrolysis. If successful, the project will greatly reduce the cost of membrane electrode assembly (MEA) manufacturing by improving manufacturing speed rate, reducing the total platinum group metal (PGM) catalyst loading by 75%, and reducing labor costs by a factor of 10.

Project Scoring

The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach to move toward R2R processing for catalyst layers on substrate is absolutely the correct approach for the long term. The transition from screen printing to R2R poses a significant number of challenges, but it has been done successfully already in the fuel cell industry.

- The approach is good, albeit mainly empirical-focused, and it is unclear how the dissemination will happen. The outline of work is well-suited to look at scale-up and translation. The project needs some more characterization to understand some of the observed performance changes.
- The project listed areas of interest and targets and gave a flow chart of tasks. There was no discussion of what would be done in the tasks; just their titles were provided. This is not very helpful for reviewing the project.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- R2R coating was demonstrated using gravure direct coating. This is very important for both electrolysis and fuel cells. Nel Hydrogen's new ink formulation (new catalyst material) and R2R were demonstrated successfully with this gravure direct coating. This work demonstrated the research team's capabilities. Knowledge was transferred to Kodak for the pilot operation. There is correlation of mixing results in the laboratory with results in the pilot processing facility. There is good coordination between research organizations. The project determined that coatability improves with moderate-viscosity inks (through coordination with Oak Ridge National Laboratory). The adhesion issue was observed. The recombination layer down-select identified the bilayer concept as more effective than the single-layer concept. The thinner membrane increased rates of degradation at the end of the test at 1,500 hours.
- The accomplishments on this project are adequate, as they are moving toward the goals of the project. It does feel a bit like reinventing the wheel compared to the work done by W.L. Gore on three-layer MEA coating. Overall, the goal was to take a process dominated by sheet-to-sheet screen printing and make it continuous, thereby reducing the cost. There are some challenges in ink development related to the shear thinning nature of the ink, the inclusion of oxygen evolution reaction catalyst materials, and coating uniformity issues that can be solved by dual-pass coating. Overall, the progress is acceptable and on track to meet the targets as defined.
- The project needs more understanding and not just a few two-point correlations. There appear to be many accomplishments that were mentioned, but it is not clear what exactly was learned. It is hard to judge everything since the presentation ran out of time.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- There seems to be good collaboration between all the partners on this project. The partners have expertise in their relative fields and have shown success with this type of development effort previously.
- The partners and team are good. They should reach out to work alongside other DOE manufacturing projects and the R2R and other consortia. The project leverages expertise across the partners.
- Three industry groups and two national laboratories brought their specialties to a successful project.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is driven to achieve DOE targets of reducing catalyst loadings, lowering cost, and maintaining performance. These are all positives.
- Overall, the work done on this project is important to achieving long-term, low-cost electrode manufacturing for hydrogen production. The scale-up of this technology is limited to only the main partners associated with the project, however, and the impact on the overall goals of the DOE Hydrogen Program will be limited in this case, as is clear by the proprietary nature of the ink and coating properties, as shown in the presentation.
- The project is tackling key scalability problems in the manufacturing and translating that to R2R. It is unclear how the impact will extend beyond Nel Hydrogen.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The proposed future work shows a good understanding of the challenges that currently exist with the process and moves toward creating a uniform, continuous coating process and validating the performance in a stack. It is highly likely the team put together will achieve the goals and produce a good R2R process for coating these electrodes.
- The project identified three challenges and barriers and addressed how to resolve issues. Future work is outlined. Moving to pilot plant production and establishing tests are what this project needs, and the project team plans to do those things.
- Future work is aligned in terms of scale-up and is reasonable.

Project strengths:

- The project is clearly addressing a barrier to low-cost electrodes through the development of a continuous coating process. The team has put together a solid plan for moving away from sheet-to-sheet processing and toward R2R processing, and that plan has a high likelihood of success.
- There is a comprehensive down-select approach of multiple components and technology transfer to the R2R and manufacturing process.
- The team is very talented and is the source of strength.

Project weaknesses:

- There are no conspicuous weaknesses.
- The major weaknesses associated with this project are the lack of any breakthrough technology to advance the cause and the minimal impact the success will have on the DOE Hydrogen Program, aside from the collaborators directly involved. It is important work that needs to happen, but the proprietary nature of the coating ink design and coating parameters makes it unlikely that others will benefit from the efforts made on this project.
- This project is performing an empirical optimization that may be specific to proprietary multiple sets. It is focused on performance but not so much on understanding.

Recommendations for additions/deletions to project scope:

- The scope of the project is adequate to meeting the defined project goals, with a high likelihood of successfully developing an R2R coating process for electrode materials.
- The project should provide some more translational findings that will help the community. It is unclear what the underlying structure–function relationships are. The project needs some more characterization to understand some of the observed performance changes.
- Stack testing would be next.

Project #TA-037: Demonstration and Framework for H2@Scale in Texas and Beyond

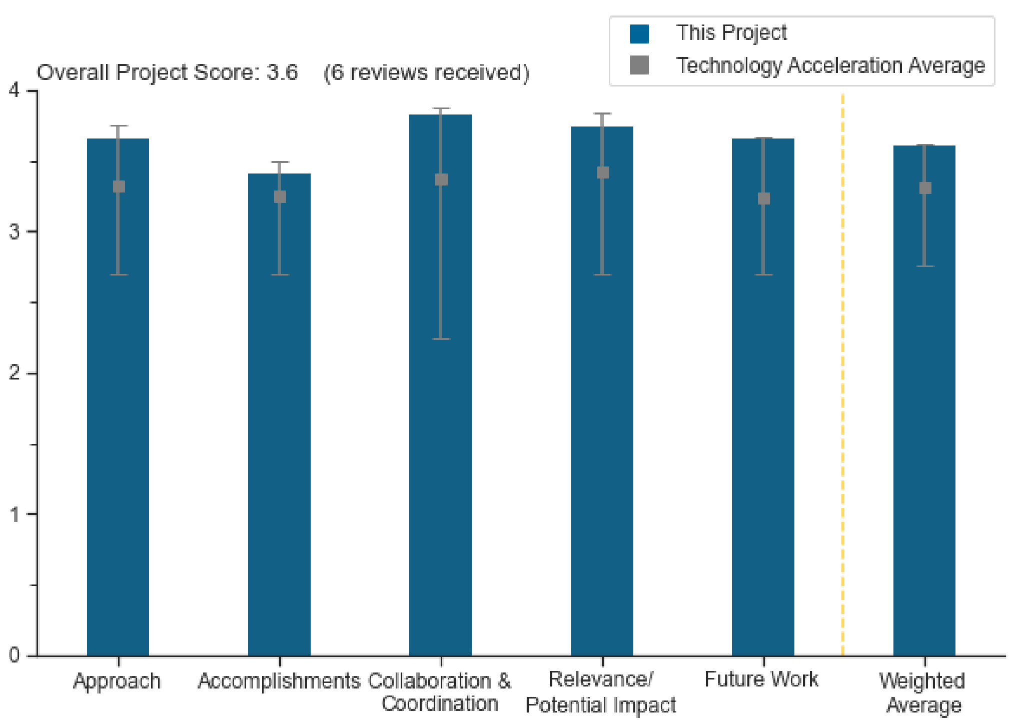
Nico Bouwkamp, Frontier Energy, Inc.

DOE Contract #	DE-EE0008850
Start and End Dates	1/10/2019 to 7/31/2023
Partners/Collaborators	Air Liquide, Chart Industries, ConocoPhillips, Gas Technology Institute, Mitsubishi Heavy Industries, OneH2, Inc., ONE Gas, Inc., ONEOK, Inc., Shell, Southern California Gas Company, Toyota, University of Texas at Austin, Waste Management
Barriers Addressed	• Hydrogen and fuel cell technologies need to be demonstrated in complete, integrated systems operating under real-world conditions • There is a high investment risk for developing hydrogen delivery infrastructure, given the current absence of demand for hydrogen from the transportation sector

Project Goal and Brief Summary

This project will determine how hydrogen production costs can be minimized by using multiple generation sources, including steam methane reforming (SMR) units that use renewable natural gas and electrolysis that uses wind and solar power. The project will also demonstrate hydrogen end uses, including using a 100 kW fuel cell to power a computing center. Base-load stationary power generation will be co-located with hydrogen vehicle fueling. The project will also develop a five-year plan for the Port of Houston area that considers existing hydrogen generation, distribution, and infrastructure assets to enable deployment of stationary fuel cell power and hydrogen-fueled vehicles. The plan will identify key barriers and partners, as well as the economic and environmental benefits of hydrogen deployment for the region.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The demonstration section is an especially useful approach, and much will be learned (including what stumbling blocks lay hidden ahead). Using multiple forms of renewable hydrogen is also a good approach, as the team will learn about more options and what works well and where. The team should also learn, by operating the system for interconnected generations and users, about timing and logistics issues in this simple case (no lag due to transport and minimal cost of transport). The framework for the Port of Houston is a good first step but will yield its real value only if it is then implemented in a project. To that end, the team should be proactive in seeking buy-in to move forward rather than just data from the many partners. Technology modeling is a key part.
- The project uses a combination of two research, development, and demonstration (RD&D) tracks, demonstrations and a deployment framework, to address well-defined key barriers to hydrogen scale-up. The demonstration tasks contribute new knowledge of paths and barriers toward low-cost, near-term integration of a variety of hydrogen systems with grid and end-use applications. The deployment framework via industrial outreach, workshops, and research is essential for mitigating the high upfront investment risk for developing hydrogen infrastructure.
- The acceptance of hydrogen and fuel cell technology in Texas and other "red states" will be aided by showcasing real-world applications applied in Texas and proving out the value in terms of economics, resilience in extreme conditions, and appealing to Texans' strong sense of independence and non-reliance on other states. While there may be high risk, if the project is successful, the framework developed from the project, the project team, and stakeholder involvement seems nicely set up for high reward when replicated elsewhere.
- The demonstration addressed multiple aspects of H2@Scale, from different hydrogen sources to different hydrogen uses. The one potential drawback is that spreading the demonstration across so many facets may prevent pieces from being demonstrated at a representative scale for these applications.
- The dual RD&D tracks are well-explained. The approach seems sound. Understandably, there are some delays due to the COVID-19 pandemic.
- This project has a sound approach.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Most progress of this project is in its modeling and planning. Very few funds have been spent to date, considering the number of partners in the project. Good progress has been made on site selection and preparing equipment, as well as the modeling of Texas Computing power requirements completed for sizing of fuel cells and electrolyzers. The regional analysis for Houston will also be a key portion of the project, and although it was somewhat unclear, progress on that has started.
- This project has made good progress in a difficult time. The team has made good choices, such as changing location even though that increases the project timeline. The project has also made sufficient progress on the site and models. It looks like there is good opportunity based on hydrogen generation and peak shaving opportunities from modeling. Logically, the team chose electrolyzers and fuel cells based on needs. The team has had discussions about how its system would handle severe weather and other disruptions. Fuel cells could help in such events by releasing stored energy in times of need.
- The project is on track with meeting its milestones and go/no-go. The team made impressive progress on getting site approval, finalizing negotiations, and contracting. The project's first workshop already yielded interesting feedback from stakeholders and highlighted a critical question around the transition from pilot projects to commercial-scale hydrogen hubs and systems.
- The project is making very good progress, despite some delays on the deployment task. The project really seems well-conceived and targeted to DOE goals.
- The timeline is long enough that the project can make up the time lost to the COVID-19 pandemic.
- The progress made is significant, considering that work on this project started only one year ago.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The partnerships on the project stand out the most. Having major energy companies (especially petroleum), utilities, original equipment manufacturers, and a major supplier of renewable natural gas (RNG) involved not only speaks to the potential impact of a successful project but also lends credibility and could elevate the project's visibility.
- This team consists of a large group of partners working toward this goal. It is an inherently cooperative project. Also, the principal investigators have partnering companies that could scale the results nationally or internationally.
- This is a very good team of collaborators that combines an innovative set of elements at the port, the data center, etc.
- The collaboration and coordination of academic, government, and industrial partners are excellent and clearly described.
- There is good definition of partners across the range of stakeholders and the supply chain. It was not clear whether there are regular team meetings or other interactions.
- There is a good variety of collaborators, especially in industry.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Determining multiple ways in which hydrogen production costs can be lowered by using different generation sources (electrolysis and renewable [SMR]) and power and fuel cell electric vehicle (FCEV) end uses is highly relevant to H2@Scale goals. The region of analysis, the Port of Houston, is a promising area for a hydrogen hub because of existing infrastructure, availability of renewables, and historical experience and demand for hydrogen. The feedback confirms the importance of de-risking investment in hydrogen infrastructure. Data center application is a growing demand for hydrogen, and this project will help to determine whether it is a promising and scalable early market for hydrogen.
- The project will prove out small-scale microgrid-type installation, but the analysis is scalable. The hydrogen production may be small (100 kg/day), but the approach and solution are scalable for sites requiring far more energy/storage for stationary and mobile fuel cell applications and having access to more resources (e.g., solar, wind, and RNG).
- This project has the potential to demonstrate key principles of the H2@Scale vision, from hydrogen generation to use. The project also includes interactions with local stakeholders of an important geographic region.
- This project is aligned well with the later phases of the DOE Hydrogen Program goal of adoption of hydrogen technologies. Reducing costs is, of course, key to implementation. The much larger project plan, the Port of Houston, is moving to hydrogen at large scale. Both are clearly aligned.
- This project is very much in line with the H2@Scale vision. The work on optimal sizing of systems for data centers is a great example.
- This project combines a critical set of elements around hydrogen at ports, integration of renewable resources, and fuel cells for power—highly relevant and likely impactful, once fully executed.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- The project's technical plans make sense. It is doing workshops to elicit concerns of potential participation in the larger Port of Houston project.
- A number of challenges facing the project were described, and logical contingency plans were discussed for barriers that are within the project manager's control. The proposed future work aligns with the scope and is consistent with the project objectives. The organization and data collection conducted at the Port of Houston workshops were not well-described. Strong outreach with stakeholders and publications will enhance the impact of the project prior to the project's end date.

- The proposed work appears to be more focused (versus progress to date) on local engagement with quantified workshops and communication plans. The modeling will be completed, and the demonstration will be initiated.
- The proposed future work, with outreach integrated from the beginning, aligns well with H2@Scale objectives.
- The team has its work cut out for it, but progress seems to be good, and the easing of the COVID-19 pandemic should improve the prospects for the demonstration progress.
- The future work seems appropriate, although there does not seem to be a resolution to the cost increases, so the project seems at risk.

Project strengths:

- This is an ambitious and exciting project that combines a number of critical elements in an innovative way. There is some degree of technology risk related to the source of hydrogen and the SMR element. This will be an interesting project to hear more about next year.
- Evaluation and comparison of different generation sources in a hydrogen hub, including renewable SMR, is an understudied area of research. This is a promising demonstration project for critical infrastructure, specifically a campus and data center, which may be an important early market for hydrogen.
- The project is located in Texas, where businesses care more about their independence and economics and elected officials seem to care less about the environment. The project approach integrates, from the beginning, the ability to replicate in other ports. Economics and factors other than environmental ones will ”speak to” officials in other red states.
- This project addresses a very valuable topic. The team has partners who could take this to the national or international level, if they wanted to do so. Also, the project is looking at smaller- and larger-scale issues. The results will be at least partially scalable. At worst, they will serve as a template of how to proceed and show the issues that one would need to address in a new region.
- The white paper/case study for the Port of Houston is a great first step in expanding hydrogen demand in the region beyond conventional uses.
- The project’s strengths include the breadth of team and scope, engagement with the local jurisdiction, and modeling to support business case and demonstration relevance.

Project weaknesses:

- Perhaps some technology risk associated with integrating the SMR generator is being understated, as the reviewer does not know much about OneH2, Inc.’s track record, especially for gas cleanup. Nonetheless, it is clear that the project team is well aware of these challenges. It would be ideal to have combined the two elements into a slightly more coherent overall project at the Port of Houston, according to the original plan, but it is understandable that those were best pursued in this way.
- The approach for extrapolating findings of the study to other promising regions of the country is lacking. The integration of systems was addressed at inconsistent levels of detail. It would be good to see more review on the potential challenges associated with resource availability of RNG or renewables for hydrogen generation, impact of carbon policy, and the need for storage.
- The planned work in the Port of Houston portion of the project is simply a plan, with no assurance of implementation. The value will come in the implementation, so this portion needs commitment from all partners and many groups that are not yet included to implement at least a major segment of the plan to reap its full value.
- The project’s breadth may lead to the use of hardware that does not accurately project costs to scale. For example, small electrolyzers and reformers are quite expensive and involve long extrapolations with changes in manufacturing methods and design approaches versus multi-ton systems.
- The hydrogen station seems to be small and thus does not really support further deployment of fuel cell vehicles.
- The small capacity of the hydrogen production systems is a weakness, but it is clear why that is necessary.

Recommendations for additions/deletions to project scope:

- The highest value will come from expanding the project to other buildings on the campus, and the cost of expansion will be lower than the initial effort because part of the infrastructure will exist already. However, expanding the system requires buy-in from many groups. Likewise, the plan for the greater Houston area really yields true value only when it is used and thus helps bring up the hydrogen supply chain, as well as implement the technology. Accordingly, the project needs to partner with social, political, and business groups to get the process going. There will be many hurdles that a good technical plan and analysis will not overcome, such as “not in my back yard” (NIMBY), entrenched interests, and political polarization. These take time, will, and momentum, and it is certainly not too early to start accumulating the support needed. There should be a much stronger effort toward setting the groundwork for these future expansions of the project. It does not work to end this project and then start working on getting a new one going. One needs to flow smoothly into the next, even if the funding shifts from DOE to the state of Texas.
- The approach for evaluating the use of hydrogen for the data center beyond “typical” operation, such as powering backup power and emergency energy needs of the data center, was not well-defined. This seems to be an important area for mitigating risk of investment but was not covered.
- The project should broaden statewide acceptance by enhancing messaging in the communication plan to align with the project benefits that are important to stakeholders, such as economics and resilient energy systems, and then find a way to sneak in the health and environmental-justice-type benefits into the messaging.
- If anything, perhaps small simplifications can be added to the physical part of the project to streamline, given the project demonstration status. A few more bells and whistles could perhaps be added after the basic system is running, with thought for forward planning.
- The project could strategize how to leverage the vehicles for outreach to help promote FCEV adoption.
- Technoeconomic analysis should include reference data for larger-scale equipment, if it is not included already.

Project #TA-041: Truck Duty Cycle Analysis

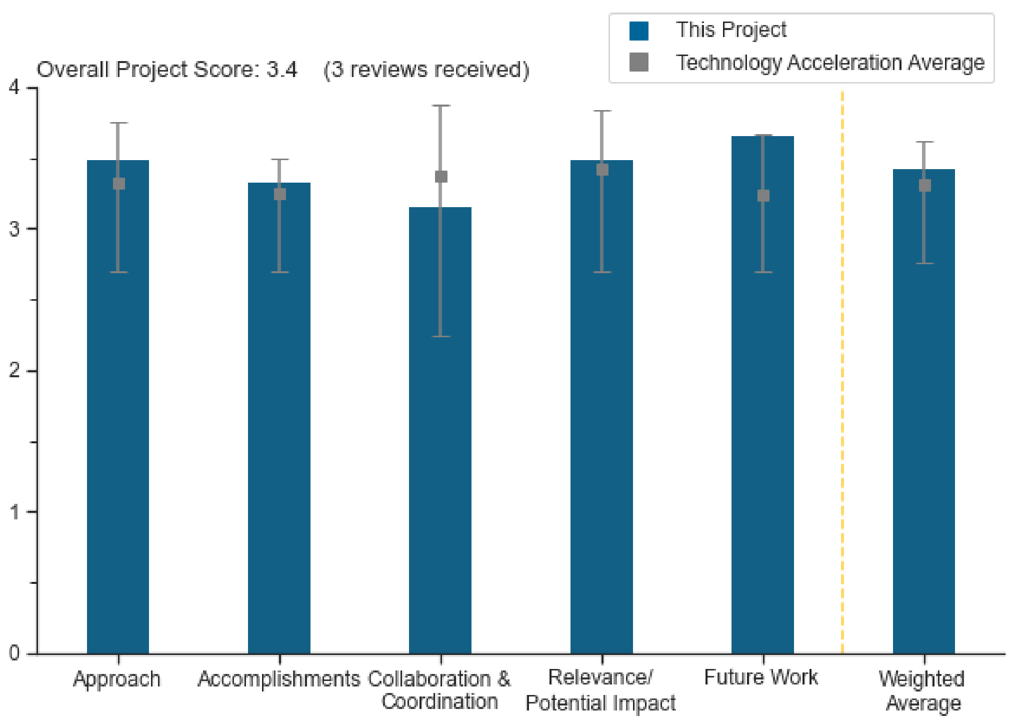
Jason Lustbader, National Renewable Energy Laboratory

DOE Contract #	WBS 7.3.8.2
Start and End Dates	10/1/2020
Partners/Collaborators	Argonne National Laboratory
Barriers Addressed	• Lack of package delivery vehicle performance data • Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools

Project Goal and Brief Summary

Operational drive cycle data are limited, making it difficult to analyze opportunities for hydrogen fuel cell vehicle design and adoption. This project aims to close that gap by developing real-world representative operational duty cycles for commercial vehicles to improve medium-duty hydrogen fuel cell vehicle simulation and technical target analysis. The project team will leverage existing fleet data to develop initial drive cycles for development, use data analytics to quantify the importance of existing data and identify areas where more data are needed, partner with fleets to collect additional data to fill gaps, and develop region-specific duty cycles to enable broad vehicle optimization. The work will support development of zero-emission hydrogen fuel cell delivery vehicles for last-mile delivery, reducing fleet emissions.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The team summarized their approach concisely in a milestones chart showing how tasks relate to one another. The approach appears quite sound. The intent to develop the capability to estimate national-level duty cycles appears feasible based on the presentation.
- This is an excellent presentation and a great start. Using population and geographic considerations is a great start. Adding vehicle-to-load (auxiliary) loads for different types of services will be of interest in future projects. Connecting the project to include grid services based on the duty cycles would also be an ideal next step.
- The project is very well described and understood. The presentation flow where the approach of each separate task was described right before each accomplishment rather than presenting the entire approach upfront is appreciated. It allowed for much better understanding. The presentation is missing some discussion for why certain vehicles and regions were chosen.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has been meeting its milestones, as shown in several charts on results for Class 5 and Class 6 vehicles.
- Great insight has been presented to date. There are a few areas for improvement. The representative and bounding design cycles appear to have been identified but would benefit from a clearer graphic. It is curious how different the average is from the actual boundary design point for the vehicle (range, performance requirements, etc.). A lot of great work went into mapping the population density and hilliness, yet all of the initial data comes from just one section. The project could have provided more benefit with some strategic thinking upfront to capture a few more regional differences.
- The project is in preliminary stages. A bit more preliminary results and trends that may be emerging from the project would have been nice to see.

Question 3: Collaboration and coordination

This project was rated **3.2** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration and coordination between ANL, National Renewable Energy Laboratory, and DOE was well described and well received.
- More collaboration with industry partners to prioritize what vehicle types and regions to gather data from is suggested. The project should also have more discussions with the fleets to bring their insight beyond simply collecting data on their trucks. There is a great connection with Argonne National Laboratory (ANL) to leverage this data.
- While it’s difficult to get delivery services to offer up their routing plans (usually quite proprietary), having some delivery services as a partner to offer generalized guidance on routing may be useful.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project will be useful in understanding vehicle sizing requirements, total fueling infrastructure requirements, and important use case scenarios.
- The combination of gathering real-world data and segmenting the entire United States is very interesting and valuable. More data and insights are anticipated.
- The project aligns well with DOE’s research, development, and demonstration objectives and has the potential to advance progress toward DOE goals and objectives in these segments of the transportation sector.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- The proposed future work shows a clear understanding for what gaps remain and how to expand the project. This actually stands out compared to many other projects.
- The proposed activities are very logical continuations of this year's activities. The data collection effort will be a very important piece involving industry input.
- Adding vehicle-to-load (auxiliary) loads for different types of services will be of interest in future projects. Connecting the project to include grid services based on the duty cycles would also be an ideal next step.

Project strengths:

- This is an outstanding analysis topic. The project has a sound approach and a highly qualified principal investigator and partners. There is excellent progress and collaboration or coordination between partners and DOE.
- The project is well set up from an algorithm perspective to capture the variations in routes and frequency that can be expected in the United States.
- Access to more real-world data is always valuable, especially when it is already being utilized in a related project. The broad scope to categorize national operation is also surprisingly insightful and will help establish performance benchmarks.

Project weaknesses:

- There is a good amount of data collected, but the presentation and summary of key metrics could be compiled and improved to create more impact and understanding. The project also could have benefited from more diverse regional data rather than all from a similar category.
- The project needs some coordination with actual last-mile delivery fleet owners to better capture scenarios and considerations that might be missed with a model/algorithm-only approach.

Recommendations for additions/deletions to project scope:

- The project needs to get more data (as already intended). This includes both a variety of vehicle types and U.S. regions. Also, the project should look for a more effective way to package the key insights of the representative and boundary condition (design condition) data. The work is well done.
- Adding vehicle-to-load (auxiliary) loads for different types of services will be of interest in future projects. Connecting the project to include grid services based on the duty cycles would also be an ideal next step.
- As the presentation shows, additional vocation vehicles will be considered once this phase is completed.

Project #TA-042: Next-Generation Hydrogen Station Analysis

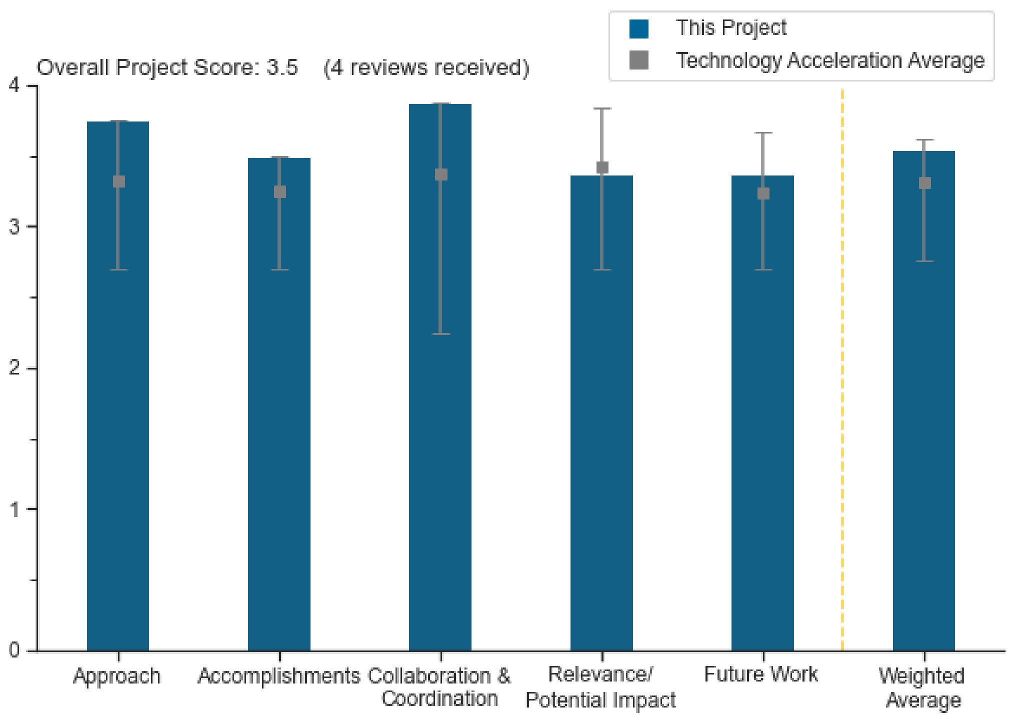
Genevieve Saur, National Renewable Energy Laboratory

DOE Contract #	WBS 7.3.8.2
Start and End Dates	10/1/2011
Partners/Collaborators	California Energy Commission, California Air Resources Board, South Coast Air Quality Management District, California Fuel Cell Partnership, IPHE (International Partnership for Hydrogen and Fuel Cells in the Economy), Association of Hydrogen Supply and Utilization Technology, Gas Technology Institute, California Department of Food and Agriculture's Division of Measurement Standards, Air Liquide S.A., Air Products, California State University, Los Angeles, Equilon Enterprises LLC, FirstElement Fuel, H2 Frontier Inc, ITM Power, Iwatani, Linde plc, Messer Group GmbH, Proton OnSite, Nel Hydrogen, Shell, StratosFuel, Inc
Barriers Addressed	• Lack of current hydrogen refueling infrastructure performance and availability data

Project Goal and Brief Summary

This project will evaluate existing hydrogen stations and equipment to provide an independent analysis of advanced hydrogen and fuel cell technologies operating in real-world conditions. The evaluations will provide insight into the research and development needed to improve performance and adoption, validate existing technologies against technical targets, provide regular technology reporting to align industry without revealing proprietary information, and establish the status and trends of durability, fuel economy, range, and driver behavior.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is excellent and has proven so over the years through composite data products (CDPs) used by DOE and stakeholders.
- The project has a great approach and does an excellent job obtaining a robust data set through collaboration with industry partners.
- The approach is optimized over years of data collection.
- Additional data cleaning and investigation of outliers would be helpful, though it is understood that the input data and communication with the station operators are limited.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has been generating highly useful data on an emerging industry, thanks to the trust placed in the National Renewable Energy Laboratory (NREL) by industry.
- A vast set of CDPs are available. The CDPs are useful and relevant.
- This project achieved all goals laid out in objectives/goals set by DOE. The project could benefit from shifting from light-duty (LD) vehicles and an LD infrastructure focus to heavy-duty (HD) vehicles and an HD infrastructure focus, where more transparency of equipment performance and durability is needed because of the expected rapid transition from conventional technology to zero-emissions technology. This could also help to better align expectations of future LD vehicle station capacity and gaps where lessons can still be learned. The comparison to compressed natural gas and liquefied natural gas station equipment components and maintenance may be helpful for benchmarking purposes and knowing when data collected are satisfactory.
- The consistent updating of the CDPs is of great value to the community in identifying where improvements for stations are needed the most, though better analysis of how downtime and other unplanned events affect costs would be even better.

Question 3: Collaboration and coordination

This project was rated **3.9** for its engagement with and coordination of project partners and interaction with other entities.

- The collaboration with those who provide confidential information has been outstanding.
- The project has great collaborations, which are necessary to obtain statistically significant and broad data sets.
- Collaboration in this project is excellent.
- The collaboration with California agencies seems strong, but better communication/collaboration with station operators would improve this project (though that is understandably difficult).

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is very relevant and useful to both DOE and the broader industry for making decisions. The data appear trustworthy and reasonable. Where it is possible, CDPs should be used to inform and validate future-looking (modeling- and simulation-based) DOE programs.
- The project aligns well with DOE’s research, development, and demonstration objectives and has the potential to advance progress toward DOE goals and objectives related to hydrogen infrastructure and fuel cell electric vehicle (FCEV) deployment.
- This is not the most exciting project, but it is definitely impactful. This work helps in understanding trends and estimating future costs of hydrogen and refueling stations.

- The current project objectives appear outdated compared to the state of technology and the rate of technology development by industry. NREL is delivering on the set objectives, but it is recommended that the project shift focus and re-align to provide cutting-edge value.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- More work on component reliability and maintenance trends will be very helpful. It is good that this was proposed by the team.
- The future work is on target. It is good to hear that new CDPs can be developed by reaching out to principal investigators/researchers.
- The future work is good, but it is business as usual. The team should consider exploring how this can be accelerated to align with the pace of technology development and industry focus on rapid acceleration of infrastructure rollout. The team might consider assessing whether some ultimate targets from the Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan may be too high and whether industry and users are satisfied with current equipment performance (e.g., slide 14).
- Including an analysis by station and component age would be very helpful.

Project strengths:

- Obtaining and aggregating fueling station data are very important for the industry, both to benchmark where progress has been made and to help predict where it is going. This project does a great job of doing that in a controlled and consistent manner.
- Tracking performance parameters of technology components is useful for public understanding of these parameters.
- The project has a sound approach and a highly qualified team. There are great partners, particularly from California. The project has useful results.
- The project is developing a great data set for the community, in particular the maintenance/downtime data.

Project weaknesses:

- The project's weakness is the ongoing data collection on the same components and variables, while expanding and refocusing the scope over the years. The focus should shift from "collection of all data available" to "key station components or variables that are new to industry data collection." Another weakness is the state of technology focus. Technology is developing rapidly, with increased attention on station rollout and scale-up. With every new round of government-incentivized station rollout, shifts in use of specific technology and capacity of technology occur. It appears that industry is learning rapidly, and by the time data are assessed and analyzed, the data collected are already "old news."
- The project could be improved through further analysis on the costs of downtime (estimated missed fueling events) and clear presentation detailing station capacity.
- It is unclear whether private transit bus fueling stations are included in this analysis. It would be important for our industry to be able to produce results and CDPs specifically for these fleets.
- There are no weaknesses.

Recommendations for additions/deletions to project scope:

- The project could benefit from a shift from LD vehicles and an LD infrastructure focus to HD vehicles and an HD infrastructure focus, where more transparency of equipment performance and durability is needed because of the expected rapid transition from conventional technology to zero-emissions technology. This could also help to better align expectations of future LD vehicle station capacity and gaps where lessons can still be learned.
- More CDPs are recommended for private stations, including and separated by transit bus fleets, Class 8 truck fleets, and medium-duty truck fleets.
- An age-based and FCEV stock-based analysis of utilization should be included.

Project #TA-043: Electrolyzer Stack Development and Manufacturing

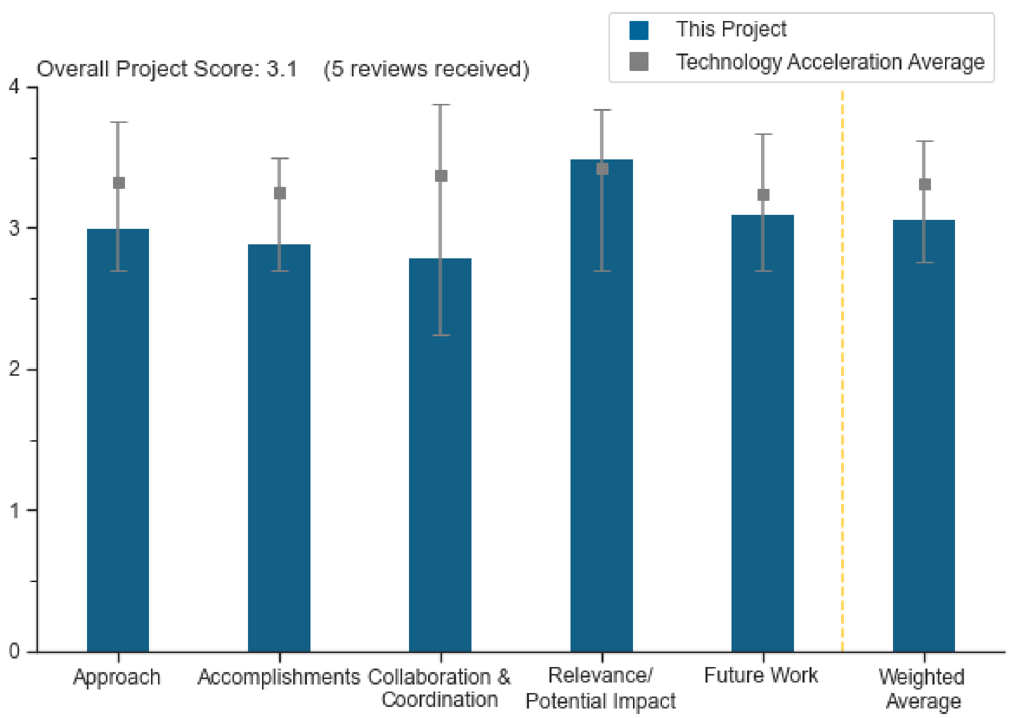
Olga Marina, Pacific Northwest National Laboratory

DOE Contract #	WBS 7.2.9.2
Start and End Dates	10/1/2019
Partners/Collaborators	Pacific Northwest National Laboratory, Idaho National Laboratory
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Renewable electricity generation integration • Manufacturing

Project Goal and Brief Summary

Pacific Northwest National Laboratory (PNNL) and Idaho National Laboratory (INL) are collaborating to develop complete high-temperature electrolyzer membrane electrode assemblies (MEAs) and make them available to other national laboratories, universities, and industry for testing and further development. The project team will also initiate stack and related component degradation studies using a baseline stack, investigate new fabrication techniques to lower cost, and develop a predictive stack digital twin.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Establishing a baseline solid oxide electrolysis cell (SOEC) and SOEC stack from which material and process development studies can be launched seems to be a useful concept for the Hydrogen and Fuel Cell

Technologies Office (HFTO) and its support of SOECs within HydroGEN and the high-temperature electrolysis (HTE) part of Hydrogen from Next-generation Electrolyzers of Water (H2NEW). PNNL has worked on solid oxide technologies for a long time and brings a good deal of material and process knowledge. The degree to which the designs of the PNNL cell and stack are similar to what industry may be pursuing should be further detailed. If this is to be an ongoing testbed and capability for HFTO, then relevance to industry should be well-understood and improved if needed.

- The approach to achieving a goal to develop anode-supported cells and make them available to laboratories, universities, and industry is feasible, but more focus should be truly given to validation of large cells in a stack (at least a short stack of three to five cells). The cells seem to have significant camber and should be evaluated in stacks (for both performance and durability) before significant efforts are made to reduce the cost since the data may identify different priorities, such as cell forging, which will significantly affect the cell cost.
- The project framework fits into a larger program and has an array of single cell sizes, as well as 300 cm^2 stack platforms, to conduct the experimental testing. However, it is not clear from the presentation how the small cell test results transfer to the larger-scale stacks. The items being developed are key to obtaining good efficiency and a low degradation rate.
- PNNL is leveraging its considerable experience in stack design and development from its many years of working the solid oxide cell technology and, specifically, in stack development with Delphi Corporation. PNNL also is using its stack modeling expertise to support the design of the stack platform. The focus on large-area cells for the stack being developed by PNNL should be explained. A stated project goal is to "develop complete HTE MEAs and make them available to other national labs, universities, and industry for faster transition material development progress to realistic testing." If this is the goal, the reason for designing the stack for large-area cells is unclear. This needlessly increases the cost of the validation testing of the developmental cell and stack materials. Further, stack development is an extremely challenging endeavor in the first place and is made much more difficult when stack active area is increased. Another pragmatic question about 375 cm^2 active area cells is related to how current will be delivered to the stack when operated at high current density (1 A/cm^2). This corresponds to 375 amps, which may be difficult, given the high temperatures involved. PNNL has likely identified a solution to this challenge.
- While generally the approach seems reasonable, it is unclear exactly how the standardized HTE MEAs will enable faster transition of material developments to realistic testing. It would be useful to provide more information on the exact vision of how this will be implemented once the project is complete. PNNL noted that commercially available MEAs are cost-prohibitive, and one objective of the project is to provide MEAs to laboratories, universities, and industry (presumably) at a lower cost. It is unclear at what scale PNNL is intending to make the MEAs and at what price PNNL is intending to sell them. Moreover, since PNNL is not a manufacturer, it is unclear what quality control steps can realistically be put into place to ensure high-quality MEAs at scale for testing unless the project intends to set up a pilot production facility. This may not be the ultimate goal, but without more information, it is unclear how to fully gauge the approach. Similarly, in addressing performance and cost targets, PNNL described moving toward a thinner yttria-stabilized zirconia (YSZ) in a flat part of a relatively large part, but details on how yield was assessed are somewhat lacking (even after the presenter answered questions from the reviewers); the advantages of larger cell size are clear, but yield can be much lower, both in cell production and in use in stack assembly. If not already part of the approach, PNNL may want to look at such relationships as a way to achieve the cost and performance targets of the U.S. Department of Energy.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Establishing cell materials, cell build at a useful scale, stack build, stack testing, and thermal/mechanical models all appear to be strong accomplishments, presumably highly leveraging past efforts on solid oxide fuel cells (SOFCs). The microchannel vaporizer is a nice example of how the team innovated to overcome challenges on the project.
- The primary accomplishments were the successful fabrication of large-area anode-supported cells and the establishment of a stack platform based on these cells. PNNL completed a milestone for making 20–30 cells with a yield of >90%, but the yield metrics were not specified. Certainly, cell camber was one of the

metrics, and PNNL demonstrated a substantial improvement in camber by reducing YSZ membrane thickness (as shown in slide 6). That said, even the "flatter" cell shown on slide 6 had more camber than would be desired for use in actual stacks. It is suggested that quantifiable quality control (QC) metrics are needed for cell yields (e.g., camber and geometric measurements, dye intrusion for quantifying defect density, high-pot testing, etc.). PNNL will be making many cells over the next year to support stack testing, so there is opportunity to obtain these QC data.

- Taking into consideration delays due to COVID, the team has made significant strides in successfully scaling the cells to 300 cm and has achieved over 90% yield using the tape casting process. This is indeed a great achievement. Based on the milestones, there has been significant delay in 1 kW stack testing with 200-hour runs, which is understandable, but the team is at 80% completion on the task, meaning that a stack will be tested any time now. However, it would be beneficial to at least demonstrate short stacks of three to five cells as soon as possible and see whether cell and/or stack modifications need to be made (camber, performance, durability) before perhaps committing to durability testing and performance targets.
- It is good to see that the MEAs were made with very thin YSZ membranes, but the key achievement will be to show the stack performance (degradation), which will show the true value of the development. The 1,000-hour test data shown in a graph were obtained in different operating conditions, making it difficult to self-assess the degradation rate.
- While progress seems to have been made on making a thinner electrolyte to reduce cell cost, additional details would be useful in gauging actual progress toward project objectives. The thinner electrolyte was described as being 6–7 microns and made using tape casting. It was further mentioned that there were no issues with handling the thin tapes. While tape casting is done on a carrier film, which can help with handling of thin tapes, tapes in production environments are rarely done below ~10 microns, especially when further laminating multiple tapes together (because of handling issues). To gauge progress and comment on potential risk in scaled-up manufacturing, it would be helpful if PNNL provided additional details on the exact cell structure and process, the cost target for cell manufacturing, and the intended scale of manufacturing the team eventually intends to use to meet the goal of providing cells to national laboratories, universities, and industry for faster transition of material developments. To gauge progress on the 5 kW stack testing platform, it would be useful to know if this unit benefited from designs and approaches used by PNNL for the laboratory's SOFC stack test stand. Since that equipment has already been built and evaluated, it would benefit the PNNL researchers to mention whether they reduced risk in this way. If they did not do this, then PNNL should go into more detail regarding what they did to ensure the test platform functions as intended and can be used throughout the remainder of the project without any issues.

Question 3: Collaboration and coordination

This project was rated **2.8** for its engagement with and coordination of project partners and interaction with other entities.

- There is strong need for these material developments for the SOEC industry, so it should not be too difficult to gain interest from third parties to adopt this technology and subscribe to the roadmap at an early stage (also in the international arena). The technical achievement to make steam in situ also looked like something partners and peers would be willing to adopt quickly.
- Partnership between PNNL and INL makes a good deal of sense and is good to see. Going forward, a more explicit connection with the HTE part of H2NEW should be pursued and incorporated, especially if the intent is for this to be an ongoing development testbed. More explicit and direct connection to industry really should be pursued in the next budget period to ensure relevance and address industry interest and needs.
- The team has been collaborating and working closely with INL, has engaged with SOEC manufacturers, and has been establishing collaboration with supply chain companies. It would be helpful to get more details for each of the statements made in the presentation, such as the feedback from the U.S. manufacturers and supply chain companies and whether any bottlenecks or areas of prioritization were identified based on the customers' needs.
- PNNL is working in close coordination with INL. While PNNL researchers mentioned that they are also engaging with U.S. SOEC manufacturers, it is unclear how the project intends to engage with them. Since a primary goal of this project is to provide standardized MEAs to national laboratories, universities, and industry, it would benefit PNNL to discuss the approach with as many of these organizations as possible so

as to avoid potential issues with the eventual sale of MEAs and/or sharing of knowledge (e.g., cell/stack manufacturing) that will ultimately help the U.S. accelerate its HTE technology development.
- No real evidence of collaboration was presented, aside from PNNL's collaboration with INL. The nature of collaborations that will be possible with U.S. SOEC manufacturers is unclear, given that all of them are pursuing stack designs that are significantly different from the one being pursued by PNNL.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project will make significant advances toward the DOE Hydrogen Program goals and objectives by scaling small anode-supported button cells to large cells and making them available for testing and product development. This will allow teams to accelerate development of electrodes, seals, and coatings. Moreover, the capital cost target, along with an aggressive current density target at high efficiency, will help the mission of hydrogen production at lower cost.
- If PNNL is successful in developing the SOFC stack platform on this project, there is potential for significant future impact if this platform can be used for future stack material developments, especially in conjunction with long-term stack testing at INL. A good example could be in developing improved contact paste materials, in addition to more commonly mentioned seals and air electrode materials.
- Achieving this thin membrane successfully is key to getting SOEC to deliver on its efficiency promise, making it more attractive as a technology to make hydrogen cheaply. The work on the electrodes was not discussed as much but is also essential, and this area (including interfaces with YSZ) is not yet understood well. The team has key expertise that will generate the right answers soon.
- The potential benefits in some operational cases of SOECs over polymer electrolyte membranes do demand support from HFTO in the broader H2@Scale and H2NEW pictures, so this testbed and activity are highly relevant in the big picture. Closer into the details, industry feedback and participation is a large need. Also, if this is meant to be an ongoing activity, then a mechanism for this activity to connect with and support other HFTO/H2NEW activities needs to be established. Otherwise, the benefit of an ongoing activity is not clear.
- Generally, the project seems to have a good objective in mind and could potentially have the intended impact. However, a concern is that, in practice, there will be issues that may limit the effectiveness of project outcomes on achieving the intended goal. (Some of these limitations—e.g., tape size and handling and confirmation that the test platform functions as intended—are discussed in the response to question 2.) The PNNL team may have thought through many of these potential issues, but if that is the case, it would be beneficial to discuss them.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The combination of process, testing, and modeling efforts seems very appropriate for a testbed type of activity. Integration between these efforts will be very important. The digital twinning could be very interesting; more information about how it will be developed and used will be necessary. If the intention is for this to be an ongoing support ("core lab") activity, more direct connection to H2NEW seems like it should be an absolute necessity. Otherwise, the value of the ongoing activity is questionable. There were good comments during the presentation about quality; further work here could potentially be useful and could leverage other HFTO capabilities in this space. H2NEW could be a vehicle for this.
- The plan for future work is reasonable. Understanding whether the large cell camber/forging needs to be modified, based on the preliminary stack tests, should be included.
- It will be good to see the 300 cm^2 stack being validated with the new developments included in the MEA design. The next steps are unclear, as it was mentioned that the thickness of the membrane was already minimized.
- PNNL has an aggressive set of milestones to be achieved in 2021, such as a 200-hour test of a 1 kW stack in June and achieving high performance in a 5 kW stack in September. Without knowing what the stack "improvement opportunities" (mentioned on slide 10) are, it is difficult to assess the plan to meet these milestones.
- Logically speaking, it makes sense for PNNL to shift now to short stack testing. However, given that quality control was described as having been assessed as a simple visual check (e.g., no evidence of

obvious pin holes), it is advised that PNNL also strive to truly determine whether the quality control yield is as high as the team says it is. Combined with various metrology methods, the testing should probably include making batches of cells and testing single cells to assess performance. Then the team should shift to short stack testing and do the same thing. Very little detail was provided about the digital twin model and the purpose of this method over past efforts.

Project strengths:

- The project has a comprehensive understanding of the MEAs for SOECs, including electrodes, membranes, and interfaces, with results presented that were cutting-edge according to the status quo in industry.
- PNNL seems to have achieved a manufacturing process that can make cells of different sizes, which may be useful for the intended eventual use of different national laboratories, universities, and industry for the purpose of speeding up of the transition of material developments into actual HTE systems.
- PNNL is leveraging its considerable stack design, modeling, and development experience in this project. Cell fabrication skills are evidenced by the team's successful cell size scale-up work to date.
- The project has benefitted from great leveraging of past capabilities at PNNL and INL. The project has a good combination of experimental and numerical work efforts.
- The demonstration of large cells with reduced electrolyte thickness is encouraging. The initial performance in SOEC mode is encouraging, but it is not clear what cell size (button or large) was used to generate such data.

Project weaknesses:

- It was initially unclear how the initial results on small cells will translate to bigger plates, taking into account the variability of operating conditions, but this question was answered after the presentation. Also, strong interest from industry in these pending results (on a stack) is expected, but this "channel to market application" was not elaborated clearly.
- The overall intention of this project is not clear. It is unclear whether this is supposed to be an ongoing testbed supporting HFTO SOEC activities broadly. If so, a broader approach and understanding of how this activity should connect with HydroGEN, and especially with H2NEW HTE activities, seems like a must. The approach cannot look like just a separate research project doing some testing and modeling. The approach has to be how the activity will support the community. Industry connections also seem like a necessity.
- It is still early to say (based on the presentation) whether cell warping remains a challenge and whether forging/flattening can be eliminated. Stack tests are needed to fully address this area. The electrolyte leakage/absence of such has not been addressed/quantified on the large cells.
- The details of the project are lacking. It is unclear whether the described status (e.g., yield) is actually as good as described and/or whether such metrics will hold as scale is increased.
- There is questionable focus on large-area cells for the stack.

Recommendations for additions/deletions to project scope:

- The team is asked to elaborate on the performance degradation, utilizing the multiphysics and the array of cell platforms, to identify clearly whether the good performance is lost as a result of off-specification conditions, non-uniformity, or just basic material degradation mechanisms (diffusion). The variety between small to large cells and five-cell stacks should provide sufficient statistics.
- More focus should truly be given to validation of large cells in a stack (at least a short stack of three to five cells). The cells seem to have significant camber and should be evaluated in stacks (both performance and durability) before significant efforts are made to reduce the cost, as the data may identify different priorities, such as cell forging, which will significantly affect the cell cost.
- The project needs to clarify the scope and intention of the activity. If it is supposed to be an ongoing support testbed, then how that will be accomplished within related HFTO and industry activities needs to be clearly defined and pursued. It cannot be an ongoing project but support only its own goals. To be clear, there is a good opportunity here for an ongoing supporting testbed, but that aspect needs to be better defined and enabled.
- It is unclear what the purpose of the digital twin modeling is and how it supports the project. This is not an advocation for the digital twin modeling's deletion, but it would be beneficial for PNNL to emphasize the purpose of this particular approach and how it helps achieve the overall project objectives.

Project #TA-047: Rail Refueling Analysis

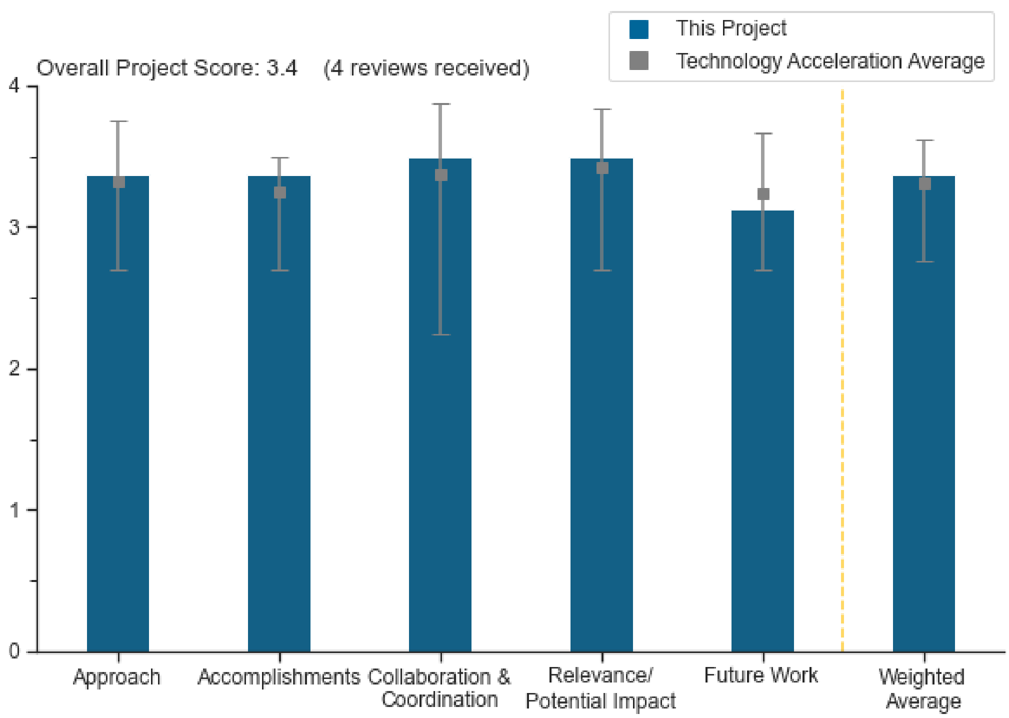
Brian Ehrhart, Sandia National Laboratories

DOE Contract #	WBS 9.2.0.2
Start and End Dates	5/1/2020
Partners/Collaborators	Argonne National Laboratory, California Department of Transportation, San Bernardino County Transportation Authority, DB Engineering & Consulting
Barriers Addressed	• Lack of hydrogen/carrier and infrastructure • Options analysis • Other fueling site/terminal operations • Safety, codes and standards, permitting

Project Goal and Brief Summary

This project aims to assess gaseous and liquid hydrogen refueling for freight and passenger rail to identify examples of scale, size, and cost of refueling infrastructure. This assessment will better inform future efforts to design and construct rail refueling infrastructure and identify areas for future improvement. Sandia National Laboratories (SNL) is collaborating with Argonne National Laboratory (ANL), California Department of Transportation (Caltrans), the San Bernardino County Transportation Authority (SBCTA), and DB Engineering & Consulting on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- SNL has made a good start on bottom-up designs for rail refueling. The range of options for gaseous hydrogen (GH2) to liquid hydrogen (LH2) storage and the low number of 10 trains to 200 trains show how difficult it may be to build out fuel depots. The project has identified the key metrics (and barriers) quite well: scale, footprint, and a very rough estimated cost. It will be interesting to see how this information can be used to inform passenger versus freight transition priorities. These figures will be key to overcoming knowledge gaps and barriers holding up deployment of hydrogen trains in the United States.
- The project approach addresses the identified barriers. Assessing both LH2 and GH2 fuel options, along with varying numbers of train assets and configurations, provides a lot of information in a concise manner. Providing example station design concepts, but not complete solutions, gives potential interested parties an idea of cost, complexity, and footprint.
- Bounding the infrastructure requirements for rail using analysis is a very logical first step in informing key stakeholders about this future application. It was not clear what level of analysis was performed and if the analysis is a full process simulation or more of a mass/energy balance in a spreadsheet.
- The approach of a bottom-up design is reasonable. The various trade-offs being considered, such as GH2 versus LH2 , large versus small fueling, and passenger versus freight operations, are the major items to be considered given the vast difference in size and operations of the various segments in the rail industry. The key metrics are scale, footprint, and cost, with cost and footprint having a major impact on the feasibility of utilizing current hydrogen fueling concepts and the need to develop new technologies and designs. There is some concern that the hydrogen fueling station designs rely too heavily on hydrogen fueling station designs for heavy-duty (HD) trucks and buses. These designs may not be adequate to meet the rail needs, particularly with respect to the footprint of the station relative to the footprint of the current diesel fueling pads.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- SNL has made good progress in scoping out the design parameters. This is critical to meeting the DOE goals for costing out infrastructure and determining what the main barriers are to decarbonizing transportation beyond cars and trucks. Detailed attributes have been scoped out such as passenger refueling pressure (350 bar) and refueling rates. The project goal is straightforward in assessing both GH2 and LH2 for rail using key infrastructure attributes such as scale, size and cost. This short, one-year progress has shown the trade-offs needed when considering LH2 or GH2 fueling for trains relative to footprint, refueling speed, and codes and standards requirements.
- The progress on this project has been extensive. The project has done a thorough job at developing refueling designs and the equipment required with each selected refueling option.
- The initial results were illuminating. Providing more context by comparing to the incumbent technology would be appreciated, especially for the larger freight systems. For example, the following information could be provided: (1) how diesel refueling is accomplished today; (2) if the depot has a fuel pipeline or if diesel is trucked or shipped in; (3) whether the technology is refueled overnight in series or parallel; (4) if a new approach to refueling needs to be invented or if the previous one can be copied with right-sized equipment for hydrogen.
- The project is developing cost estimates for various hydrogen refueling designs and is reported to be on schedule for delivering a final report at the end of June 2021. A comparison of the estimated cost for a hydrogen fueling pad and the cost of installing and maintaining a new diesel fueling pad would be very beneficial for identifying potential research and development needs to reduce costs and enable deployment within the current confines of existing fueling pads. In the table of results shown for "Multiple Units Passenger Rail Preliminary Results," explain if 341 cascade storage tanks for the compressor cascade and the cryopump cascade is really a reasonable conclusion.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- SNL has done an excellent job of coordinating stakeholder input and finding key partners who are most likely to pilot and enable hydrogen-powered rail here in the United States. Caltrans is instrumental in getting the first projects in the ground for California. ANL has a wealth of knowledge on refueling costs and hydrogen delivery design choices. Deutsche Bahn (DB) Engineering and Consulting is closely related to the relatively mature and expanding fuel cell train pilots currently being tested in Europe. Chart Industries, Inc. has extensive knowledge on large-scale hydrogen storage and is embarking on studies of LH2 tanks. SBCTA appears to be the nearest and most interested location to trial a hydrogen train in California. This extensive group of collaborators is critical to SNL starting with the correct input and demand required to complete the project of estimating needs of rail infrastructure.
- The project has good collaboration with ANL, which is developing the total cost of ownership (TCO) for locomotives in the three different types of rail operations to understand the fueling requirements for each type of locomotive. It is not clear if SNL is collaborating with ANL staff who developed the Hydrogen Delivery Scenario Analysis Model (HDSAM) tool for fueling delivery analysis. If not, it is suggested that the team collaborate with ANL's Systems Analysis Team. Collaboration with Caltrans and SBCTA provides an understanding of the fueling requirements for different types of commuter operations. Collaboration with DB Engineering and Consulting provides insight into the design and operating requirements for current hydrogen fueling stations. The project would greatly benefit from collaboration with a Class I railroad, The Association of American Railroads, or a consultant familiar with the industry to better understand the fueling needs and requirements for long-haul diesel locomotives, which constitute the majority of locomotives and fuel consumption in the rail industry.
- The team is strong and has a good number of stakeholders that appear to be providing feedback. Since this project is highly design-focused, it is expected to have a smaller team due to no physical build requirements.
- The extensive list of industrial collaborators is admired.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This work on evaluating hydrogen rail will be critical in bringing hydrogen demand to the scale that is required to be economical. This is a key objective of DOE. The size of these stations and the breadth of both passenger rail and freight rail will be important to support emerging passenger car demand and may outstrip demand from hydrogen trucking. This early evaluation of station types and identifying key barriers is the first step in meeting DOE's research, development, and demonstration objectives for additional hydrogen fuel cell deployments.
- This project is providing an extensive amount of information for stakeholders to review. The impact of this work is great in that it provides information required for decision makers. Additionally, the setback distance analysis will have a far-reaching impact on current LH2 users and those that have not used it due to the current safety requirements.
- Understanding the infrastructure requirements and the associated costs required to support the deployment of hydrogen-fueled/fuel-cell-powered locomotives and multiple units in the rail industry is critical for enabling the railroad operators to make the decision to convert to hydrogen/fuel cell locomotives and multiple units (MUs). TCO focused solely on the locomotive or MU is not sufficient for the railroads to make this decision. This project supports the DOE Hydrogen Program (the Program) goal of developing the technologies needed to enable the conversion of HD transportation, in this case railroads, from diesel to hydrogen/fuel cell technologies.
- This work is very important to understand the potential hydrogen-in-rail applications and if rail yards can function as mega hydrogen hubs.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- Developing cost estimates for the various designs is critical for developing a path forward for determining the best fueling option for the various types of rail service. Estimating the footprint for the various fueling options being studied is critical for accessing the feasibility of deploying a hydrogen fueling pad at an existing diesel fueling pad. Depending on the outcome, new designs and/or new safety regulations and codes may be required to enable deploying hydrogen fueling pads at existing diesel fueling pads. It is assumed that the work scope, focused on estimating basic delivery or production needs for each design, will only address the amount of hydrogen needed on a daily, weekly, or monthly timeframe and will not address how the hydrogen will be produced or delivered to the hydrogen fueling pad. This reviewer does not see any benefit to addressing how the hydrogen will be produced or delivered given that there are many factors that will determine how this is done in the future and it is beyond the scope of the project.
- The proposed future work to further refine cost estimates and facility designs will keep the project on track. The most interesting work may be on how to look at combined fuel depots or radical new fueling schemes as the throughput of hydrogen outstrips LH2 truck delivery, and even hydrogen pipeline throughput. These facilities will likely require an integrated production and refueling facility, which can further reduce boil-off and enable further economies of scale with extensive process integration.
- The proposed work is in line with the current approach. Obtaining accurate cost and additional footprint information will be critical to decision makers.
- The 2021 goals are logical, but the project states that the 2022 goals will be presented in a later report. It would have been preferred to hear a clear vision for 2022. Also, remove the caveat about future funding; it is tacit and comes off as hesitant. Present a bold vision; even if it is missed, at least it is aiming high.

Project strengths:

- The strength of the project lies in the clear quantitative analysis of refueling needs: throughput of hydrogen (refueling rates), footprint, and storage of onsite fuel with required setback distances. Very quickly, SNL has captured the scale of a few trains at a few tonnes per day all the way up to 1,500 tonnes per day for a major freight train fuel depot.
- The overall strength of this project is that it is important work to inform an important application with a clear approach. It is systematic and comprehensive at looking at different vehicle configurations and different fueling configurations. The results are interesting, especially when put into context with the scale of U.S. LH2 generation.
- The strong analytical approach with a great deal of useful and informative information is the project's strength.
- Understanding the cost of hydrogen fueling pads is a critical factor in understanding the overall cost of the infrastructure changes required to support the deployment and operation of hydrogen-fueled/fuel-cell-powered locomotives and MUs. From the railroads' perspective, a TCO focused solely on the locomotive or MU does not provide a true picture of the total cost that will be incurred in switching from today's diesel locomotives to hydrogen-fueled/fuel cell locomotives. For example, when railroads switched from steam to diesel in the 1940s–1950s, a TCO focused solely on the locomotive would have shown that the cost of the diesel locomotive and diesel fuel were significantly higher than the cost of a steam locomotive and coal. However, the lower cost for the supporting infrastructure and manpower for diesels more than offset the higher cost of the diesel locomotive and diesel fuel. Understanding the cost of the infrastructure required for hydrogen-fueled fuel cell locomotives is important in understanding the total cost railroads will incur in switching to hydrogen.

Project weaknesses:

- If ANL's HDSAM is being used in this analysis, it should be acknowledged. If not, it is unclear what the shortcomings are in HDSAM that would not make it applicable for this application, since HDSAM is used in the vast majority, if not all, of the Program's hydrogen delivery analyses. The team should speak with Class I railroads to better understand their fueling requirements, such as the required fueling rate and expected fueling times, as well as the design of the fueling pad. The design of the fueling pad can have a major impact not only on cost, but also on operations, which will equate to a cost. Freight locomotives are

often operated in combinations of two to three units, and the locomotives are fueled simultaneously without uncoupling the locomotives. These factors will have a significant impact on the hydrogen fueling station design. A fueling rate of 10 kg/min, as shown on the “Freight Rail Preliminary Design Inputs” slide, is unrealistic given the volume of the fuel required for long-haul freight. For regional passenger locomotives, the fueling infrastructures will differ significantly depending on the size of the operation. For example, a smaller commuter operation, Virginia Rail Express in the Washington, D.C., area, has two routes that diverge from a single route out of Washington, D.C., and it operates a limited number of trains daily. One fueling pad may be sufficient to meet its needs. Larger commuter rail systems such as Chicago’s Metra have multiple routes with multiple fueling pads. Again, understanding their fueling requirements is critical for costing and designing hydrogen fueling that meets their requirements.
- It would have been interesting to see how these results could be applied to a physical location to better understand the true barrier of dispensing hydrogen at this scale. Presenting the figures and numbers alone, without an overlay to a real-world location, is a weakness. This would be especially interesting at the higher end of demand with freight rail. The chart comparing the different compression and cryopump options with flow rate was interesting but could have been more relevant if power was also included in the table. The transformer and power connections could have an impact on footprint when considering the throughput required. This may be outside the scope of the project.
- The overall weakness of this project is the lack of pipeline consideration and adequately describing the current incumbent technology/methodology.

Recommendations for additions/deletions to project scope:

- The project needs to take into consideration the larger footprint required for a hydrogen fueling station compared to a diesel fueling station. It is unclear if space is available at existing fuel pads to accommodate a hydrogen fueling station. Space is limited, particularly in urban areas where many fueling pads are located. It is unclear if existing designs for hydrogen fueling stations, based on station designs for HD trucks and buses, will be adequate for rail or if new designs will be required. It is not clear if the design of the hydrogen fueling pad accounts for the need for large hydrogen storage tanks to support the fueling pad; however, this will be critical to meet demand. Again, this will be an added footprint issue as well as introduce additional safety requirements.
- Where appropriate, it would be interesting to have closer coordination between the first few rail project demonstrations in California and the United States. SNL has a wealth of knowledge, and it would be good to see this more directly applied to upcoming pilots and demonstrations. It would be interesting to further understand practical implementation at 1,500 tonnes per day or the average upper limit for freight rail fuel depots in the next five years.
- It is recommended, in future presentations, to outline how the incumbent technology performs refueling and the infrastructure required. Highlight where hydrogen can copy and where innovation is needed. Optimization was mentioned in slide 8, but it was unclear what property the project was optimizing for (e.g., cost, footprint, etc.). Please clarify in the future. Also, it is not clear why the project uses 350 bar and not 700 bar, as many HD applications are considering 700 bar. That raises a question of whether rail has a special concern.

Project #TA-048: Advanced Research on Integrated Energy Systems (ARIES)/Flatirons Facility – Hydrogen System Capability Buildout

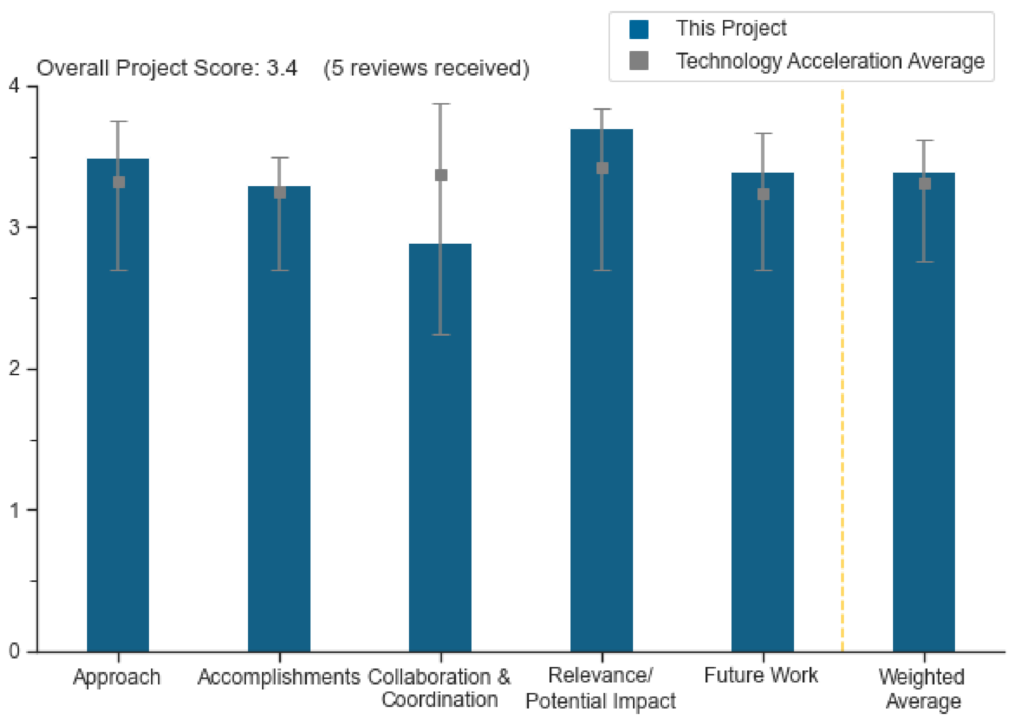
Daniel Leighton, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.9
Start and End Dates	5/6/2020
Partners/Collaborators	N/A
Barriers Addressed	• Demonstration of electrolyzer and stationary fuel cell technology under real-world conditions • Production of hydrogen using directly coupled zero-carbon energy sources • Hydrogen energy storage and grid stabilization for high-penetration renewable electric grid

Project Goal and Brief Summary

This project will design and commission a megawatt-scale electrolyzer, storage system, and fuel cell generator at the National Renewable Energy Laboratory's (NREL's) Flatirons Campus. The system is designed with flexibility to demonstrate systems integration, grid services, energy storage, direct renewable hydrogen production, and innovative end-use applications. If successful, this project will support H2@Scale goals by enabling integrated systems research and development to study the science of scaling for hydrogen energy systems.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Building an Advanced Research on Integrated Energy Systems (ARIES)/Flatirons facility to study both fuel cell and electrolyzers at NREL is highly significant. The project combines hydrogen production, compression, ground storage, and fuel cell application.
- The overall approach to the work is great. If non-technical project-based learnings from the facility buildout and safety analysis can be made available to the public, then that would be very helpful, especially for entities now getting involved in the piloting or build-up of large-scale green hydrogen and associated storage, as well as power systems.
- The approach is very well-defined and shows a clear path to hydrogen-at-scale demonstration.
- Overall, the researchers should highlight what is unique about their microgrid approach in future presentations. Some context of what can be learned with scale that cannot be learned from smaller previous grids would be helpful. It is unclear whether the lessons learned from previous programs scale—and why they would or would not.
- Long lead items ordered by the project appear to have comfortable budget flexibility to take interim steps to address length of infrastructure construction timelines. The 2021 project start date on slide 3 does not align with other dates/timelines presented throughout the slide deck. It is unclear what the NREL contribution is for this project (if any) in addition to U.S. Department of Energy funds that appear to pay for design and hardware.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has shown progress toward milestones and successfully accomplished, or nearly accomplished, all as required when the presentation was submitted. The project clearly identified discrete accomplishments that support the project milestones.
- The project has progressed well, and most major milestones have been met. System design and procurement have gone well.
- The project has been making excellent progress, given supply chain and logistics issues due to COVID-19.
- There appears to be good progress for a project that has been under way for less than a year. It is challenging to compare to projects that have cost-share requirements. The impression is that this is mostly a fully funded, typical construction project in progress (with limited concerns about budget restrictions).
- The rating would have been higher, but the supply chain problem has hampered some of the milestones, which have to be captured somewhere. After the pandemic, this should be excellent.

Question 3: Collaboration and coordination

This project was rated **2.9** for its engagement with and coordination of project partners and interaction with other entities.

- It is great that the project is working with a major industrial partner such as Nel Hydrogen. It would be good if the project could disclose its fuel cell collaborator in future presentations. This energy campus seems like an excellent opportunity for outrage, especially to environmental justice communities. Maybe the project could partner with the local school district for outreach.
- The full extent is to be determined because this project is working toward becoming a research capability for future projects.
- The collaborators are primarily equipment suppliers. These suppliers have been involved with design and development activities, as well as in hazard and operability studies for the planned systems.
- It is recommended that the project collaborate with an industrial gas or energy company with experience in hydrogen production/handling to further accelerate the project. Also, it would be a good opportunity for the industrial partners to get more practical experience in terms of deploying emerging green hydrogen technologies.
- Collaborators other than Nel Hydrogen were not evident.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project addresses a very important problem in the overall green hydrogen space, i.e., integration with upstream electricity production and downstream storage. Megawatt-scale systems are the right size capability to build as well, as it provides relevant technology de-risking data for full-scale deployment (hundreds of megawatts or even gigawatts).
- The potential impact is well-defined, and the relevance of the work is made clear. Building the capability to conduct research on integrated systems will help the deployment of commercial systems and show value.
- This project is very important for showing how hydrogen can work at scale for the grid.
- The project should bring in/line up contracts with interested industry and research partners to execute applicable projects on this equipment.
- This project can be a significant demonstration project for hydrogen production, storage, and application. It is uncertain what electricity source will be used. It would be more meaningful if it were integrated with solar or wind.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- Future work is clearly described, as well as expected dates of completion. All show a path to the culminating commissioning activity.
- The proposed future work seems logical. Some discussion of water arability and the possibility of well water is recommended. Trucking in water seems non-ideal. The caveat about funding should be removed. That is tacit and comes off hesitant. The project should present a bold vison; if missed, at least the project is aiming high.
- A generally good future plan is included. More concrete timelines could be included in the future plan.
- This project could benefit from an assessment to add operational flexibility that allows for hydrogen production for time periods longer than 27 hours. The project should consider looking into a way to be able to “dump” hydrogen either through a virtual pipeline or use of hydrogen (blend) in a large genset tied into the grid. The project should explore how to address the missing permanent tie to the water supply source (instead of trucking in deionized water), such as using NREL campus wastewater.
- Adding industrial players from the utilities, gas, or energy sectors to the team would be great, especially as applications of the capability are being developed.

Project strengths:

- The project works with equipment experts throughout the design and development process. Establishing a fully integrated research location to understand integration, response, total consumables, and optimization of each device, independently and connected to each other, will support deployment of these devices in a commercial setting.
- This project provides an important scaling-up demonstration with real-world equipment and connection to the grid. The project helps enable the H2@Scale vision. Slide 6 shows a graphic with an overview of the equipment, coupled with slides 10 and 11 that show that the graphic has engineering rigor behind it. It would be great to see it in person someday—or at least see the results at future DOE Hydrogen Program Annual Merit Review (AMR).
- A significant demonstration project includes hydrogen production, storage, and application. The project has completed system design and most procurements in less than a year.
- The project overall builds a very important capability on integrated green hydrogen production systems and at a relevant scale.
- Overall equipment capabilities and capacity are strengths.

Project weaknesses:

- There are no weaknesses. The project is doing well so far.

- The biggest weakness of the project is not highlighting its uniqueness or how it builds on past microgrid projects. Slide 13 was not very effective. Maybe there is a better way to communicate the lack commercial off-the-shelf items. The slide reads as an incomplete computer-aided design rendering. A standard human reference model could be added for scale. A secondary weakness is the lack of onsite water. Looking at well water and a water purification unit is a must to make it "real-world." A leech field or sewer is also important.
- The external collaboration is weak. Only Nel Hydrogen is listed as a collaborator. The future plans need to include more details for such a big project.
- There are limitations for longer-term hydrogen production (projects) due to hydrogen storage system size.

Recommendations for additions/deletions to project scope:

- The project should add an option to allow for continuous hydrogen production, either through virtual pipeline partners or use of hydrogen (blend) in a large genset tied into the grid. The project needs to resolve the water supply source issue to replace the practice of trucking in deionized water. A study, a collaboration with the U.S. Environmental Protection Agency Office of Water (or another office with water-related expertise/responsibility), and/or an exercise in ideation can provide more robust insight into how this issue could be resolved in arid or drought-stricken regions around the United States where electrolysis is desired, but water availability is the limiting factor. This could help address a gap in understanding about required resources for hydrogen from electrolysis and therefore add significant value for this project.
- In addition to AMR, a quarterly review meeting with DOE is recommended for a project with such a high budget. It would be great if solar or wind could be integrated in the system so the intermittency of renewable energy could be studied.
- The project should use continuous instead of batch water handling of both feedstock and effluent.
- The end use of the hydrogen was a bit unclear. It is unclear whether it can be sold or used for other downstream applications. It is recommended that the team look into this further and make a concrete plan.
- No additions or deletions are recommended.

Project #TA-049: High-Pressure, High-Flow-Rate Dispenser and Nozzle Assembly for Heavy-Duty Vehicles

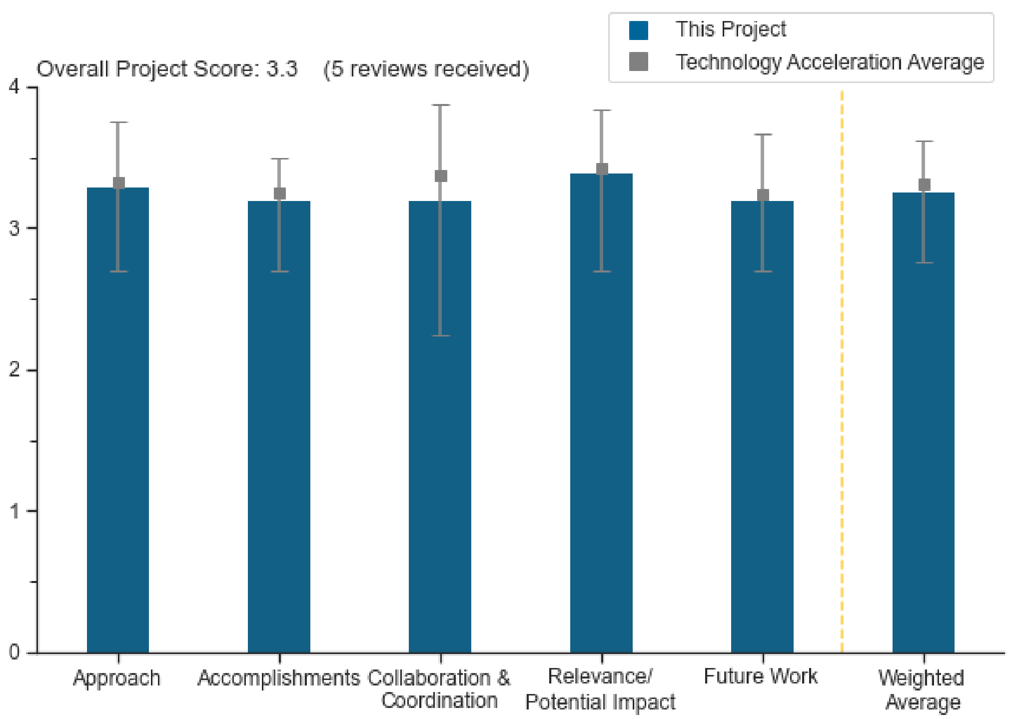
Spencer Quong, Electricore Inc.

DOE Contract #	DE-EE0008817
Start and End Dates	10/1/2019 to 8/31/2022
Partners/Collaborators	WEH Technologies Inc., Bennett Pump Company, Quong & Associates Inc., National Renewable Energy Laboratory
Barriers Addressed	• Need for a robust, domestic manufacturing and component supplier base for hydrogen and fuel cell technologies • Lack of hydrogen refueling infrastructure performance and availability data to revise standards

Project Goal and Brief Summary

This project team will develop, test, and demonstrate a hydrogen fuel dispenser and nozzle assembly (nozzle, receptacle, hose, and breakaway) capable of fueling heavy-duty (HD) vehicles. Based on industry feedback, the assembly's fuel transfer rate will be 100 kg in 10 minutes at a nominal pressure of 70 MPa. If successful, this project will accelerate the development and adoption of sustainable transportation technologies.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- An excellent approach was taken to the high-pressure, high-flow-rate dispenser/nozzle project for HD vehicles for several reasons:

  - The industry stakeholder survey and required specifications are fundamental to providing a working product, and the deliverables are quite logical, including a costly real-world demonstration.
  - The project surveyed 27 companies/organizations, with a good breadth and depth, where important representation is needed both downstream of the nozzle and upstream of the dispenser. However, the limited interest in hydrogen at 50 MPa (500 bar) is questionable, when the largest fleet of fuel cell trucks in the world are using 350 bar, with a few hundred on the road now and about 1,600 planned.
  - There is a clear outline of challenges to high-flow dispenser design and various components.
  - The project has a clear explanation and quantitative results from the dispenser flow analysis, with a detailed pressure drop reported for each component.
  - Barriers were clearly communicated and mapped to project goals, giving confidence that the project will be successful.

  It will be interesting to see what companies commit to using the project's design.
- This project has an excellent approach, starting with the industry (i.e., the customer) survey to establish goals and constraints. Also, it is good to see the inclusion of failure modes and effects analysis and coordination with the Hydrogen Safety Panel.
- There are rational steps toward the development of a robust solution for a HD dispenser and nozzle assembly and inclusion of dispensers in addition to a breakaway, hose(s), and nozzle.
- The project demonstrates a sound approach to accomplishing tasks. The project objectives are clearly identified, and the project addresses barriers in the hydrogen fuel cell HD vehicle sector. It is not clear whether the cost analysis is part of the project; it would be great to better understand the economic impacts of the technology development.
- It would be good to see a piece of work around external interfaces, as this is where the value of this project will or will not be realized. The dispenser by itself is valuable only if it integrates with the storage/compression/thermal management balance of plant (BOP) effectively, which is a controls and data issue, not so much a mechanical or electrical power issue. Also, the flow rates required will need new vehicle interface standards. It is not clear whether there is engagement with pre-normative working groups to ensure this work is influencing those efforts. It would be good to see some emphasis on packaging and constructability. Light-duty (LD) dispensers were difficult to build and costly, with maintenance issues in part because their components were distributed throughout the site (the in-ground heat exchanger, for example). The HD dispenser development should have a clear strategy for implementing the full system on site; an integrated product approach has value for quality and verification in production.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- DOE goals are clearly outlined, and three goals were tightly linked:
  - Accelerate HD high-flow nozzle development where no commercial products are available, as well as enable easy introduction of these to the zero-emission vehicle market.
  - Increase domestic jobs in clean energy and local manufacturing.
  - Expand zero-emission trucks, which will support DOE goals of inclusion, equity, and diversity. Often, pollution from ports and high-density/use transportation networks are at the border of low-income communities.

  When this project is successful and can be moved beyond trucks to rail and maritime, this small element of the supply chain will unlock enormous demand for hydrogen, thereby increasing demand for low- to zero-carbon hydrogen production, which could further increase the demand for variable energy such as wind and solar power. In the coming decade, the grid will have more difficulties integrating these variable renewable energy options; hydrogen storage is the perfect option for storing zero-carbon energy to be used later in zero-emissions transportation.
- The project demonstrates significant progress toward overall project and DOE goals.
- Solid progress has been achieved in the first year of the project.
- Understanding that it is a new project and minimal funding has been expended, there is good progress on solicitation of stakeholder specifications and identification of applicable standards.
- It would be good to see some work on metering strategy.

Question 3: Collaboration and coordination

This project was rated **3.2** for its engagement with and coordination of project partners and interaction with other entities.

- The high-flow-rate dispenser project has done an excellent job of coordinating partners and bringing together key expertise. WEH Technologies Inc. is a world leader in hydrogen nozzles, and Bennett Pump Company is critical for simulation and modeling. The National Renewable Energy Laboratory (NREL) will be critical to testing the nozzle and offering third-party validation. It would be interesting to have tighter collaboration between HD70 tank users and a station builder that would purchase the dispenser. For now, it is fine to incorporate stakeholder community input through surveys.
- The number of entities involved in the survey is an indication of the broad collaboration. This is a strong team of leading project partners.
- The project has great collaboration with industry stakeholders in establishing specifications.
- The project demonstrates close collaboration and good coordination with the project partners Bennett Pump Company and WEH Technologies Inc. However, it would be great to see more feedback from potential cross-sector users such as the maritime or rail industry.
- This project really needs to be plugged into ongoing industry working groups and have a strategy for interfacing the dispenser with different BOP components (via an interface control document). The latter requires engagement with hydrogen refueling station manufacturers.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- It is clear that this project will be a critical path in the pivot of the Hydrogen and Fuel Cell Technologies Office to focus on HD, rail, and maritime applications for large-scale hydrogen in transportation. The project is aligned well with DOE goals to reduce barriers to HD trucks. Meeting project goals and successful commercialization of the nozzle will have a significant impact on fast-tracking the introduction of new medium-duty and HD trucks using high-capacity 70 MPa tanks. The focus on reducing cooling requirements and enabling refueling temperatures higher than -40°C will be especially helpful to the fuel cell trucking industry.
- The project aligns well with DOE Hydrogen Program and DOE research, development, and demonstration (RD&D) objectives, and the project has the potential to enable progress toward DOE RD&D goals and objectives. If successful, this project would have a relevant impact in the HD fuel cell sector.
- This project will definitely address high-flow-rate fueling equipment needs for the HD market by proving out technology that meets the needs of a broad range of stakeholders. However, the extent to which new standards and/or standards revisions will be necessary to drive compatibility and interoperability is unclear. Changes to driving standards are not part of the scope of this project, but an understanding is needed of whether the solution is completely bound by existing standards and what needs to change, and this should be appropriately identified.
- Fast fueling is a must for acceptance and adoption of HD hydrogen fuel cell electric vehicles (FCEVs).
- High-flow 70 MPa dispensers do not exist.

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- The future work and next steps look reasonable. A key go/no-go is planned, though a few barriers have been identified with thermocouples and measured flow rates. A key milestone next year will be successful validation at NREL’s HD station.
- The project’s future work plan is well-established.
- The project demonstrates a satisfactory approach to the proposed future work. It would be good to see the go/no-go decision points in future presentations to better understand project progress and plans. Other issues that can be addressed would be supply chain robustness and manufacturing challenges for technology commercialization, in addition to technology integration with existing stations.

- The presentation should explain whether there are alternative locations for the breakaway device. Considering the difference with the conventional liquid fueling approach (e.g., nozzle spout in the opening, not with the clamping mechanism, but still able to get stuck during driveaway), this may be worth exploring. The breakaway device has a higher weight due to a larger internal diameter (compared to a LD H70 hose assembly) and is H70 and ultra-high flow. Related to breakaway, the team should explore whether the disconnection force (1,000 N) is or needs to be the same as for LD hydrogen fueling (or develop a rationale). The team should include the alternative to the Infrared Data Association (IrDA) protocol, such as the Shell/Bosch wireless option, and how this could improve the design.

Project strengths:

- This project is taking on the challenge of practically resolving the technical barrier to accomplishing HD fast fueling at H70 to make hydrogen FCEVs acceptable to HD fleet operators as an alternative to conventional technology. There are many collaborators.
- There is certainly a need for this development for the fuel cell HD truck industry. The partners are experienced and well-qualified to carry out the project. The project approach is well-planned.
- A major strength of the project is the breadth of stakeholder input and the ability to have key players, such as WEH Technologies Inc., manufacture the first nozzle hardware. The ultimate test will be validation and final demonstration with a full-scale truck refueling to confirm flow rates and potential station economics.
- The project is relevant for HD fuel cell sector development and can have impacts in growing sectors such as trucking, maritime, and rail.
- The topic is on point, with qualified parties participating.

Project weaknesses:

- The extent to which new standards and/or standards revisions will be necessary to drive compatibility and interoperability is unclear. Changes in driving standards do not appear to be part of the scope of this project, but an understanding is needed of whether the solution is completely bound by existing standards and what needs to change, and this should be appropriately identified. The widespread adoption of technological developments will be dependent on interoperability. Also, there was no mention of communication specifications.
- The weaknesses include addressing supply chain robustness and manufacturing challenges for mass commercialization, considering technology compatibility with other hydrogen pressures or cryogenic hydrogen, addressing cost impacts of technology, and challenges with different station integration approaches.
- Building a mechanical design for the dispenser is likely not the highest-risk or most challenging portion of a commercially viable dispenser. External interface standardization and the integration of components into a single package to support quality, testing, manufacturing, and constructability will be commercial roadblocks that need attention as well.
- Possible weaknesses include not having an explicit station customer who will pilot the first hardware and not having a clear high-flow 700 bar tank integrator ready to use the nozzle.
- This is new territory. H70 may not be the ultimate/optimal solution for HD hydrogen fast fueling.

Recommendations for additions/deletions to project scope:

- The project might consider exploring whether there is any need for inclusion of HD nozzle design characteristics that allow for receptacle design that facilitates cryo-compressed hydrogen fueling or other forms of hydrogen (i.e., not only 700 bar gaseous hydrogen).
- The robustness of the nozzle must be higher than that for LD vehicles, considering the higher weight of vehicles that could drive over it. Thus, the project might possibly need to consider abandoning the idea of IrDA altogether for when commercializing the nozzle.
- Additional time could be devoted to nozzle design and scenario planning if the first choice fails at validation. The four options look radically different, and simulation may not capture the optimum nozzle-to-hose configuration options.
- The project should identify necessary standards modifications and communicate those changes with standards committees.

Project #TA-050: Overall Research on Electrode Coating Processes (OREO)

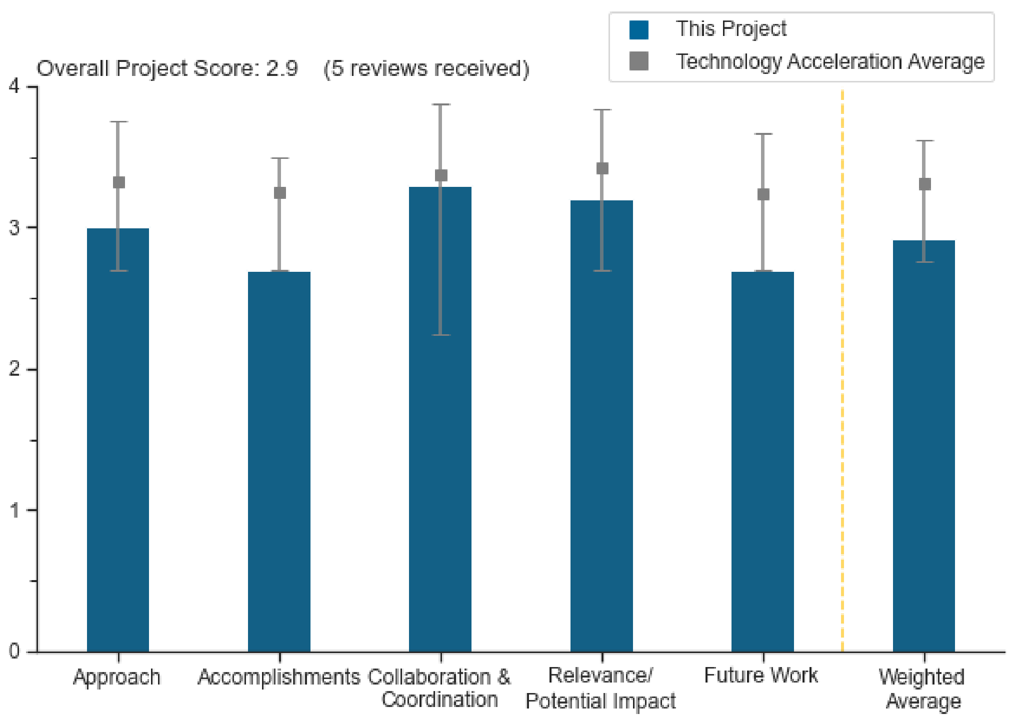
Michael Ulsh, National Renewable Energy Laboratory

DOE Contract #	WBS 10.2.0.502
Start and End Dates	10/1/2019
Partners/Collaborators	Fraunhofer ISE, University of Connecticut, Colorado School of Mines
Barriers Addressed	• Lack of high-volume MEA processes • Low levels of quality control

Project Goal and Brief Summary

Current projections of membrane electrode assembly (MEA) manufacturing costs assume roll-to-roll (R2R) processing technologies that have not actually been proven at scale. This project aims to address the unknowns by bringing together a network of experts in fuel cell and electrochemical ink and electrode fabrication, novel materials, advanced characterization, and in situ device testing. The team will evaluate and compare material and process parameters across a wide range of different processes of interest to the MEA industry. Researchers will use a platform of characterization tools to understand the impacts of materials, inks, and processes on the nano- and micro-scale structure of the electrode and how these structural impacts affect MEA performance.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project is just beginning, but the overall approach looks very promising on addressing critical barriers associated with electrode coatings. Evaluating the cost–benefit analysis of coating type, carbon particle type, and drying conditions on production-style equipment will provide critical feedback to manufacturers, allowing for generalized process improvements.
- This project follows a very systematic approach, from the core fundamentals well below the cell level to one type of industrial-scale manufacturing. Within the scope of work, there are many complex and complicated interactions to characterize and understand for implementing in the identified R2R manufacturing process. From that effort, an attempt will be made to scale what was learned at the laboratory to an industrial scale of production. This is a significant scope of work. The provided materials included no high-level parameter matrices. If one does not exist, this activity would benefit from having a communicable parameter matrix to convey the multitude of parameters to characterize and tests to conduct. This common matrix may help to organize the work across the wide range of formal and informal collaboration partners.
- The approach of various characterizations and testing is good. It is not clear, though, how the data will be used in optimization or in the increased understanding. Linking to modeling efforts and durability and not just performance would be more impactful, but that may be covered in R2R or in other consortia.
- It is not clear whether there is enough data for monolayer. It would be good to see some kind of flow diagram of the different variables being investigated. It is not clear what the budget of the partners is and if that should be included. It is not clear where the materials are coming from in terms of novel catalysts or whether these are commercial or in-development catalysts.
- The reviewer read the Project Goal slide at least five times and still did not fully understand the basis or expected outcomes of the project. R2R manufacturing at scale seems to be the target, but the formal project team consists of national laboratories and universities. It is unclear which companies are running the largest volume today and what issues they have. The project goal is to "Address these unknowns by bringing together a unique network of experts in [fuel cell] and electrode coating (EC) ink/electrode fabrication, novel materials, advanced characterization, and in situ device testing, who have capabilities ... Evaluate and compare material and process parameters ... Access a common and unique platform of characterization tools." It is not clear if there is a specific problem being addressed or if the purpose is to go find a problem to address. This project is building a science-based understanding of how materials and fabrication techniques govern catalyst layer properties. The combination of R2R-relevant manufacturing techniques with physical and chemical characterization and MEA testing represents a strong approach to building necessary understanding of MEA manufacturing processes.

Question 2: Accomplishments and progress

This project was rated **2.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project is just beginning, so the number of data available is relatively limited. The data that are currently available show how the results from this project could be useful for the industry as a whole; for example, the comparison of slot die versus gravure coatings and the comparison between a water- and alcohol-based solution on the surface characteristics will be helpful for any organization looking to improve its coating technology. This project takes a good approach in evaluating the critical parameters necessary to achieve consistent, high-performing coatings.
- Given the pandemic complications and the recent formal additions to the collaborative effort, the project has made reasonable progress characterizing many of the interactions and processes involved in the R2R manufacturing method. Many of these processes remain to be explored at higher production rates and at larger scales.
- There is good progress in looking at different deposition, although most of the work is still very correlative without the understanding that should be seen. Data are being generated but still need some better understanding. The accomplishments do not seem consistent with the budget. There is speculation (e.g., impact of carbon) but not much data and progress, and it is unclear how much is in scope for this project.

Also, there are many words about physics, but no real detail is given, and only qualitative comparisons are shown. It would be helpful to know the cost impact of the overlayer.
- One of the key findings was that gas diffusion electrode (GDE) surface composition is more important than surface morphology in determining performance, with monotonic increases in performance with increasing ionomer content at the interface. This observation seems to indicate that interfacial effects are limiting the performance of the GDEs developed in the project and further suggests that non-interfacial phenomena (e.g., transport and kinetics within the bulk of the GDE) cannot be adequately probed. Approaches are needed that can standardize the interface and thus allow a fair comparison of non-interfacial effects. This could likely be achieved through use of ionomer topcoats on the GDE to standardize the interface. The observations on effects of drying times on catalyst layer properties are potentially valuable and should be expanded to provide a science-based understanding of how drying processes influence the properties of the resulting catalyst layer. The work on effects of catalyst support and Pt weight percent on catalyst layer properties is potentially valuable, though there do not seem to be many results yet.
- It is unclear whether the study of the Mayer rod coating method is appropriate for at-scale manufacturing processes (slide 10). It is unclear why the project runs these tests if they are not relevant (slide 16) to volume manufacturing.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- There appears to be good collaboration between all of the partners associated with this project. The roles of each collaborator are clearly highlighted, and the output from each is evident from the initial project data presented.
- This project capitalizes on both formal and informal relationships and on related projects funded by multiple agencies and organizations. This significantly reduces project risks and increases the probability of producing the desired technical innovations.
- The strong interaction with Fraunhofer ISE, as well as the characterization provided by the Colorado School of Mines and the University of Connecticut, makes for a strong team.
- Industry partners on the core team may have helped to start out with specific manufacturing problems that need to be addressed.
- It is not clear what is being done here and what the overlap is with R2R, Million Mile Fuel Cell Truck (M2FCT), Hydrogen from the Next-generation Electrolyzers of Water (H2NEW), and other related efforts. It is said they are working together, but this should be better delineated. The international collaboration is noteworthy and good. The other collaborations are confusing in terms of whether they are for this project or being leveraged from other projects. Presumably, H2NEW and M2FCT are collaborators—or perhaps this project is duplicative and not aligned with those efforts.

Question 4: Relevance/potential impact

This project was rated **3.2** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project will establish a common framework and provide an elevated point of entry for organizations intending to use the R2R manufacturing process for electrochemical processes. From a "rising tide raises all boats" perspective, it has the potential for impacts on existing or potential MEA vendors by fostering competition, thereby improving the rate of innovation and reducing the production cost of hydrogen.
- This project is building a fundamental understanding of how material properties, ink properties, and deposition methods control resulting properties of catalyst layers. This is highly relevant to the Hydrogen Program, and there is potential to have significant impact on MEA manufacturing.
- The efforts being undertaken in this project are applicable to anyone using an electrode coating process and should have an impact on improving coating uniformity and consistency on any materials moving forward. The limited data from the project so far make it difficult to assess accurately, but the general trends seen so far show the potential for this type of fundamental study.
- This is important technology and science to go after in terms of ink processing, R2R translation, etc.

- The overall theme of addressing manufacturing challenges is highly appropriate. However, there appears to be very little focus on a specific problem and more of an attempt to find something to go fix.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- This project has completed only the early portions of the identified work plan. The future work includes the required in situ testing and scale-up demonstrations necessary to generate the required data to inform the manufacturing process.
- The future work is relatively broad, especially in terms of characterization, and some of it (e.g., in situ testing) seems duplicative of other Hydrogen and Fuel Cell Technologies Office efforts. The focus to look at both EC and fuel cells is good for understanding general trends and similarities, but it is not clear how the GDE work will translate when looking at EC materials. It is unclear whether the catalyst-coated membranes or just GDEs will be investigated. Scale-up to R2R is good.
- The future work is reasonable, but a stronger emphasis is needed on understanding how coating parameters control resulting structure and properties. The future work sounds a bit like a fishing expedition; the team is going to examine multiple deposition techniques and see how the resulting MEAs compare. A more science-driven approach to the future work would be beneficial.
- The proposed future work highlights key areas that need to be addressed moving forward, particularly EC anode catalyst inks and in situ electrochemical testing. There is a general lack of clarity on what process conditions and novel materials will be evaluated in the future work, but the progress so far gives hope that it will be successful.
- It looks like more of the same. A specific focus for this project is not evident.

Project strengths:

- The work so far has done a reasonably good job of exploring the science of how coating techniques control electrode properties. Some interesting initial results have been reported on effects of interfacial composition on performance and drying methods on resulting structure.
- The overall strength of this project is the emphasis on general processing parameters and component impact on processing. The results generated here will give any developer an understanding of how best to create the most uniform, high-performing electrode coatings with the developer's system.
- The primary project strength is the broad range of formal and informal collaborations across multiple organizations, projects, and funding sources. After identifying the critical processes and interactions, the project has started to characterize them and revealed new uncertainties and questions to explore.
- The project is addressing manufacturing scale-up challenges.
- The project is focused on relevant issues of different fabrication techniques.

Project weaknesses:

- It is difficult to assess the weakness in this project, as it is relatively new, and the data collected so far show much promise. The biggest potential weakness that is seen is a limited range of processing parameters available for study, owing to equipment and material availability. Overall, the project looks very promising, however.
- The project is mainly just making MEAs and some correlations. The effort seems very much duplicative of existing consortia, including H2NEW, R2R, and M2FCT, and so perhaps this should be combined with those or be better aligned to focus on specific aspects not covered. There is discussion of bringing in new materials, but it is very unclear how that would happen. It is uncertain how the GDEs and fuel cells will translate to EC materials, as they are very different in terms of materials, coatability, surface tension, etc.
- There is a lack of a specific problem. The stated goal is to address unknowns by bringing together unique experts with certain capabilities. This seems like a very high-level approach to go solve a problem. However, the problem is hypothesized to be cost models having been based on unproven manufacturing processes that might not work. The project basis is weak. It is not clear there is an actual problem to solve.
- Because of the rapidly expanding hydrogen economy, this project will likely encounter intellectual property issues if a particularly advantageous process or configuration develops. The provided materials include no mechanism to address this beyond the "licensing" process.

- The project seems rather exploratory. It lacks a hypothesis-driven approach.

Recommendations for additions/deletions to project scope:

- The scope of the project is clear and well-defined. It may be helpful to include a clear list of what process parameters will be evaluated throughout this project. A list of proposed novel materials and their potential benefits would also be beneficial.
- Recommended additions include the following: the project should get data showing this is a real problem and let those results guide the project, and the project should pull in industrial coating experts who currently perform coatings. Regarding recommended subtractions, the project should stop working on processes that are clearly not in the stated focus of high-volume R2R manufacturing processes. The project should be canceled unless actual manufacturing problems are shown to be addressed (i.e., the project should determine what help W.L. Gore, General Motors, and the Eastman Chemical Company need with process improvements).
- Linking to modeling efforts and underlying physics would be good, as well as focusing on durability and not just performance. The project is missing the understanding, and perhaps the scope should be focused on some key questions to gain more of the structure–function relationships.
- It may be advantageous to periodically purchase industrially produced MEAs to serve as check standards during the in situ characterization testing of the MEAs produced by the project.

Safety, Codes and Standards – 2021

Overview

Introduction

The Safety, Codes and Standards (SCS) activity area is part of the Technology Acceleration portfolio. SCS supports research, development, and demonstration (RD&D) to improve the fundamental understanding of the relevant physics and to provide the critical data and safety information needed to develop and revise technically sound and defensible codes and standards. These codes and standards provide the technical basis to facilitate and enable the safe and consistent deployment and commercialization of hydrogen and fuel cell technologies in multiple applications. SCS activities include identifying and evaluating safety and risk management measures that are used to define requirements and close the knowledge gaps in codes and standards in a timely manner. SCS activities also focus on promoting safety practices among U.S. Department of Energy (DOE) projects and developing information resources and best practices.

In fiscal year (FY) 2020 and 2021, SCS focused on:

- Validating liquid hydrogen release models to help reduce separation distance requirements for liquid hydrogen storage
- Developing sensor use guidance and wide area monitoring capabilities to address improper or inadequate deployment of safety sensors
- Developing low-cost contaminant detection technology to address fuel quality assurance issues
- Analyzing component failure modes and quantified leak size to address component reliability.

Most of these activities are not specific to any particular application but provide information that will enable safe hydrogen use across multiple sectors.

Goals

The overarching goal of the SCS activity area is to enable the safe deployment and use of hydrogen and fuel cell technologies and ensure that key stakeholders have confidence in that safety. This goal is pursued by:

- Facilitating the creation, adoption, and harmonization of regulations, codes, and standards (RCS) for hydrogen and fuel cell technologies
- Conducting research to generate the valid scientific bases needed to define requirements in developing RCS
- Performing RD&D to inform deployment and enable compliance with RCS
- Developing and enabling widespread dissemination of safety-related information resources and lessons learned
- Ensuring that best safety practices are followed in activities sponsored by the Hydrogen Program; to that end, soliciting and reviewing project safety plans and directing project teams to safety-related resources.

Key Milestones

- Identify ways to reduce the siting burdens that prohibit expansion of hydrogen fueling stations by using hydrogen research and development to enable a 40% reduction in station footprint, as compared to the 2016 baseline of 18,000 square feet, by 2022.
- Develop compendium of gaps and priorities requiring harmonization for global codes and standards for hydrogen infrastructure and mobility technologies.
- Initiate at least three new non-automotive-related applied risk assessment and modeling efforts pertaining to large-scale hydrogen deployment applications.

Fiscal Year 2021 Technology Status and Accomplishments

A number of codes and standards, essential to enabling widespread deployment and market entry of hydrogen and fuel cell technologies, have been completed and are now in various stages of the revision cycle. Of particular significance is NFPA 2, the National Fire Protection Association's Hydrogen Technologies Code. NFPA 2 is a critical element of the framework for deploying hydrogen technologies in the United States. Enabling the revision of the separation distances laid out in the code document is a major element of the SCS RD&D portfolio. Significant progress has been made this year on further improvements to the requirements in NFPA 2 for bulk liquid hydrogen storage, including revisions to separation distances based on models and experimental results.

While significant progress has been made in establishing needed RCS and in developing and disseminating safety information, a number of safety-related barriers remain. Near-term barriers to safe deployment include:

- Prohibitive separation distances for liquid hydrogen storage
- Improper or inadequate deployment of safety sensors
- Inconsistent fuel quality assurance
- Lack of component failure data.

Longer-term barriers to both safe deployment and scale-up include:

- Lack of standards for high-throughput fueling for heavy-duty applications, including trucks, marine, and rail
- Incomplete codes and standards for bulk storage of hydrogen
- Unknown regulatory processes for emerging applications, such as those for bulk transport of hydrogen as cargo.

Accomplishments

The SCS activity area continues to perform RD&D to provide the scientific basis for codes and standards development with projects in a wide range of areas, including hydrogen behavior, hazard analysis, materials and components compatibility, and hydrogen sensor technologies. Using the results from these RD&D activities, the subprogram continues to actively participate in discussions with standards development organizations such as the NFPA, the International Code Council, SAE International, the CSA Group, and the International Organization for Standardization (ISO) to promote domestic and international collaboration and harmonization of RCS.[1]

A number of codes and standards relevant to the hydrogen industry were published or revised during FY 2020 and 2021. A database of these codes and standards is maintained on the Hydrogen Safety Panel's H2Tools website.[2]

The H2Tools website provides up-to-date information relevant to the status of SCS activities and enables dissemination of key safety knowledge resources, including several that were updated in FY 2020 and 2021:

- Hydrogen Incident Examples
- Example Hydrogen Safety Plan
- Simplified Safety Planning for Low-Volume Hydrogen and Fuel Cell Projects.

In FY 2020 and 2021, the SCS activity has continued to make progress in the areas of hydrogen behavior, risk assessment, materials compatibility, hydrogen fuel quality assurance, and codes and standards harmonization. Some of the project accomplishments are highlighted below.

[1] The full text of relevant RCS can be found at their respective codes and standards development organization websites: NFPA (https://www.nfpa.org/), International Electrochemical Commission (https://www.iec.ch/), SAE International (https://www.sae.org/), American National Standards Institute (https://www.ansi.org/), and ISO (https://www.iso.org/home.html).

[2] Hydrogen Safety Panel, "H2Tools," accessed September 2021, https://h2tools.org/.

Project-Level Accomplishments

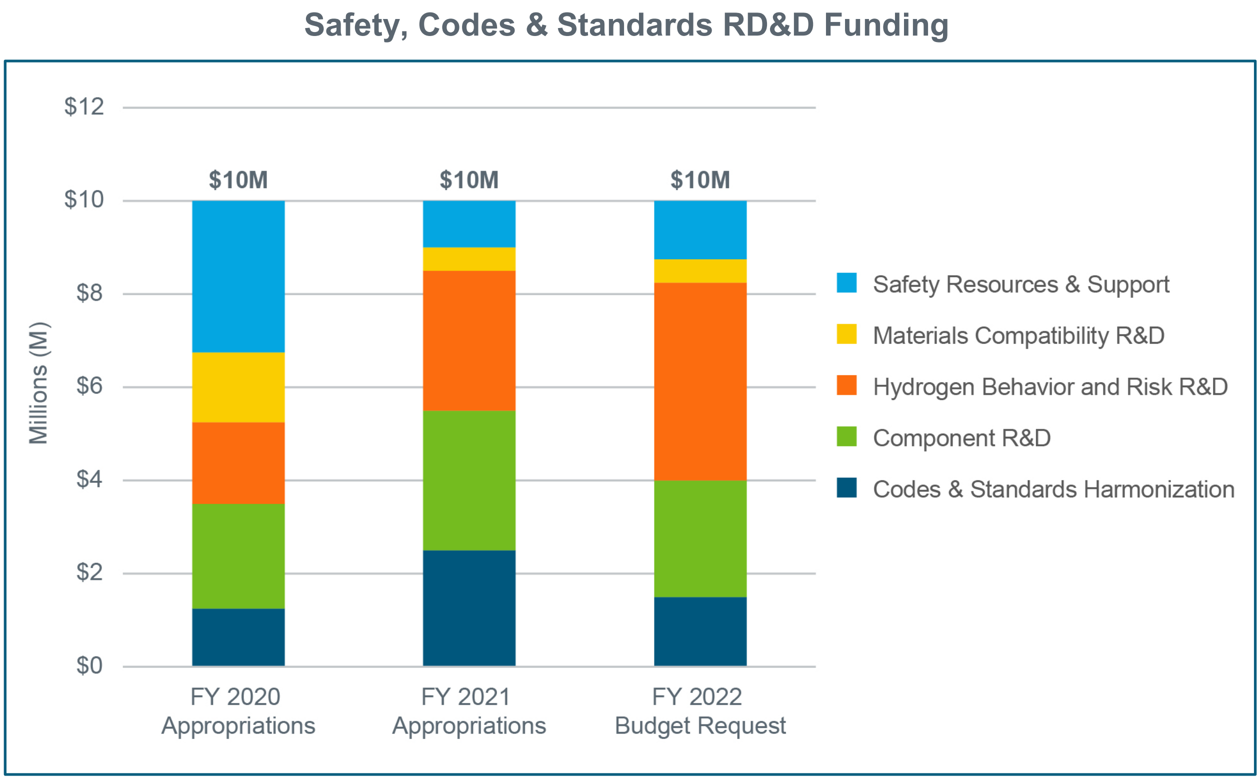
- In field validation of cryogenic hydrogen behavior, confirmed that hydrogen is concurrent with visible plume and demonstrated humidity's minimal effect on hydrogen plume. (Sandia National Laboratories)
- Defined and documented a basic design of a liquid hydrogen onsite storage system, identified failure modes for the liquid hydrogen system during operation using failure mode and effects analysis, and developed event sequence diagrams documenting failure scenarios encompassing both gaseous and liquid hydrogen systems. (National Renewable Energy Laboratory)
- Developed input to the SAE J3219 Technical Information Report, which will establish polymer electrolyte membrane fuel cell (PEMFC) testing and characterization methods of chemicals used in hydrogen refueling stations during operation/maintenance that could have adverse impacts on PEMFC performance. (Los Alamos National Laboratory)
- Created new safety courses leading to updated safety best practices through collaboration with the Center for Hydrogen Safety. (Pacific Northwest National Laboratory)
- Developed ASME Code Case 2938, which enables up to three times longer design life for Type I and II tanks. (Sandia National Laboratories)
- Published a regulatory map identifying federal oversight of hydrogen systems and opportunities for federal coordination. (Sandia National Laboratories)

New Project Selections

- Fuel Cell and Hydrogen Energy Association – Codes and Standards Support (Small Business Innovation Research [SBIR] project)
- NuMat Technologies, Inc. – Point-of-Use Hydrogen Purification and Impurity Reporting Systems that Utilize Metal–Organic Frameworks (SBIR project)
- Electric Power Research Institute – Hydrogen Education for a Decarbonized Economy (H2EDGE)

Budget

The FY 2021 appropriation for the SCS activity totaled $10 million. Funding was balanced between codes and standards harmonization, component RD&D, and hydrogen behavior and risk RD&D, with lower levels of funding for safety resources, safety support, and materials compatibility RD&D. The following figure shows the breakdown. Future work in the SCS activity is expected to focus on applied risk assessment, applied sensor deployment validation, behavior of liquid hydrogen in large-scale pooling scenarios, workforce development, and application-specific safety knowledge resources.



Annual Merit Review of the Safety, Codes and Standards Activity

Summary of Safety, Codes and Standards Activity Reviewer Comments

Hydrogen Program reviewers were highly supportive of the SCS projects and noted that the work of the SCS activity enables accomplishment of the broader goals of DOE and the Hydrogen and Fuel Cell Technologies Office. The SCS activity was applauded for providing information resources for the safe deployment of hydrogen to the community, including the H2Tools website, lessons learned, and gap analysis, as well as the H2Safe regulatory map. Reviewers praised the continued participation of the SCS activity in international engagement activities, especially the International Partnership for a Hydrogen Economy, and encouraged continued efforts in international codes and standards harmonization. Specific suggestions included greater coordination with Canada and an effort to standardize the accounting and reporting of market development progress internationally. Reviewers acknowledged the challenges imposed on international collaborations by intellectual property concerns and identified a need for U.S. industry to increase transparency and participation in international collaborations, including collaborative European fuel cell and hydrogen projects.

Key accomplishments identified include RD&D feedback to enable a significant reduction in the separation distances for liquid hydrogen storage in NFPA 2, incorporation of liquid hydrogen quantitative risk assessment methodology into the Hydrogen Risk Assessment Model (HyRAM), progress on a fuel quality standard, and the expansion of capabilities at the National Renewable Energy Laboratory's Hydrogen Sensor Laboratory. Projects were commended for their flexibility in responding to changing needs. Reviewers recommended expanding the SCS RD&D and codes and standards development efforts to include scenarios beyond transportation applications in support of the H2@Scale initiative, more focus on hydrogen behavior and detection in enclosed environments, and continued support of liquid hydrogen RD&D. Additionally, reviewers highlighted the need for education and outreach targeting state and local governments/policymakers, as well as the importance of training first responders in handling hydrogen fires. Reviewers anticipated an increased number of hydrogen projects in the future, with a corresponding increase in the need for safety reviews and training of unique groups of stakeholders.

During the 2021 Annual Merit Review, eight projects were reviewed, receiving scores ranging from 3.1 to 3.6, with an average score of 3.4. Following this subprogram introduction are individual project reports for each of the projects reviewed. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Project Reviews

Project #SCS-005: Research and Development for Safety, Codes and Standards: Material and Component Compatibility

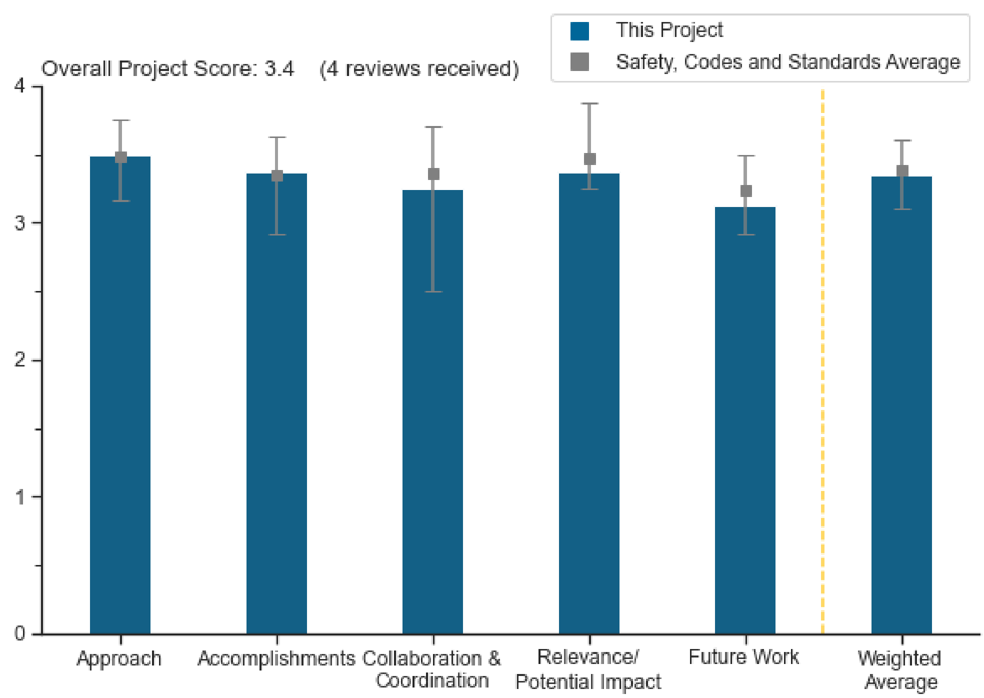
Chris San Marchi, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	Canadian Standards Association, American Society of Mechanical Engineers, SAE International, International Organization of Standardization, FIBA Technologies, Tenaris Dalmine, JSW Group, Swagelok, NASA – White Sands Test Facility, Hexagon Digital Wave, National Institute of Advanced Industrial Science and Technology – Tsukaba, International Institute for Carbon-Neutral Energy Research, Materialprüfungsanstalt Stuttgart, Korea Research Institute of Standards and Science
Barriers Addressed	• Limited access and availability of safety data and information • Lack of consistent regulations, codes, and standards to enable national and international markets • Insufficient technical data to revise standards

Project Goal and Brief Summary

The main goals of this project are to enable technology deployment by providing science-based resources for standards and hydrogen component development and to participate directly in formulating standards. The project will (1) develop and maintain a materials property database and identify materials property data gaps, (2) develop more efficient and reliable materials test methods in standards, (3) develop design and safety qualification standards for components and materials testing standards, and (4) execute materials testing to address targeted data gaps in standards and critical technology development.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project demonstrates a good balance of specific material evaluation, test method streamlining, and codes and standards harmonization for better ease of use by industry worldwide. In addition, the experimental work on tank life extension has significant potential commercial implications for the expansion of hydrogen infrastructure.
- The roles of hosting workshops to identify research and development (R&D) needs, conducting testing to address deficits, and providing the findings in an online database comprise a comprehensive approach. The focus on materials at the subcomponent level is critical, given the typically higher-stress demands made of the functions they perform. Investigation of fatigue crack growth at low pressures serves a variety of industry applications. Finding a methodology to extend the lifetime of Type II tanks would be a cost-saving win for industry.
- This is a balanced approach to cover all three identified barriers.
- The approach taken is valid but limited. Generating test methods on hydrogen compatibility for metal and non-metal materials should ultimately be published with ASTM International (ASTM) and the American Society of Mechanical Engineers (ASME) for stationary applications and SAE International (SAE) for transportation. The Sandia National Laboratories (SNL) website is not making this information readily available to the U.S. taxpayer. The International Organization for Standardization is not a U.S. code development organization or standards development organization (SDO).

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made outstanding progress and accomplishments covering key materials topics for transportation, heating and power, and industrial uses.
- A great deal of progress has been made, keeping in mind that this project has been going on for a long time (a good thing). Going forward, as the project reaches maturity, it would be helpful to see a focus on summarizing and communicating specifically how industry can access and use the results.
- The progress reported on the stated goals is good. However, this reviewer is not positioned to know whether the work reported addresses the most critical needs regarding material compatibility.
- Very few new data were shown in this presentation, and the lack of using ASTM/ASME or unified numbering system (UNS) identifiers makes using the data problematic. Four materials are discussed: American Petroleum Institute (API) 5L-x52 (ASME SA-372), ASME SA-732, XM-19 (UNS 20910), and MP35N. API 5L-x52 (ASME SA-372) is a low-alloy carbon steel used for pipelines. Much of this data collection was generated for ASME by the National Institute of Standards and Technology under the U.S. Department of Commerce. ASME SA-723 is a high-strength, low-alloy steel that has higher ultimate tensile strength (UTS) and yield than API 5L. The grades for SA-372 and SA-732 were not mentioned. XM-19, also known as UNS 20910, is an austenitic stainless steel with high carbon, chromium, and nickel content. The UTS of XM-19 is 100 kilopounds per square inch (ksi) with a yield of 55 ksi. For comparison, ASTM A-213 Type 304 has a UTS of 70 ksi and a yield of 30 ksi. MP35N is a high-alloy material made up of 35% Ni, 35% Co, 20% Cr, and 10% Mo. It is strong; it has a UTS of 260 ksi and a yield of 230 ksi. Research on API 5L-x52 makes sense. It helps answer the question of whether existing compressed natural gas pipelines could be repurposed for CH_4. However, the reasons behind the selection of ASTM F-562 grade MP35N (Aerospace Material Specifications [AMS] 5844 grade MP35N) are unclear. It has very high UTS and yield but is difficult to make and is expensive. Perhaps this selection was to bound the problem. There is also some testing on Type II tanks and a sleight of the hand on how to extend tank life.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The project demonstrates a wide-ranging group of collaborators in industry, government, and SDOs. While achieving a high level of international harmonization in this area is a significant challenge, it is vital to achieving commercial success for the hydrogen industry and as such remains a critical part of the project.
- The project has made outstanding collaborations covering a diverse spectrum of stakeholders, such as standards development and regulatory bodies, industry, and research institutions.
- A previous reviewer comment suggested that more U.S. company participation would be appropriate, and the response suggested that international institutions were better prepared to participate in materials compatibility R&D. Given the practical benefits of this research collaboration, one might conclude that U.S. industry might need to "up their game." If there is an issue, it certainly is not the responsibility of this project team to come up with a solution. Perhaps DOE needs to foster more research to support more industry participation.
- On paper, the collaboration looks good. This task is 18 years old and does not appear to have moved the ball on material compatibility in hydrogen. A report on all the data collected, a rationale for the alloys selected, and oversight by the Codes and Standards Technical Team may help focus the task. It is unclear why SNL is looking at the effects of hydrogen in an atmosphere containing oxygen, a condition that SAE J2719 does not allow.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The work performed is highly relevant and will have an impact by providing a body of research to support materials selection for what will, it is to be hoped, be known as the era of hydrogen use.
- A major element of the relevance of this project is the safety benefit of assuring that there is ready and easily accessible information on materials as more companies with less hydrogen experience join the industry and start offering products.
- The conducted research is critical for the successful commercialization of hydrogen technologies.
- The relevance and potential impact are high, but do not appear focused, as a commercial project might. It is unclear which alloys SNL tested, standardized, and graded; which alloys other labs tested, standardized, and graded; or why these alloys were selected. It is also not clear what this work tells us and where the next step is, whether looking at alloy cost, alloy properties, alloy life, or something else.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The project team proposes focused and needed work, building on the success of the previous accomplishments.
- The proposed activities appear relevant and useful. However, this reviewer does not have a sufficiently broad view of issues to know whether these efforts are the most important ones to pursue.
- It would be good to see a specific focus on the tank life extension work regarding the impact of cycles at less than full pressure and the impact of different types of usage on tank life. There is talk in industry about cycle life testing being too conservative since cylinders are often not fully emptied before being refilled.
- The work to date should be documented. A review other research projects is recommended. The team should look for gaps. The team should also ensure use of the same test methods. In addition, the test methods should be published in venues expected by the engineering public, such as ASTM, ASME, API, and SAE AMS.

Project strengths:

- The approach is comprehensive and includes collaboration, workshops, R&D, and publications/online database offerings. The issues investigated are relevant, and the supporting R&D is solid and well-presented. The effort shows organization and progress.
- The project is filling in gaps in knowledge and standards and providing valuable guidance to industry and SDOs.
- The project has a balanced approach and outstanding progress, accomplishments, and collaborations.
- This could be an interesting project. Some of the test data and test methods have been generated.

Project weaknesses:

- The project should continue to look for ways to communicate material compatibility and safety information to a growing number of companies that may have limited hydrogen experience. There might be an opportunity to collaborate with the Center for Hydrogen Safety, for example, to publish information (maybe through the Hydrogen Tools Portal) in a place where it is easily accessible.
- A clear and detailed approach is needed to document what has been done and what will be done. When supplying data, the project should make it clear what standard(s) and grade(s) define this material. The project should generate a matrix of what has been tested and what needs to be generated. It is unclear how data from other DOE projects fit into the matrix. It is also unclear what the crack growth as a function of the material yield strength is.
- The project should work to increase U.S. industry participation.

Recommendations for additions/deletions to project scope:

- This may be beyond the scope of this project, but a better understanding of the impact of temperatures on material behavior and life would be very valuable, especially as it relates to the materials utilized in the construction of Type IV tanks.
- It is important that DOE continue this work and maintain the capabilities.
- The project should proceed as planned.
- This project needs to resolve its weaknesses.

Project #SCS-007: Fuel Quality Assurance Research and Development and Impurity Testing in Support of Codes and Standards

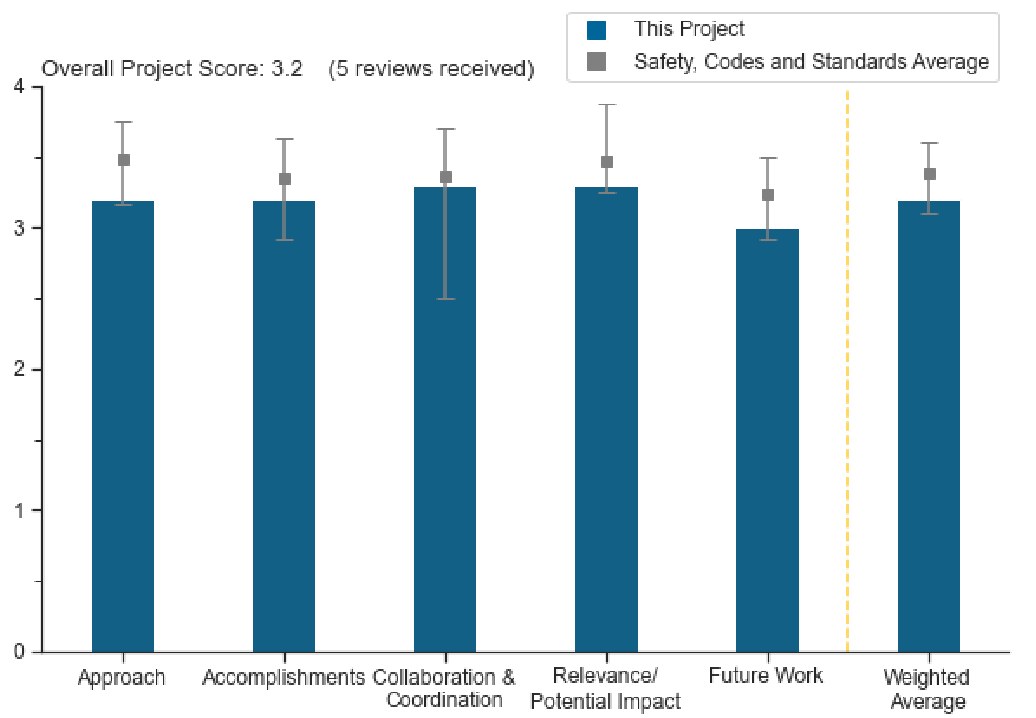
Tommy Rockward, Los Alamos National Laboratory

DOE Contract #	WBS 6.2.0.401
Start and End Dates	10/1/2006
Partners/Collaborators	H2 Frontier Inc., Skyre, Inc., National Renewable Energy Laboratory, VI Control Systems of Los Alamos, Ford Motor Company, Hawaii Natural Energy Institute, University of Connecticut, Japan Automobile Research Institute, SINTEF, VTT Technical Research Centre of Finland, Commissariat à l'Energie Atomique
Barriers Addressed	• Insufficient technical data to revise standards • No consistent codification plan and process for synchronization of code research and development

Project Goal and Brief Summary

The objectives of this project are to (1) focus on polymer electrolyte membrane fuel cell testing and collaborations and work with the American Society for Testing and Materials (ASTM) to develop standards and (2) develop an electrochemical analyzer to measure impurities in the fuel stream. The analyzer will be inexpensive, will be sensitive to the same impurities that would poison a fuel cell stack, and will support quick responses to contaminants.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This work continues to move systematically to an affordable commercial unit while continuing to improve contaminant sensitivity (carbon monoxide [CO], in this case) and temporal response of less than five minutes. This is a very nice approach.
- Offline hydrogen contaminant detection (HCD) deployment, in-line HCD development, and fuel quality work all have clear objectives with the potential to address the barriers noted. The efforts are integrated well with many relevant national and international efforts.
- The approach is systematic and methodical. First, off-line HCD was deployed, and in-line HCD development efforts continued. Working with SAE International (SAE) and the International Organization for Standardization (ISO) on hydrogen quality is also good.
- The approach is direct and appropriate. Many of the goals mentioned are dated. It is surprising to see work on cleansers included. Data were generated on this topic by the University of Connecticut (UConn) for the U.S. Department of Energy (DOE) and SAE. The data indicated that improper rinsing by eight commercial cleansers quickly degraded the performance of the test cell. In retrospect, some degradation is to be expected, as cleansers are, by definition, surfactants. However, the immediate and radical decay at concentrations of 2%–5% was a surprise. Skyre, Inc., may still have a spreadsheet, generated previously for DOE, on likely heat transfer fluids. Note that NH_3 and diols have been tested and were found not to be compatible.
- Los Alamos National Laboratory's (LANL's) fuel quality activity has been continuing for many years and is not currently aligned with the direction of the broader hydrogen community. The fuel quality detector has seen nice progress, but there is definitely a need to transition this to a commercial entity. DOE's Technology Commercialization Fund (TCF) is one pathway, but it is not clear what will happen once the TCF support ends.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- It was surprising to learn that this current version was tested on the output of the reformer in relation to the input of the storage system, focusing on CO detection. Previous work from this project tested a suite of contaminants that would be more appropriately located at maybe the breakaway point, which might be an appropriate place to sample for cleaning solvents and other possible contaminants. When asked about this, the presenter answered that the focus on CO detection and the reasoning for the location selected were based on testing site needs. Responding to the site needs is particularly good, and clearly the unit preformed. Sensitivity was at levels as low as 200 parts per billion (ppb) CO. Improved electrode design to enhance response time and CO sensitivity is anticipated. This project continues to stay on track and make good progress on the path to successful development of HCD.
- All three efforts have shown good progress, with solutions to improve shortcomings implemented to improve techniques that can be used worldwide. Results show promise to provide better contaminant detection at reduced cost.
- The project is meeting, or is on track to meet, all the milestones for 2021, and planned future activities are reasonable and appropriate based on current efforts.
- The work on fuel contamination detection is progressing. Off-line analysis has progressed well—in-line analysis, not so well. The sensors need to be hydrated. The hydration is a contaminant. Perhaps the team could try installing a desiccant cylinder downstream of the sensor. The progress on a fuel quality standard has been excellent. The fuel standards are harmonized and published by SAE (J 2719) and ISO (14687). This was a major accomplishment. Perhaps Mike Steele's work with SAE should have been mentioned.
- LANL has made nice progress on the fuel quality detector in reducing overall costs and packaging requirements. The ability to partner with a station operator has been critical to the project's success. While

cleaners are important to understand with regard to the impact on fuel cell operation, it was not clear what accomplishments or progress have been made in the area of fuel quality testing.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- LANL has developed an excellent set of international and national collaborators, such as the Japan Automobile Research Institute (JARI), ISO (14687), European Union (EU), SAE, Ford Motor Company (Ford), UConn, and Hawai'i Natural Energy Institute (HNEI). It is notable that JARI invited this LANL group to join a LANL/EU/JARI collaboration team. This is excellent.
- Coordination activities with SAE, Ford, UConn, and HNEI on the development of SAE J2319, as well as working with JARI, LANL, and ISO on hydrogen quality, constitute a great approach.
- The fuel quality detector effort involves strong collaboration and coordination with industrial suppliers and end users (e.g., station operators). The coordination was made stronger through the TCF opportunity. The fuel quality testing activity showed international coordination with JARI, the Vehicle Technical Team, SINTEF, and Commissariat à l'Energie Atomique (the French Alternative Energies and Atomic Energy Commission), but it was not clear what the extent of the coordination was or what is being planned to support the cleanser testing. There is good coordination with Ford and the National Renewable Energy Laboratory (via SAE).
- National and international partners are appropriate to the tasks, and the partnerships are likely to result in meaningful technology transfer to industry. One important collaboration that seems to be missing is one with ASTM International Committee D03 on Gaseous Fuels. The committee is actively working on test methods for hydrogen monitoring and is holding a workshop on in-line hydrogen fuel analyzers on December 8, 2021, in Anaheim, California. Collaboration with ASTM Committee D03 could significantly enhance the potential of this project to achieve its objectives.
- The selection of collaborators is incomplete. The impurities testing included Clemson University, UConn, HNEI, JARI, and the University of South Carolina. All cooperated with each other to generate repeatable and reproduceable results.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The need for in-line HCD is clearly an important issue. It goes straight to the need to ensure the vehicle's fuel cell is supplied with hydrogen that passes tolerance specifications (ISO 14687). Participation in ISO and SAE efforts on fuel quality helps to ensure humanization and early attention to proposed new fuel quality tolerances. This activity should be instrumental in these national (SAE) and international (ISO) efforts. This is very good.
- This project has the potential to make significant contributions to technologies and methodologies to ensure hydrogen fuel quality at a reasonable cost.
- Improving the quality of hydrogen will extend the life and performance of equipment and vehicles using hydrogen as a fuel source.
- The fuel standard is a home run. Without a standard, fuel cell electric vehicles are a non-starter. Off-line and in-line sensors are a nice idea, but there are workarounds.
- As the fuel quality detector activity wraps up, it will be important to evaluate the role of fuel quality in the larger H2@Scale activities (beyond automotive applications).

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The proposed work for both the HCD and the fuel quality work (J3219 and ISO 14687) is very appropriate. It would be good to see this project aim to develop a system that would sample the fuel in the fuel line just upstream of the fueling nozzle, e.g., at the breakaway point. Participating in the development of SAE J3219 will be very helpful in understanding what is needed.

- Future work is well-thought-out and a natural outgrowth of current efforts.
- Future work plans are what was expected: improving systems, conducting extensive field testing in real-world hydrogen stations, and ensuring technology transfer to partners to commercialize the technologies. A direct link between this project and ASTM Committee D03 would be a welcome addition.
- Qualification of the sensors and monitoring of the fuel quality standards as the code cycles progress is needed and proposed.
- The proposed future work seemed vague.

Project strengths:

- Overall, this project is focused, is making excellent progress, and has established very relevant and strong international collaborations.
- The fuel quality detector team, who also supported past sensor development activities, has done a tremendous job reducing cost and packaging while improving operation. Finding and adding an end user early in the detector development was critical to this activity's success.
- This project is well-integrated, with many complementary activities, and is poised to lead to important technology solutions for monitoring hydrogen quality in real-world applications.
- The project is planned well, and the goals are aligned well with the overall goals of the Hydrogen and Fuel Cell Technologies Office.
- An academic network cooperated to make these projects a success. An effort should be made to keep that team together.

Project weaknesses:

- Technically, it looks great, but it would be good to see collaboration with ASTM Committee D03, as well as more written publications about the work at some point.
- It would be good to include in-line detection of contaminants--which might be introduced from maintenance—just upstream of the nozzle.
- The overall direction of the fuel quality testing is unclear.

Recommendations for additions/deletions to project scope:

- It would be good to include in-line detection of contaminants—which might be introduced from maintenance—just upstream of the nozzle. The project should keep up the excellent work.
- A direct link between this project and ASTM Committee D03 would be a welcome addition.

Project #SCS-010: Research and Development for Safety, Codes and Standards: Hydrogen Behavior

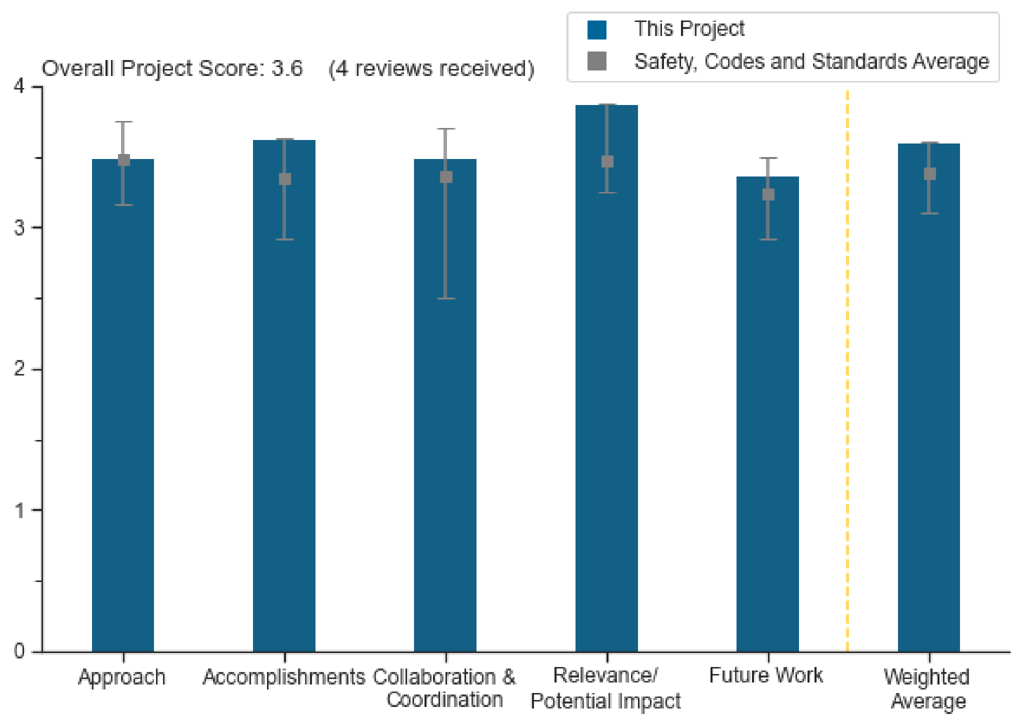
Ethan Hecht, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	Air Liquide (via H2@Scale CRADA), Lawrence Livermore National Laboratory, National Renewable Energy Laboratory, Compressed Gas Association 5.5 testing task force, Fuel Cells and Hydrogen Joint Undertaking, National Fire Protection Association 2, Massachusetts Institute of Technology, BKi (via previous CRADA which included CaFCP Auto OEM Group, Linde, Shell)
Barriers Addressed	• Limited access and availability of safety data and information • Insufficient technical data to revise standards

Project Goal and Brief Summary

The project's purpose is to perform research and development to provide the science and engineering basis for the release, ignition, and combustion behavior of hydrogen across its range of uses (including high-pressure and cryogenic applications). The research includes model and tool development to facilitate the assessment of the safety (i.e., risk) of hydrogen systems and enable use of that information for revision of regulations, codes, and standards (RCS) and for permitting hydrogen installations. Sandia National Laboratories (SNL) is working to address the lack of safety data and technical information relevant to the development of safety, codes and standards (SCS) by (1) providing a science and engineering basis for understanding the release, ignition, and combustion behavior of hydrogen across its range of use (i.e., high-pressure and cryogenic applications), (2) generating data to address targeted gaps in the understanding of hydrogen behavior physics (and modeling), and (3) developing and validating scientific models to facilitate quantitative risk assessment of hydrogen systems and enable revision of RCS to accelerate permitting of hydrogen installations. The project began in 2003.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The experimental results for cryogenic release have long been needed, and within the scope laid out, the work is excellent. The presentation could benefit from an upfront explanation to delineate the vapor plume hazard from cryogenic spills and other considerable hazards (which were discussed later in the presentation) that may arise from unplanned release of cryogenic hydrogen. This, of course, is difficult to achieve with a 20-minute presentation format. However, within the broader context of SCS needs on hydrogen cryogenic hazards, it may be premature to advertise a footprint reduction on the basis of this one hazard mode. The project should consider that a reviewer from a previous year wanted investigation of walls. A hydrogen–air mixture confinement by two walls and ground can lead to overpressure if combustion occurs. This may or may not be acceptable based upon the design, but it illustrates the interactions that can alter decisions. It is understood that a key goal is to provide risk assessment information to address hazards for hydrogen dispensing stations and the like. However, this work also supports the National Fire Protection Association’s (NFPA’s) Hydrogen Technologies Code (NFPA 2) and ultimately will address general hydrogen applications. Hydrogen system designs that can address hazards in one configuration may, if changed (sometimes in ways that seem inconsequential to those making the change), result in very different hazards. The best practice for this Jekyll-and-Hyde possibility is that any changes must be carefully reviewed by experts. There are multiple hazards possible from release of cryogenic hydrogen, so it is important to state basic assumptions regarding both the scenario for release and for hydrogen behavior. The response provided by the presenter on this topic is that, for the leak size modeled (1%), there would be no spill accumulation (any liquid hydrogen [LH2] flashes), and the exiting hydrogen would be mostly cold vapor. More explanation might have been beneficial. From the vantage point of the rollout of hydrogen infrastructure, the 1% value seems to be a good assumption for the scenario addressed (conventional storage or dispensing station). Should a serious and rapid rollout of hydrogen infrastructure take place to address the climate crisis, there will undoubtedly be a shortage of expertise to address critical modifications of facilities that invalidate such basic assumptions. It is hoped that the notable hydrogen cryogenic hazards would be identified and context and logic for how to consider the various hazards would be provided. Later in this presentation, future work was discussed, and other behaviors that can arise from cryogenic spills were noted as part of the experimental agenda for subsequent study.
- The project has a well-defined approach and has shown significant improvement this past year with regard to making progress against the objectives. It is well-organized and -managed.
- The project has a very well-coordinated approach that includes key activities of the SCS subprogram.
- The work being performed in this project is critical to shepherding in a transformation of hydrogen infrastructure. While many of the needs for improving the modeling (i.e., more experiments to validate the models) are identified, the timeline for developing subsequent rationale to be proposed for NFPA 2 improvements is not clearly defined (see slide 17, “Out Years”). Some proposals for NFPA 2 language changes are being published this year, which is good. This element does not earn the 4.0 rating because overcoming the identified barriers is not “sharply focused.”

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- A significant number of accomplishments were made within this year:
    - Calculating hazards for 1% flow area leaks from an LH2 system
    - Analyzing hazards to develop separation distances for different exposure groups
    - Developing science-based LH2 exposure distance tables for NFPA 2
    - Performing a series of outdoor cryogenic hydrogen release experiments that included Raman spectroscopy to identify hydrogen versus condensation behavior.

- Significant progress was made this year regarding models and calculations to provide LH2 separation material for NFPA 2's evaluation, as well as being responsive to NFPA's input.
- The project has excellent accomplishments and progress to achieve a reduction in hazard distances.
- The work presented is excellent. The rating selection of "good" reflects that other topics (spills, etc.) critically need to be addressed and that results have been needed for some time (see comments from prior reviewers). This comment is directed at the Hydrogen and Fuel Cell Technologies Office (HFTO), rather than this project.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The project has outstanding international collaborations, including European Union and North American partners.
- This effort benefits greatly from the cooperative research and development agreements (CRADAs), and the companies partnering in these CRADAs have clear potential benefits from this work. This presentation identifies good collaboration between the partners. There is nothing necessarily highlighting how the partners are full participants and are well-coordinated (with the exception of Lawrence Livermore National Laboratory).
- There are numerous collaborative partners, with a good cross-section of partners that are directly relevant to the work. However, it is not clear that any of the partners have the capability and/or provide meaningful feedback on the technical merits of the work. Given the complexity, this feedback would be helpful for the project and provide confidence in the results.
- The institutions listed appear more advisory in nature, with the exception of Shell, who has performed related work with the United Kingdom's Health and Safety Laboratory (HSL). The presentation did not make clear what sort of collaborations were in place. The facility requirements to support LH2 release experimentation are considerable, and there are only a few institutions capable (BAM [the German Federal Institute for Materials Research and Testing], in the past, and SNL at present).

Question 4: Relevance/potential impact

This project was rated **3.9** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The work being performed in this project is critical to shepherding in a transformation of hydrogen infrastructure. Market transformation (replacing gasoline stations with hydrogen stations) is difficult now because of existing separation distances for gaseous and liquid hydrogen. This work has the potential to reduce those distances, demonstrate smaller hazard areas, and pave the way for implementation of more hydrogen stations in congested areas.
- This work has a direct impact on the ability to safely and economically deploy hydrogen infrastructure, which is critical to DOE's goals. Separation distances have been based on tribal knowledge over years of experience and have worked well. However, applying a scientific process with modern techniques and analyses is critical to understanding where those distances might be conservative and where they might not meet acceptable risk.
- This project's goals do match the DOE Hydrogen Program goals. There is no question of relevance. For over a decade, SCS groups have needed the results on upgraded code criteria to address LH2 handling hazards.
- The project provides critical research to facilitate deployment of LH2-based infrastructure for hydrogen energy.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The proposed future work (fiscal year 2022 and out years) identifies clearly laid-out initiatives for the test needs. These are large, difficult, expensive tests and may require increasing the number of future partners/CRADAs with significant funding to make progress on these efforts.
- The presentation has a well-defined scope for future work for short-, medium- and long-term durations. The project is well-done. The work is consistent with the overall direction of the project.
- The project plan has been thought through well.
- The description for future work is too generalized to enable comments. Greater detail is needed with regard to experimentation that might be pursued. There are several phenomena or situations that occur with LH2 that are known to cause severe hazards. Past experimental efforts were limited by the technology of the times, and the fidelity of the measurements does not support modern modeling. Given the focus on primary infrastructure (vehicles, fuel dispensing, and logistics of fuel distribution), it seems hazards deemed not associated with this infrastructure may not receive adequate attention. NFPA 2 code addresses more than just the vehicles and associated infrastructure. It would be helpful if a more in-depth description of future experimental planning were available for comment. An additional question involves initiatives to use high-pressure LH2. It would be good to know whether systems for 10,000 psi LH2 present an increased hazard and whether the hazards of such systems will be considered.

Project strengths:

- The work produced in this effort directly supports DOE's research, development, and demonstration goals by providing commercial companies the necessary safety information to install hydrogen stations and equipment in places previously off limits, thus making hydrogen more available where it is needed.
- The work of this project has had a significant beneficial impact on the codes and standards process, particularly for NFPA separation distance work through the generation and validation of the release models.
- The project brings together DOE and SNL research capabilities, national and international collaboration on codes and standards development, and technical challenges and peer review. The research has taken longer than desired but step-by-step is successfully meeting technical challenges. This work is not easily performed.
- The project has excellent balance of relevance, approach, and accomplishments.

Project weaknesses:

- The inputs used to date are based on gaseous hydrogen leak size and frequency. It is not clear if this is a good basis, and leaks are likely not due to the cryogenic nature of LH2, which results in thermal cycling of pipes. More input is needed prior to this work being finalized. The basis for this work, particularly for the separation distances, does not include the results of overpressure that can be caused by large-size releases that are significantly above the 1% leak size basis. While rare, these do occur, and it is not conservative to ignore the potential consequences in discussions with codes and standards organizations.
- There is still a good deal of model validation and testing to be performed, and the timelines and cost for this work are not well-defined or -identified.
- The codes and standards bodies would benefit from more results sooner. Presentation of more future planning would be beneficial.

Recommendations for additions/deletions to project scope:

- A laundry list of general research topics could include:
  - Pool formation, evaporation, and engineering information for confining pool spread and means to control or increase the rate of evaporation

  - Condensation of air and formation of oxygen enriched in LH2 pools, shock sensitivity, and risk (industry representatives claim this is not a hazard, but the project should consider HSL's surprise occurrence)
  - Vapor cloud formation from cryogenic releases, formation of condensed air within such releases, combustion yields, overpressure, and acoustic hazards
  - Barrier/wall design to loft vapors into a safer region for dissipation and to mitigate overpressure should ignition occur.
- Adding a notional timeline and a rough-order-of-magnitude cost for the remaining tests is recommended. The end state (when testing and model validation would be completed) should also be identified for this effort. Prioritizing how these topics should be pursued requires more consideration.
- The project should include work to predict and calculate the impact of explosions based on releases with delayed ignition, as well as jet explosions from large releases. These have occurred at several recent incidents, and the effect on surrounding equipment, buildings, and people has been significant.

Project #SCS-011: Hydrogen Quantitative Risk Assessment

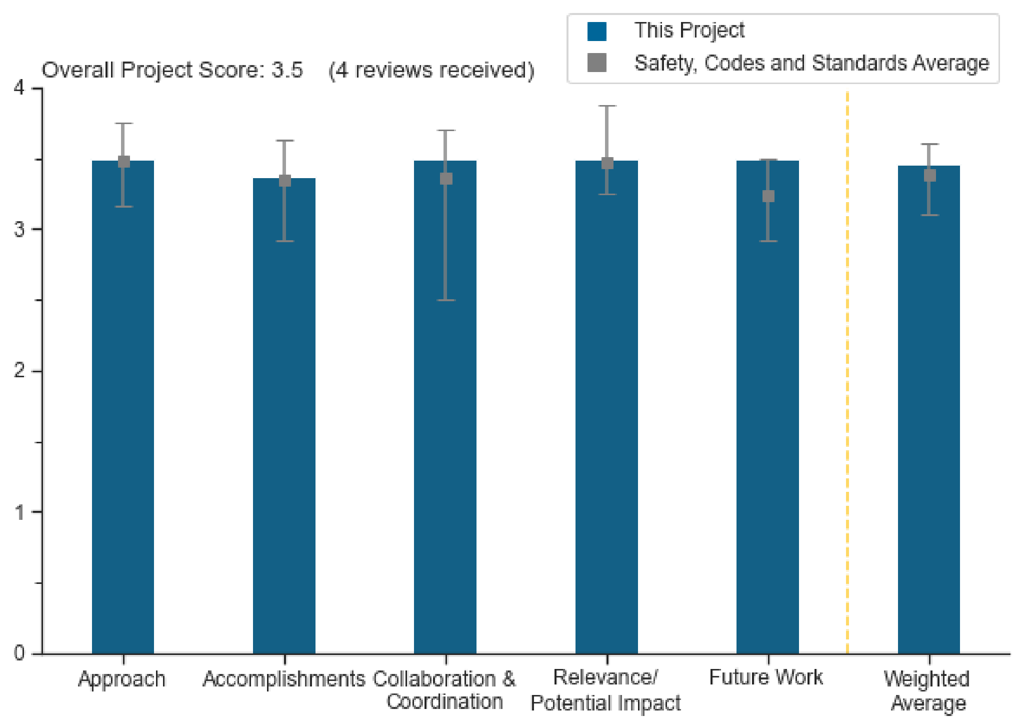
Brian Ehrhart, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	FirstElement Fuel, Air Liquide, Quong & Associates, Pacific Northwest National Laboratory, National Renewable Energy Laboratory, Argonne National Laboratory, Network of Excellence for Hydrogen Safety (HySafe), organizations using the Hydrogen Risk Assessment Model (HyRAM), National Fire Protection Agency 2/55, U.S. Department of Transportation Federal Highway Administration, California Fuel Cell Partnership, International Partnership for the Hydrogen Economy, International Electrotechnical Commission
Barriers Addressed	• Limited access and availability of safety data and information • Lack of consistent regulations, codes, and standards to enable national and international markets • No consistent codification plan or process for synchronization of code research and development • Usage and access restrictions – parking structures, tunnels, and other usage areas

Project Goal and Brief Summary

The primary objective of this project is to provide a science and engineering basis for assessing the safety of hydrogen systems and facilitate the use of that information for revising regulations, codes, and standards (RCS) and permitting stations. Sandia National Laboratories will develop and validate hydrogen behavior physics models to address targeted gaps in knowledge, build tools to enable industry-led codes and standards (C&S) revision and safety analyses, and develop hydrogen-specific quantitative risk assessment (QRA) tools and methods to support RCS decisions and to enable a performance-based design code compliance option.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project supports interaction between research and development (R&D) of hydrogen behavior; development of QRA methodology; application of the results to real-world issues; and RCS development. This approach coordinates needed R&D results with expert collaboration and promotes outreach. The advancement of liquid hydrogen (LH2) QRA methodology has been needed for some time, and its incorporation into the Hydrogen Risk Assessment Model (HyRAM) is an excellent way to promote outreach. The following efforts all support the advancement of a national hydrogen infrastructure: work supporting RCS development for fuel cell cars in tunnels and for rail applications, study of hydrogen and methane (CH_4) blend hazards, and investigation of the interconnection of federal regulation of H2@Scale activities. Pursuit of these activities also supports U.S. Department of Energy goals.
- The project is organized well and has a clear set of objectives. This is demonstrated by the effective and thorough presentation. For example, the tables showing milestones and the collaboration and coordination were succinct, easy to understand, and presented well.
- Developing HyRAM for assessing risks associated with the use of hydrogen is a methodical and systematic approach. The coordination with the Federal Highway Administration (FHWA) to permit fuel cell vehicles to drive in tunnels is a well-thought-out effort. The regulatory map is a very helpful tool.
- The project has a very good approach, including behavior and risk R&D and application of R&D results and insights to RCS.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has excellent accomplishments in regard to LH2.
- Based on the presentation and expected results for the balance of the year, the project looks on track to meet its objectives with significant and consistent progress.
- All 2021 milestones are either met or on track.
- Hazards due to an LH2 release event are governed by specific aspects of the release (e.g., quantity) and factors in the release environment (types of confinement, proximity of ignition mechanisms, weather, etc.). These factors define a scenario, and there are interactions between the factors. A large release gives pool formation; a slow, persistent release can lead to LH2 mixing with condensed air products; etc. Confining surfaces can promote formation of more sensitive mixtures and increase the chance for ignition. The point is, there is complexity in the interaction of various factors in the environment of a release scenario. The hazard evolves from the various factors. The work presented is excellent but seems to address a simplified scenario in which a small leak flashes completely to vapor, and the justification for this focus is that it is a most likely outcome, especially for existing infrastructure (storage fuel dispensing stations, etc.). The concern is that real-world facilities may have features that do not fit the assumptions applied here. The informed outreach must include some guidance on possible complexity. The presentation venue allows precious little time for any explanation of background or context. There is some overlap with the subject material of this note, and that is expressed in a comment by a 2019 reviewer (the third one noted on slide 14). Following from this note, the addition of simulation capability for cryo-plumes (in HyRAM 3), the development of rationale for estimation of LH2 separation distances from liquefied natural gas data, and incorporation of unconfined overpressure models into HyRAM are all good "bricks in the wall." However, care must be taken in how they are used to support RCS.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The list of organizations with which this project is collaborating is impressive, and they appear to be in a position to provide meaningful feedback.

- The project has outstanding collaborations, including industry, code committees, and national laboratories.
- The coordination with FHWA, Federal Railroad Administration, National Fire Protection Agency (NFPA), Caltrans, and industry is good.
- Collaboration partners for LH2 characterization are strong; however, there does not seem to be sufficient participation from the industries involved (only Air Liquide—not counting FirstElement Fuel, DB Engineering & Consulting, and Frontier Energy), especially the rail carriers.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- There is no question about the relevance of this work. The goal is to inform C&S development for hazards and provide the means for their evaluation. Accidents will occur in the future, but this work provides a resource that will help minimize the consequences and frequency of such accidents and provide the understanding necessary to correct errors. It is assumed that this project will continue and, in the end, provide a comprehensive picture of hydrogen hazards and the information to support successful system designs and safe operation.
- This work is very important to evaluating the safe use of hydrogen, which is critical to meeting DOE goals. Authorities having jurisdiction and code organizations will need the confidence that can be provided by this work to make progress on regulatory approvals and on improving C&S. Separation distances have been based on tribal knowledge over the years and have worked well. However, applying a scientific process with modern techniques and analyses is critical to understanding where these distances might be conservative and where acceptable risk may not be met.
- The tools developed under this program (HyRAM) will help promulgate hydrogen technologies and infrastructure.
- The project has excellent alignment with DOE objectives and addresses identified barriers.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- There is an excellent work plan that addresses commercialization needs.
- The future work is a logical outgrowth of current activities.
- The proposed work is consistent with the goals of the project. The future work list and timeline provided for that list provide clarity for the work scope of the project. It would be good to seek a third-party review to provide validation to the process. These calculations are complex and may not be fully understood by most who review them, so an independent report would provide additional confidence that this important work is consistent with industry-wide risk analysis.
- The description of remaining challenges and barriers is reasonable. Fiscal year (FY) 2021 work goals are fine. FY 2022 work proposes goals for modeling LH2 pool behaviors. It is unclear what experimental data will be used to support the modeling. Past experimental efforts (for example, NASA's White Sands Test Facility, 1980) have been noted as inadequate in providing corroborating data for modern models. This work is typically difficult to perform. Proposed work includes the estimation of better values, but with uncertainty regarding ignition probabilities for risk assessment, it is not clear how this work will be performed.

Project strengths:

- This is a well-managed project. Good detail of future objectives is provided, and these objectives seem well-aligned with industry needs. The progress on each, along with a timeline, is described well. The work is directly relevant to the needs of C&S organizations that are actively writing and improving the code, particularly for separation distances.
- The project continues to create important findings, foster collaboration, and support outreach, especially through HyRAM.

- The project has a groundbreaking approach to the use of engineering tools for safety and risk assessment.
- This project is designed well and allows for the safe deployment of hydrogen technology.

Project weaknesses:

- The inputs used to date are based on gaseous hydrogen leak size and frequency. Development of leak frequencies and sizes for LH2 has been a consistent gap. The cryogenic nature of LH2 results in thermal cycling of pipe and fittings, which is likely to increase both frequency and size. This is understood to be a challenging area to get feedback from industry. The project could provide a better understanding of the approach and data being used. The basis for this work, particularly for the separation distances, does not include the results of overpressure that can be caused by large releases that are significantly above the 1% leak size basis. While rare, these do occur, and it is not conservative to ignore the potential consequences in discussions with C&S organizations.
- The ultimate purpose of NFPA's Hydrogen Technology Code (NFPA 2) is to support general hydrogen applications. The C&S application seems primarily directed toward hydrogen infrastructure around transportation applications, which, understandably, is a priority. This approach will lead to C&S information gaps for applications with scenarios that are different from the hydrogen infrastructure ones. Additionally, the 2019 reviewer comments still apply. Many users proceed with a "worst-case" approach to hazard analysis that does not use the QRA approach. More commentary on assumptions applied to achieve C&S values is needed, especially where risk analysis results are based upon the high likelihood for 1% release orifice size. Discussion is needed on how the QRA approach can be applied to the more traditional analysis techniques.
- More effort is needed on hydrogen equipment enclosures.

Recommendations for additions/deletions to project scope:

- Work on unconfined releases of hydrogen is very important. A greater emphasis on work to predict and calculate the impact of explosions based on releases with delayed ignition, as well as jet explosions from large releases, would be helpful in fully evaluating the safety and risk at a given site. Explosions have occurred at several recent incidents, and the effects on surrounding equipment, buildings, and people have been significant.
- Some articulation is needed for arguments that suggest application of the QRA approach over the simpler "worst-case" approach to hazard assessment. A "menu" of potential hazards and related scenarios could be presented to users, along with the rationale to select which hazards fit a particular scenario. The project should note interrelationships with charts or tables. The project should ensure that guidance provided within HyRAM gives the background and assumptions necessary for users to apply to scenarios with inherent complexity associated with potential hazards.
- The project should test thermal and pressure effects in confined spaces.

Project #SCS-019: Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources

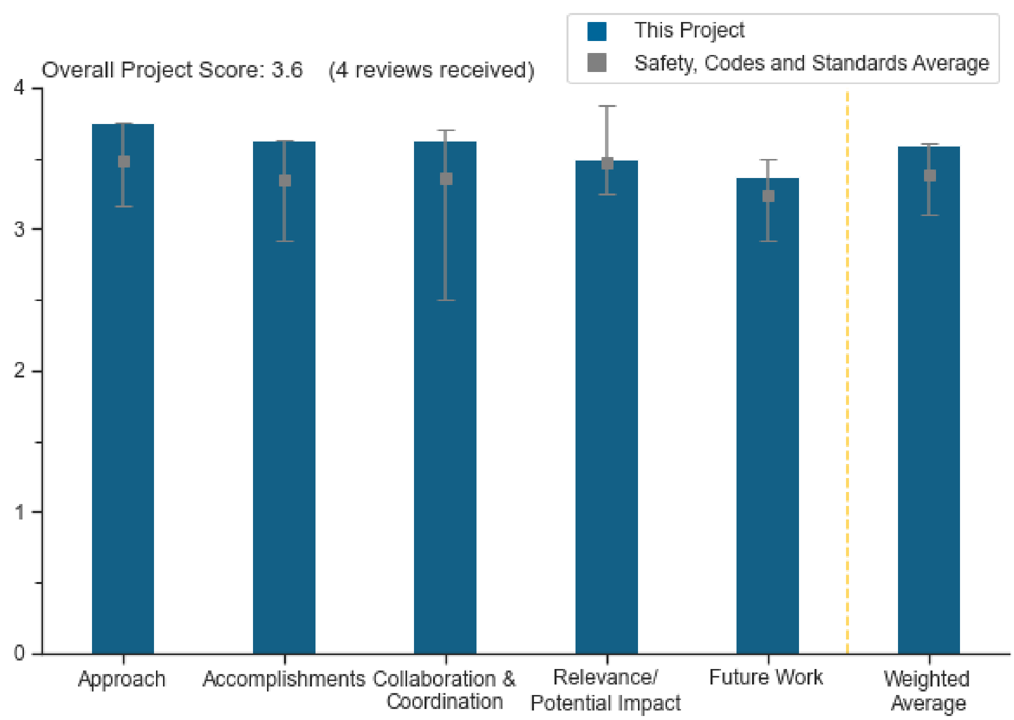
Nick Barilo, Pacific Northwest National Laboratory

DOE Contract #	6.2.0.502
Start and End Dates	3/1/2003
Partners/Collaborators	California Energy Commission, American Institute of Chemical Engineers, Center for Hydrogen Safety
Barriers Addressed	• Limited access to and availability of safety data and information • Safety not always treated as a continuous process • Lack of hydrogen knowledge by authorities having jurisdiction • Insufficient technical data to revise standards

Project Goal and Brief Summary

This project provides expertise and recommendations through the Hydrogen Safety Panel (HSP) and through the Hydrogen Tools Portal, H2Tools.org (H2Tools), to identify safety-related technical data gaps, best practices, and lessons learned, as well as help integrate safety planning into funded projects. Data from hydrogen incidents and near misses are captured and added to the growing knowledge base of hydrogen experience to share with the hydrogen community, with the goal of preventing safety events from occurring in the future. The project also aims to implement a national hydrogen emergency response training resource program with adaptable, downloadable materials for first responders and training organizations.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The partnership with the American Institute of Chemical Engineers (AIChE) is proving to be outstanding for the HSP and the outward communication of safety activity, with exposure to audiences different from the traditional audience, which is excellent. AIChE brings to this activity the increased ability for outreach in many forms (webinars, symposia, brochures, etc.). The increased exposure is very important for educating people as hydrogen deployment increases. This project is well-managed and aggressive in promoting and executing activities to improve the safe operations of hydrogen technology deployment—indeed, the project has gained such a positive reputation that others are working to emulate this. For example, the European Safety Panel was initiated because the HSP was seen as a valuable, successful activity. Imitation is the sincerest form of flattery.
- The HSP, H2Tools, lessons learned, and gap analysis are great resources for the safe deployment of hydrogen technologies and very useful to the regulatory development process and to the hydrogen industry. The work to train first responders in handling hydrogen fires is an important aspect of building acceptance of these emerging technologies.
- Both the HSP and H2Tools are well-designed and integrated with other relevant efforts. They are focused directly on overcoming the barriers identified in the presentation.
- The safety panel should continue if the demand for it exists. The incident library and the tools should be turned over to the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) or to a trade organization. Training should transition to the various state fire marshals' offices.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has outstanding productivity. The partnership with AIChE is excellent, broadening the activities, generating exposure to a new audience, and increasing the outreach through fact sheets, webinars, small symposia, etc.
- The quantitative performance indicators show progress that contributes to overcoming the stated goals. The project relies on continued lessons learned and the use of tools to inform interested parties of these lessons. The impact of the HSP's work on the specific projects it has supported is very high. Development and deployment of coursework and training is critical for ensuring lessons learned are more widely incorporated in future projects, particularly those outside the scope of the HSP.
- The project is renewed each year, and the targets have been met each year.
- The safety panel should continue if the demand for it exists. The incident library and the tools should be turned over to DOT PHMSA or to a trade organization. Training should transition to the various state fire marshals' offices.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration is excellent, from the inception of the AIChE Center for Hydrogen Safety (CHS) and the partnership with AIChE and Pacific Northwest National Laboratory (PNNL). The CHS reached out to other globally noted activities (specifically, the International Association for Hydrogen Safety, "HySafe") and established a working partnership and a memorandum of understanding to collaborate, but not compete, globally in this space. To date, the partnership with AIChE has proven to be very constructive**.**
- The collaboration with AIChE is an "outside-the-box" accomplishment with the potential to accelerate hydrogen safety understanding into the mainstream. HSP members represent the appropriate range of key stakeholders with expertise to effectively advise on projects to improve safety. Collaboration with the

California Energy Commission (CEC) is appropriate, given the advancement of hydrogen projects in California.

- The collaboration with AIChE, CEC, and the Connecticut Center for Advanced Technologies for outreach activities is very good. The panel should consider reaching out to the National Fire Protection Association (NFPA) on training first responders. NFPA currently does the training for first responders regarding battery electric vehicle fires, and manufacturers submit their first responders guides to NFPA. A similar partnership with NFPA may help provide acceptance of hydrogen-fueled vehicles.
- The selection of collaborators is extensive.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The attention to safety from the beginning of the project cannot be overstated. The work of the HSP stands on its own and is recognized globally. The outreach to the industrial, government-funded, and commercial sectors is outstanding. This is an extremely valuable activity—globally. It has gained global recognition, and its tools are used globally. This is excellent.
- The work by the HSP and resources such as H2Tools will help with the safe deployment and use of hydrogen technologies. Training first responders will help enhance safety and provide acceptance of the technology.
- Both the HSP and H2Tools have the potential to advance progress on DOE safety goals.
- These organizations (e.g., HSP) should be transitioned into the mainstream of the economy. The safety panel should transition to a code development organization or a trade organization. The incident library and the tools should be turned over to DOT PHMSA or a trade organization (e.g., the Fuel Cell and Hydrogen Energy Association or the National Association of State Fire Marshals). Training should transition to the state fire marshal's office. This should no longer be the venue of the national laboratories but rather state and commercial interests.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The work by the HSP and AIChE CHS, including maintaining H2Tools and training first responders, is important to continue until the technology is fully mature. The future plans presented provide for this continued effort.
- The proposed work shows continued effort in effective areas, as well as dissemination of best practices for new topics that are starting to be deployed.
- The proposed future work is excellent.
- The proposed work implies that the work should be transitioned.

Project strengths:

- HSP makes a critical difference in ensuring projects consider safety early on and utilize best practices. The lessons learned are then fed back into the tools, ensuring stakeholders have the latest information to establish the continued safety of projects. H2Tools ensures open access to lessons learned and best practices, as well as access to information on standards.
- The DOT has used H2Tools and has shared it with international standards development officials. This tool is very useful for people with little knowledge of hydrogen technologies.
- This project is of extremely high value globally and is being copied by other government funding agencies, such as the European Safety Panel.
- The knowledge on the HSP is the project's strength.

Project weaknesses:

- The number and range of hydrogen projects are expected to grow significantly with increased rollout of policies for clean energy technologies. It would be good to see the project address how it may handle the significantly increased number of projects to review and the increased need for specialized training of unique stakeholders. Online training courses can reach more stakeholders, yet in-person training workshops can be more tailored to individual stakeholder needs. It is not clear how the project will be able to be responsive to a significantly increased need for project reviews, training, etc., as well as how PNNL, through the CHS, will support development and deployment of courses offered through the AIChE.
- When asked what review process was in place to approve fact sheets or other materials for general distribution, no formal review process was articulated. PNNL and the CHS need to do a better job at reviewing the technical content of all products produced and released for general distribution. This project is the voice of the hydrogen safety community, so its products must be technically correct without ambiguity adhering to the current state of the art in hydrogen safety. PNNL and the CHS should create a formal review process, drawing experts from both inside and outside the organization, before approving anything for general distribution.

Recommendations for additions/deletions to project scope:

- There should be plans for increasing the ability to engage in tailored activities, particularly the timely deployment of in-person or online training of unique groups of stakeholders (e.g., bespoke training for authorities having jurisdiction for tunnels in the Northeast). Perhaps there could be a train-the-trainers program.
- Perhaps reaching out to NFPA about training to first responders would also be an effective way to reach more people. This effort is currently ongoing with respect to battery electric vehicles.

Project #SCS-021: Hydrogen Sensor Testing Laboratory

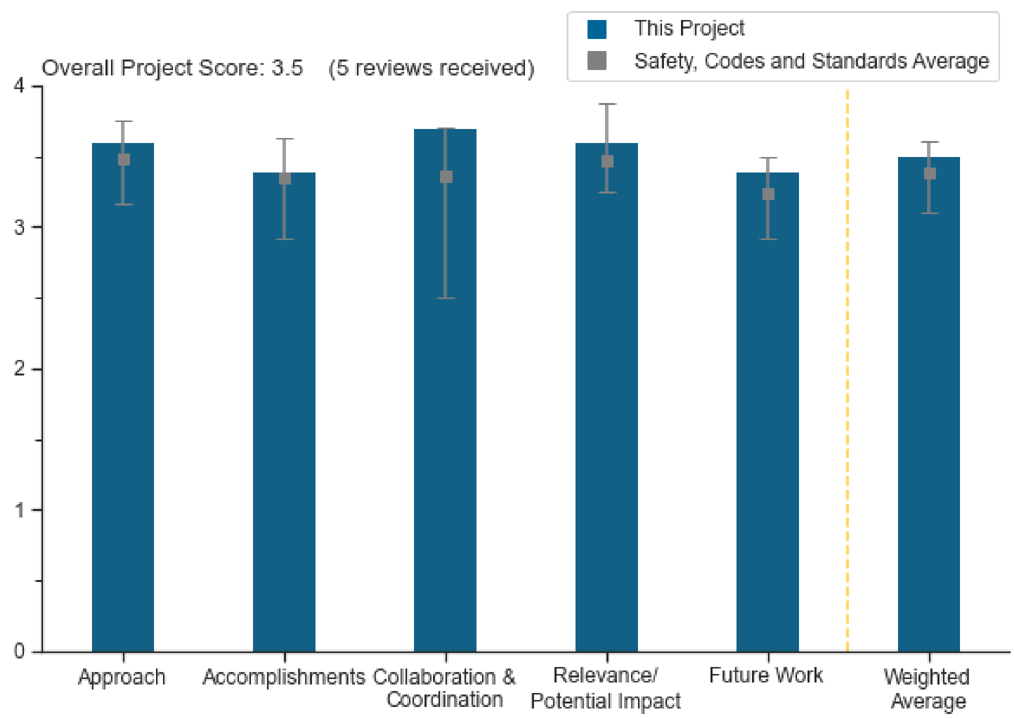
William Buttner, National Renewable Energy Laboratory

DOE Contract #	WBS 6.2.0.502
Start and End Dates	10/1/2010
Partners/Collaborators	Shell North America, Amphenol Thermometrics, AVT and Associates, Element One, KWJ Engineering Inc., First Element, Emerson, Health and Safety Executive's Health and Safety Laboratory, Transport Canada, Environment and Climate Change Canada
Barriers Addressed	• Safety is not always treated as a continuous process • Enabling national and international markets requires consistent regulations, codes, and standards • There are insufficient technical data to revise standards

Project Goal and Brief Summary

Sensors are a critical hydrogen safety element and will facilitate the safe implementation of the hydrogen infrastructure. The National Renewable Energy Laboratory (NREL) Sensor Testing Laboratory tests and verifies sensor performance for manufacturers, developers, end users, and standards developing organizations. The project also helps develop guidelines and protocols for the deployment of hydrogen safety sensors under a variety of conditions and applications.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach appears to address how to use sensors to the best advantage and tackles the issue of what the best practice is for the use (as opposed to focusing on sensor performance). A large effort would be needed to address all hydrogen sensing issues systematically; therefore, given resource limitations, a more ad hoc approach to addressing the more important issues makes sense. The effort is presently looking at some of the more important ambient gaseous leak situations. Cold gas behavior is under evaluation, and issues of dispersion and detection will be examined in future work. The examination of quantitative risk assessment (QRA) assumptions about evaluating leak size and the evaluation of the National Fire Protection Association 2 guidance on sensor placement within enclosures are critical. System design and safety evaluation are often at odds over what degree of component robustness is required to meet the "worst case" hazards. Overestimation of hazards can lead to overdesign and an impact on function and cost, while the opposite results in increased risk and consequences from hazards. Evaluation of what a sensor registers as a function of position within a confinement against estimated overpressure will aid in improving the response of active monitoring and the benefits obtained. If the system's response to potential critical situations can be made reliable, it would help reduce the system design criteria that must account for the high overpressures that are possible when sensitive mixtures are allowed to form. Better information will aid design to provide conservative safety based upon active monitoring, rather than robust structural design. The ability to do wide-area monitoring (WAM), preferably at a distance (a holy grail of hydrogen detection), must continue to be pursued, and new techniques must be evaluated (e.g., ultrasonic acoustic and fiber optic). More ad hoc efforts, such as fuel contaminants being measured in real time during dispensing and exhaust analysis, are important to certain constituencies. The team needs to continue working on detection issues for emerging markets such as hydrogen–methane blends and maritime applications. All of the considerations under study in this project have greater importance than simply examining sensor performance.
- The approach of this work is to build on the already highly successful historical laboratory work evaluating sensor performance, moving into WAM and now being proactive by working with computational fluid dynamics (CFD) and risk experts to make sensing part of the risk mitigation activity early in the design process. This makes sensors a proactive part of the overall system design rather than a passive element that signals only if an event occurs. This is excellent.
- The project has expanded beyond sensor performance into hydrogen detection and risk reduction analysis. The project is nimble enough to work multiple fronts to improve safety. The partnerships are appropriate for the expanded scope.
- The expansion of this project is impressive; all areas are well- focused and have very tangible and practical outcomes.
- There is a lack of specifics, especially with regard to the defined schedule and objectives. Slide 18 provides one-year and five-year objectives, but the one-year objectives do not have direct relevance to the rollout of new technologies, and the five-year objectives are vague and very far in the future for current needs. It would be helpful to see a specific plan over that period as to how each objective will be met, along with critical milestones. For example, for hydrogen wide-area monitoring (HyWAM), the phrase "explore and demonstrate feasibility of advanced concepts" is too general, despite the development of this equipment's being a top priority. It would be helpful to see a direct line-up of challenges/barriers and the potential solutions individually, instead of spreading them over separate slides. The slides do not seem to line up directly, and there appear to be gaps. For example, the Complex Standards Requirements section does not have a clear pathway to overcome.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There are very good, broad, and relevant accomplishments for this project. The accomplishments range from expanding the existing sensor laboratory to outdoor sensing, developing HyWAM capability, and using that capability in support of the Fuel Cells and Hydrogen Joint Undertaking's (FCH-JU's) Prenormative Research for Safe Use of Liquid Hydrogen (PRESLHY), as well as HyDeploy, hosted by Keele University in Staffordshire, England (to name a few). This is a very important project, and it is out of the laboratory, being value-added to other international programs and projects. It truly is unique.
- This project's accomplishments are excellent and very impressive. Because hydrogen sensors are the primary method of detecting leaks, this is all very important work.
- The project is able to be responsive to industry needs, and it supports important prenormative research. The value of this project to improving safety is acknowledged. Owing to the flexibility that allows responsiveness, there is less clarity in measurable performance indicators than in projects with more defined specific targets.
- The accomplishments and progress are commensurate with the level of funding. This reviewer is not in a position to comment on the prioritization of efforts. Given that the expansion of hydrogen infrastructure requires a large investment in cryogenic hydrogen, handling the equipment that is improving the adequacy of detection with regard to cold gas releases is important. This part of the project needs more progress.
- The previous feedback shown on slide 17 is echoed here. It is not clear that the questions have been sufficiently answered in terms of overall direction. The project shows progress but in a bit of a haphazard fashion. Better-defined objectives and detailed plans to achieve them for the next two to three years would be helpful.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- This project has historically mentored students, which is great. In addition, this mentoring activity has yielded several talented young professionals whom NREL has hired — excellent. Over the past couple of reporting periods, this project has generated close collaborations with a large number of world-class entities, notably, AVT and Associates (CFD calculations) and the University of Maryland (risk analysis with Professor Katrina Groth). These two collaborations are highlighted as examples of this project's being proactive in systems design up front to reduce risk. This is not meant to detract from the other outstanding collaborations.
- Appropriate partnerships are set up, and the project is making important contributions to research, as well as codes and standards.
- The collaboration is extensive, and while very positive, it also demonstrates the need for improving and advancing hydrogen sensor technology.
- The breadth of collaboration with other entities is extensive and impressive.
- The collaboration and coordination appear to have balanced participation.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is very relevant to reducing the risk associated with hydrogen deployment, and it will be even more important as hydrogen moves into activities at scale. It is exciting to see the breadth of activities addressed by this project and the level of international engagement. With the closing of the European Commission's Joint Research Center sensor activity, it is even more important that this NREL project remains as the globally unique activity that it is. It is a critical global resource.

- The project has the potential to contribute to safety in several ways, including supporting reliable sensor development, providing science-based guidance on sensor placement, and modeling for research and risk mitigation. The work is applicable to gaseous hydrogen and liquid hydrogen in many applications and is compatible with emerging markets. These efforts provide risk mitigation strategies that can be employed by industry and included as options in developing codes, standards, and regulations.
- Hydrogen's behavior makes controlled containment a challenge, and upon release, hydrogen combustion poses real safety issues. The development of mature sensor deployment and active monitoring strategies will permit systems to "safe" themselves for repair and maintenance, allow personnel proximity, and prevent more catastrophic outcomes. The work will expand the types of hydrogen applications, as well as when and where such applications will be permitted. The inclusion of interns is a form of outreach that will allow these individuals to carry relevant skills out into the workplace.
- There is no question that improved gas detection would be a significant safety benefit for the hydrogen industry, which then cascades into the broader DOE effort that involves so many projects. This work is important for that continued support.
- It is great to see how much expansion there has been with this work. It seems that the door has really been opened, and people are realizing the value of the sensor and detection technology for safety and overall system management for hydrogen. There are questions about the outdoor application, but perhaps it could be useful combined with modeling work for specific cases, for example. The new technologies being explored (e.g., fiber optic and ultrasonic) are interesting.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The proposed future work makes good sense, and the characterization of the remaining challenges and barriers is appropriate. It is important that analysis of cold plumes be completed. In concert with the HyWAM and sensor placement strategies, there would be value in including more demonstration of these technologies/techniques to characterize hazards posed by difficult enclosed environments and demonstrating means to show hazard reduction in those spaces (e.g., how to customize air flow/ventilation, block accumulation, etc., all to achieve safe operation). It is best that the NREL sensor test capability be continued because the need will continue for some time. It should be pointed out that developing the capability for safe controlled releases of hydrogen involves having not only the technical prowess but also the right location and sufficient area for work and staff. These criteria are especially important for larger outdoor capabilities. Also, there is a need for an independent test capability (independent of industry and equal to or better than our international partners). Hydrogen infrastructure will become global in scope, and there will be national value in maintaining a national sensor testing capability.
- The proposed future work is aligned and targeting the movement in the hydrogen community—hydrogen at scale. Addressing remote hydrogen sensing (HyWAM) for H2@Scale is the correct direction. Working with the CFD and QRA communities to improve our ability to design low-risk systems is right where this project needs to be. The future work is perfect.
- All proposed future work focuses on practical outcomes that are useful to industry (for example, sensor placement is a question that comes up often, and integration into HyRAM cannot be a bad thing).
- The proposed future work is aligned well to addressing issues identified as remaining challenges and barriers. The decision points were not addressed, though.
- An impressive list of future work is provided. However, specific details are lacking, especially with regard to defined schedules and objectives. Slide 18 provides one-year and five-year objectives, but the one-year objectives do not have direct relevance to the rollout of new technologies, and the five-year objectives are vague and very far in the future for current needs. It would be helpful to see a specific plan over that period as to how each objective will be met, along with the critical milestones. For example, for HyWAM's five-year goal, the phrase "explore and demonstrate feasibility of advanced concepts" is too general, despite the development of this equipment's being a top priority.

Project strengths:

- This is a highly productive project, with excellent growth potential into being proactive in applying sensor technologies to develop low-risk systems. This is particularly important as we move to H2@Scale. The collaborations developed are large in number and broad in scope, and each one is relevant to improving the deployment of low-risk systems. In particular, the attention to WAM, its improvement over time, and its application to liquid behavior is commendable. The project's further development is eagerly awaited.
- The project has been successful in the development and application of several devices and strategies to support other projects' research within the hydrogen fueling field. The NREL laboratory is unique in its capabilities for sensor research and support. This is a commendable achievement. The project works on a wide variety of efforts and is widely recognized for its expertise.
- The project has the flexibility to meet industry needs in risk mitigation analysis, appropriate collaborations, and potential applicability to emerging markets.
- This project's strength is that it is providing relevant and practically useful information that can be incorporated into documents (safety, codes and standards), into modeling, and in the field.
- The greatest strength is the project's flexibility to take on varied initiatives as needed. It is hoped that this aspect of the NREL Hydrogen Sensor Testing Laboratory is maintained.

Project weaknesses:

- While it appears to be an objective, more should be said about the integration of hydrogen-specific detection with other monitoring techniques to infer system integrity. Examples of such techniques are pressure decay (of hydrogen or other fluids), valve position indicators, and in the case of polymer electrolyte membrane systems, stack cell performance and flow. Fire detection, or component temperature monitoring, can also indicate the presence of leaking hydrogen. The objective would be to develop best practice information on how different measurements can work together to provide system performance information, support preventative care, provide multi-fault tolerance, and more.
- The project seems to be supporting other projects more than developing and proving technologies that could more immediately affect the rollout of hydrogen infrastructure. For example, the HyWAM technology is useful for research, but it is not in a useful state for deployment to active systems. The team should consider how this technology can be expedited for real-world use instead of just for scientific purposes. From a commercial availability perspective, there does not seem to be a significant increase in the capability or a decrease in the cost for sensing technology for smaller systems (e.g., typical fuel station sizes). Perhaps there is a more effective way to get new technology to market, while being more cost-effective and for smaller systems.
- The project might benefit from more quantitative goals and decision points, perhaps with regard to individual studies within the project—that is, if it is possible to do so without compromising the benefit of the project's flexibility, which allows it to be somewhat reactive to evolving needs.

Recommendations for additions/deletions to project scope:

- Continued support from NREL and DOE are recommended to ensure continued success of this critically important project.
- The sensor-placing work is likely to be challenging to apply in real-world situations, particularly for the outdoors. It would be better to focus on broader detection methods (HyWAM in its true sense), rather than discrete detection points. Developing improved technology will be a better use of resources than trying to work with the limitations on existing technology.
- This project should develop guidance information supporting the integration of hydrogen-specific detection with other systems monitoring. There is little mention in the literature (and not in the work of this project) of hydrogen detection based upon the acoustic sound speed. It is unclear whether this is overlooked or there are technical deficits.
- The project appears to be sufficiently flexible to address appropriate scope changes or areas of focus.

Project #SCS-022: Fuel Cell and Hydrogen Energy Association Codes and Standards Support

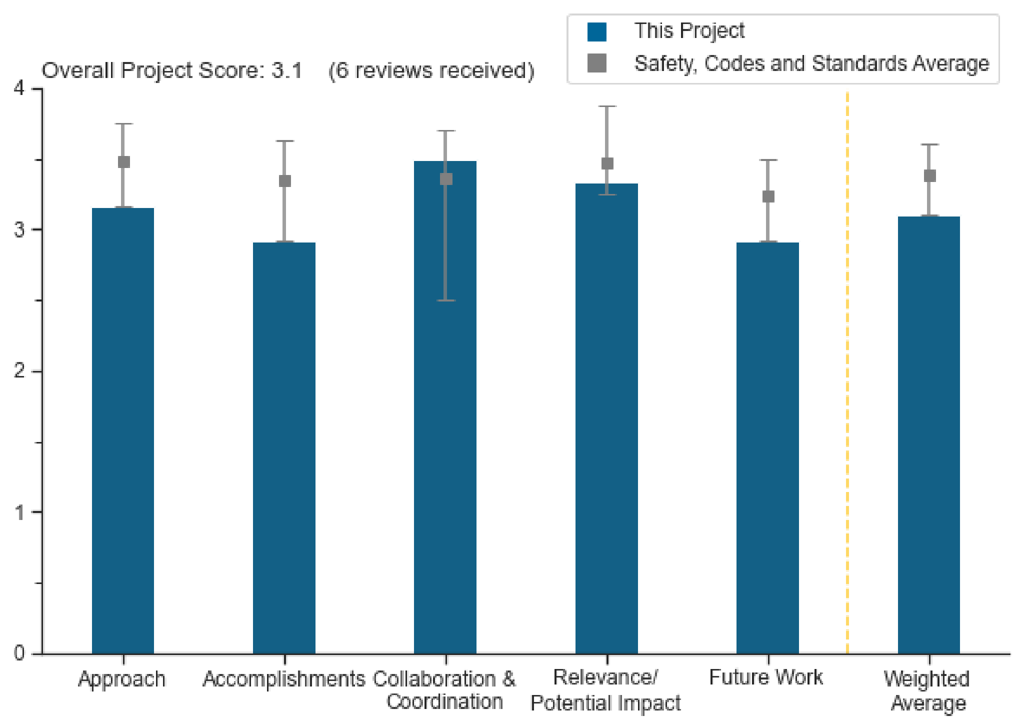
Karen Quackenbush, Fuel Cell and Hydrogen Energy Association

DOE Contract #	DE-AC05-00OR22725
Start and End Dates	9/12/2019 to 8/31/2021
Partners/Collaborators	Code and standards development organizations through the National Hydrogen and Fuel Cell Codes & Standards Coordinating Committee, Pacific Northwest National Laboratory, Oak Ridge National Laboratory
Barriers Addressed	• Enabling national and international markets requires consistent regulations, codes, and standards • Synchronization of national codes and standards is insufficient • Participation of business in the code development process is limited

Project Goal and Brief Summary

The goal of this project is to support and facilitate development and promulgation of essential codes and standards to enable widespread deployment and market entry of hydrogen and fuel cell technologies and completion of all essential domestic and international regulations, codes, and standards (RCS). The Fuel Cell and Hydrogen Energy Association (FCHEA), under contract to Oak Ridge National Laboratory, participates directly in key domestic and international RCS technical committees and encourages its members to participate directly in technical committees, working groups, and discussions. FCHEA also develops and enables widespread sharing of safety-related information resources and lessons learned with first responders, authorities having jurisdiction, and other key stakeholders.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach appears to be comprehensive. The principal investigator (PI) has clearly described how this project has established key working groups to address the immediate-need standards, clearly defined the coordination activities and stated the goals of the outreach events, and outlined certain technical challenges and their resolution approach. It is difficult to improve the approach of this effort.
- Engagement of FCHEA with standards organizations and consolidation of information is good. The approach is also aligned with the U.S. Department of Energy's overall goal for the safe deployment of hydrogen systems.
- FCHEA has always done a good job in providing a connection between their members and various codes and standards (C&S) development activities.
- This is an excellent approach for education and outreach and the resolution of technical challenges.
- The overall approach is good with regard to coordinating the industry members, tracking C&S documents' progress, and surveying members for feedback/input; however, gaining total industry consensus can be difficult.
- The project has high-level goals but does not highlight specific objectives. For example, a number of specific issues could be identified. Then the project could report out on the success or failure of those specific objectives each year, along with the role that this project played in those efforts. For example, the work on Code of Federal Regulations (CFR) 29 and its inconsistency with current National Fire Protection Association (NFPA) 2 and NFPA 55 is a useful endeavor. A first step might be actually to lead an effort to select a reasonable target date for conclusion, and then project-manage the process by identifying resources, defining the critical actions/path for success, and executing to that plan. The project should also develop a medium- to long-term project plan to chart a path forward. Without this, the project runs the risk of not having the necessary focus to succeed in targeted areas of importance. The presentation did not explain the reason for the 2021 funding increase (although this was explained in the questions). Since this is an annually funded project, there was also minimal information as to expected/required funding to complete objectives in 2022.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There are excellent accomplishments, specifically on the coordination side, such as the National Hydrogen and Fuel Cell Codes and Standards Coordinating Committee (NHFCCSCC), Hydrogen and Fuel Cell Safety Report, and FuelCellStandards.com.
- It is clear active participation on these working groups is occurring. Good progress is being made, although it is difficult to identify what the measurable performance indicators are.
- FCHEA has been integral in helping to support C&S development.
- Standards development is a long process, and FCHEA seems to be making steady progress.
- The presenter works very hard to promote the whole industry input and gain consensus and puts much effort into tracking and updating C&S.
- It is difficult to assess performance against project goals since they are very qualitative. It is good to see that the metrics provided in the presentation are trending in a positive direction regarding usage of the websites, which might be reflective of utility. It is not clear how well this project matches with DOE goals. This project basically serves as information transfer only; no technology or products are developed to enable further deployment of hydrogen. To the extent that the project can facilitate industry knowledge, it helps, but much of this information might be obtained in other ways. At best, the project serves an indirect role. For example, this project does not directly support goals such as "ensure ... best safety practices" or "conduct [research and development]," as shown on slides 6 and 7.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- FCHEA has good coordination and collaboration between its members and various standards development organizations and code development organizations.
- There is outstanding collaboration and outreach through multiple stakeholders.
- The nature of FCHEA lends itself to collaboration with numerous stakeholders. In addition, it is clear that FCHEA functions with and communicates with numerous C&S organizations worldwide.
- FCHEA coordinates with all stakeholders on a monthly basis. The U.S. Department of Transportation also participates in these meetings because FCHEA keeps tabs on the progress of hydrogen vehicle safety regulations.
- There is much relevant cross-pollination of various standards groups and members in various standards organizations.
- Key industry players are well-represented.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The presenter's leadership on committees and document development is valuable, as is management of the overall landscape of C&S. The international collaboration is essential. There are good metrics on the web resources. There is a fair amount of crossover with the existing meeting structure.
- The relevance of this effort contributes directly to meeting four out of seven DOE research, development, and demonstration (RD&D) hydrogen safety, codes and standards (Chapter 3.7).
- This project has significant impact on the harmonization of national and international RCS.
- Global standardization of regulations and industry standards will help uniformity in technology worldwide. It will enable reducing costs while ensuring safe deployment of the technologies.
- FCHEA participates in C&S activity through direct membership on numerous code committees. However, because of the nature of FCHEA and with multiple stakeholders, it is difficult to participate unless there is unanimous agreement. As a result, the relevance of the FCHEA vote can be minimal during critical opportunities.

Question 5: Proposed future work

This project was rated **2.9** for effective and logical planning.

- Continuing to facilitate harmonization of C&S and work as a platform for collaboration for a variety of stakeholders over various areas in the industry is a vital role.
- There are excellent plans to continue C&S harmonization and coordination activities.
- The proposed work is more of a continuation of current work. This is likely because the regulatory/ standards development process takes a long time.
- The focus of the proposed future work is to continue working on standards harmonization. The presentation (slide 24) indicates that next steps include determining regulations, C&S priorities, and needs for the next round of code revisions. This implies that some of the barriers still need to be identified/established.
- It is not clear that the FCHEA project serves a critical role for many of the activities listed. This work might continue in other forums if not hosted by FCHEA. For example, the NHFCCSCC could conduct its own meeting without this project.

Project strengths:

- This effort has clearly and effectively demonstrated active U.S. participation in RCS working groups that are tied directly to four of seven elements of the DOE Hydrogen and Fuel Cell Technologies Office Multi-

Year RD&D Plan. Standards work is never done, and typically, it is a sustaining effort. The PI has been able to flex her funding and increase her scope to accommodate additional working group support more than in previous years.

- The overall strength of the project is good. The project is needed for the safe deployment of hydrogen technologies. In general, this is low-cost project and will help with standardization and with determining gaps in research, safety needs, etc. Some coordination to include some of the completed relevant FCHEA codes and standards/best practices into the C&S link on H2Tools may be good.
- A project strength is conducting information exchanges and data transfers to improve harmonization in domestic and international RCS.
- Coordination and outreach are outstanding.
- The project offers a forum for multiple companies and people to learn more about hydrogen, even if otherwise they do not have the ability to do themselves.

Project weaknesses:

- The work seems duplicative of what is also done by other organizations or what might be done directly within FCHEA with its own funding. Specific achievements should be presented that show definitive successes. In addition, it should be shown how this project facilitated that activity, e.g., why it would not have happened without the direct involvement of this project. For example, slide 10 discusses the importance of harmonizing international codes, but references to pertinent successes last year or potential needs for next year should be provided in an easy-to-track format. The presentation is too ambiguous in this regard.
- The presentation is missing the prioritization of certain standards over others identified. A prioritization list of all relevant RCS that can be chosen would more quickly enable/achieve the DOE RD&D goals.
- Considering the international membership of FCHEA, its working groups can be more involved in the international harmonization, not just International Electrotechnical Commission (IEC) Technical Committee 105 Working Group 8.
- The requirement/need for true consensus can be difficult to obtain and, without it, can be a limiting factor. Perhaps full consensus needs to be re-examined moving forward.
- The weakness is that standards development is taking too long.

Recommendations for additions/deletions to project scope:

- It is recognized that many of the RCS maintenance and update efforts occur on timelines not controlled by this project. As a result, it is difficult to develop a plan for cost versus product. One suggestion for addition could be to display timelines/Gantt charts showing how long it takes to work on and process certain standards. This could help produce a metric for addressing Question 3 (measurable performance indicator).
- The project should consider merging efforts and websites with Pacific Northwest National Laboratory's DOE project. Having more information is in one location could be an improvement to the user community, leading to less confusion. The project should have a specific timeline and sunset date, preferably tied to certain objectives or code cycles. When complete, a new project could be formed with new tasks. Otherwise, this runs the risk of being a perpetual project.
- Probably reprofiling or re-orienting working groups more on international activities will bring a bigger benefit to members and DOE.
- The project should consider including or linking the FCHEA efforts with H2Tools, where relevant. Any means to expedite standards development is also good.

Project #SCS-029: Point-of-Use Hydrogen Purification and Impurity Reporting Systems that Utilize Metal–Organic Frameworks

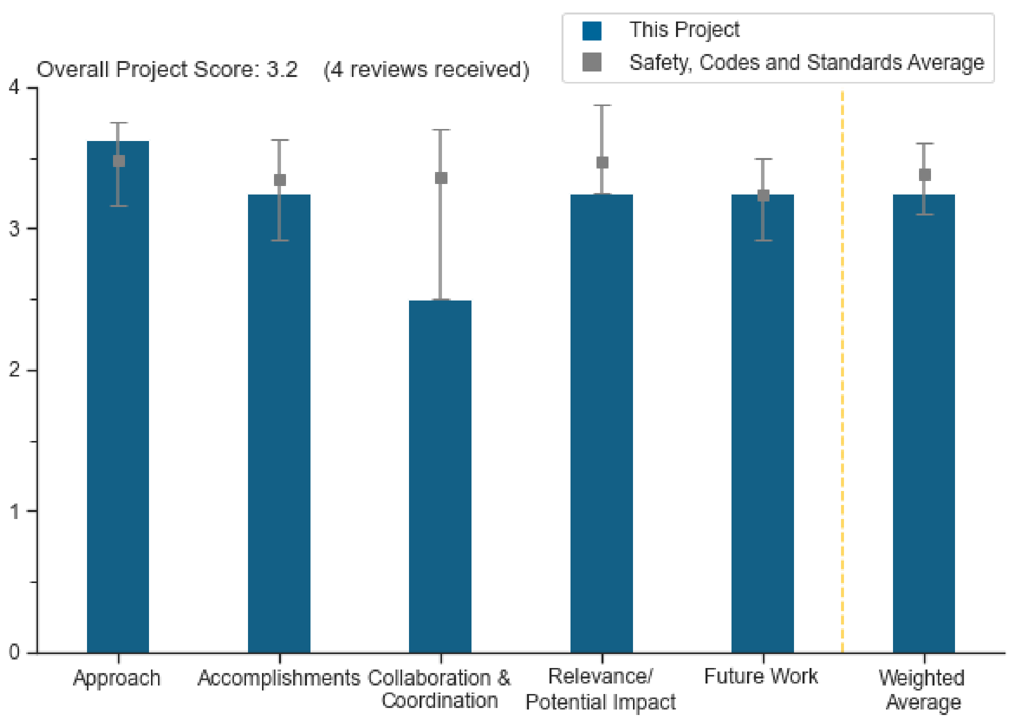
William Morris, NuMat Technologies, Inc.

DOE Contract #	DE-SC0019959
Start and End Dates	8/24/2020 to 8/23/2022
Partners/Collaborators	Hydrogen Fuel Cell Technologies Office
Barriers Addressed	• Safety is not always treated as a continuous process • There are insufficient technical data to revise standards

Project Goal and Brief Summary

This project, funded through the Small Business Innovation Research program, aims to develop filtration media that can remove impurities from hydrogen fuel streams at the point of use. The current hydrogen supply chain has the potential for introduction of impurities into the hydrogen stream at several points, making point-of-production purification ineffective at eliminating impurities. By enabling hydrogen purification at the point of use, project outcomes will reduce the risk of damage to fuel cells due to impurities.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The objectives and barriers are well-stated and are aligned with the needs of the hydrogen fuel and hydrogen fuel cell industries. The approach, with the inclusion of scale-up for validation and cost analysis, is sound. Future data/results in those areas are happily anticipated.

- Early and accurate detection of hydrogen fuel impurities is a critical component of advancing the hydrogen transportation market. This is very relevant work.
- The approach is direct and appropriate. This is the first project in a while that supplied a Gantt chart to show an organized approach.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project looks to be moving along according to plan. Emphasis on safety is always a plus. The project is making very good use of the Hydrogen Safety Panel as a resource.
- The task on fuel purification is progressing. There are 30 potential filtration options ready for testing, and 20 options have been tested. The test data for H_2S and NH_3 is 0 to 1 bar. CO is 0 to 8 bar. It is not clear that this matches the point-of-generation requirement. NH_3 is generated in the steam methane reformer (SMR), and the CO is generated in the SMR and the SMR shift converter (0 to 20 bar, 200°C). Sulfur is a housekeeping issue, as are particulates. The sulfur is usually found in lubricants and sealants (0 to 900 bar, -40°C to 200°C).
- While the presentation states that 30 materials have been screened, not much data are shown—only the graphics on slide 15 of the presentation, which are only qualitative. Whether one rises above the others for a particular contaminant is unclear. A practical filter device might need to have beds of more than one material.

Question 3: Collaboration and coordination

This project was rated **2.5** for its engagement with and coordination of project partners and interaction with other entities.

- There are no collaborations to date; while collaboration is always encouraged, it does not seem to apply in this project.
- The selection of collaborators is incomplete. This is probably not an issue. However, there should be some discussion with the researchers on the likely source of the impurities and the operating conditions.
- No collaborators are discussed. Slide 21 says, “No collaborations to date.”

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project, if successful in demonstrating a practical, scaled device, will be extremely beneficial to the hydrogen fuel and fuel cell industries.
- This project is very relevant to ensuring advancement of the hydrogen economy; ensuring the quality of hydrogen being dispensed into the numerous fuel cell applications is only positive.
- This task may not be achievable in the way that the original equipment manufacturers (OEMs) currently want. They want a “filter” to install on the nozzle or just upstream of the breakaway. The filter needs to operate from 5 bar to 1,000 bar and at temperatures from -40°C to 75°C (per SAE J2601).

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Proposed future work addresses all barriers identified.
- The proposed future work is organized and rational. It would be nice to see how these metal–organic frameworks are used, e.g., perhaps they are meant to be a replacement for zeolite and to run in a pressure swing adsorption process.

- Future work is stated as improving the technology readiness level of the technology. Quite a bit more data needs to be generated and shown to demonstrate that this technology will work under real-world conditions and that the materials identified have enough capacity to absorb or filter realistic amounts of impurities.

Project strengths:

- The project addresses a very important need, and the experience and capability within the lead organization are strong. Also, the project appears to have a clear pathway to commercialization and scale-up.
- This is an excellently designed and executed project.
- This is a key aspect to sustaining and advancing the hydrogen transportation market.

Project weaknesses:

- The potential weakness is perhaps the cost element (if this cannot be done in a cost-effective way).
- Data on the effectiveness of the materials discussed are so far not very detailed or compelling.
- OEM expectations and the researchers' expectations may not agree.

Recommendations for additions/deletions to project scope:

- The project team should consider a collaboration with a point-of-use impurity measurement/detection technology/organization. It seems as though purification and detection together could be a very powerful combination.
- An informal sit-down is recommended to discuss the likely sources of contamination and the operating conditions at those sources.

Systems Analysis – 2021

Subprogram Overview

Introduction

The Systems Analysis subprogram funds crosscutting analyses to identify technology pathways that can facilitate large-scale hydrogen use to enable decarbonization, advance environmental justice, and enhance energy system flexibility and resilience. To perform these foundational analyses, the subprogram uses a diverse portfolio of both focused and integrated models and tools that characterize technology costs, performance, impacts, and cross-sector market potential. These tools and capabilities are continuously updated and enhanced, while new tools are also developed as needed.

Cross-cutting analyses are conducted in collaboration with a range of entities:

- Other Hydrogen and Fuel Cell Technologies Office (HFTO) subprograms
- Various U.S. Department of Energy (DOE) offices: Strategic Analysis Team, Vehicle Technologies Office, Bioenergy Technologies Office, Office of Fossil Energy and Carbon Management, Office of Nuclear Energy, Wind Energy Technologies Office, Solar Energy Technologies Office, Office of Electricity, and Advanced Manufacturing Office
- State/local organizations
- Other federal agencies (e.g., U.S. Environmental Protection Agency)
- Private sector companies
- International organizations

The subprogram leverages external activities, coordinates efforts, and works with these partners to build opportunities for new technology applications and deployment.

Goals

The subprogram supports HFTO's decision-making and prioritization process by evaluating technologies and energy pathways, identifying gaps and synergies, and providing insights into future benefits, impacts, and risks.

Key Milestones

Near-Term (2020–2025):

- Develop models and analyses to prioritize program activities, including assessment of policies, creation of environmental justice goals, and areas of RD&D focus to meet Administration priorities.
- Conduct state-of-the-art technology assessments to help guide the RDD&D portfolio.

Mid-Term (2025–2035):

- Validate and refine models and tools to enable large-scale market growth, inform multisector coupling, and realize emissions reductions and jobs potential.
- Characterize market barriers and opportunities for supply chain expansion and high-volume manufacturing.

Long-Term (2035–2050):

- Assess RDD&D and market transformation processes, policies, and progress across applications and sectors to enable system resilience, emissions reduction, and sustainability, and assess jobs potential, including impacts on disadvantaged communities.

Fiscal Year 2021 Technology Status and Accomplishments

Analyses in fiscal year (FY) 2020–2021 focused on identifying the role of hydrogen in hard-to-decarbonize sectors, characterizing factors such as:

- The role of hydrogen in long-duration energy storage
- The impact of hydrogen use on lifecycle emissions of industrial applications
- Market segmentation in medium- and heavy-duty transportation
- The impact of growth in hydrogen and fuel cells on global sustainability metrics, to inform future RD&D.

Subprogram-Level Accomplishments

Global Change Analysis Model (GCAM)

GCAM represents linkages between five systems (energy, water, land, economics, and climate) at local, regional, and global scales, while identifying which sectors are economically difficult to decarbonize to reach net-zero greenhouse gases. In collaboration with other DOE offices, the subprogram launched updates to GCAM that enhance the tool's abilities to model hydrogen and fuel cells, bioenergy, and other pathways. The updated GCAM will then be able to evaluate the potential market sizes of hydrogen and fuel cells in future scenarios with drivers for decarbonization.

Role of Hydrogen in Energy Storage

Analyses showed that hydrogen technologies are among the lowest-cost pathways for multiday energy storage. The subprogram funded the development of the StoreFAST tool at National Renewable Energy Laboratory (NREL)[1] to evaluate the cost of hydrogen energy storage relative to alternatives, such as flow batteries, thermal storage, compressed air, and more, in user-defined scenarios. Systems Analysis also co-funded the completion of an analysis led by DOE's Strategic Analysis Team, along with the Solar Energy Technologies Office and Wind Energy Technologies Office, evaluating current and future costs of long-duration energy storage in high-renewable grids.[2] Additionally, the subprogram joined with the Office of Electricity in co-funding the development of Pacific Northwest National Laboratory's (PNNL's) Hydrogen Energy Storage Evaluation Tool (HESET)[3]; this tool characterizes the costs and revenue streams of user-defined power-to-gas systems and can enable developers to optimize the size and operation of power-to-gas components.

Market Segmentation in Medium- and Heavy-Duty Transportation

HFTO and the Vehicle Technologies Office collaboratively managed completion of an analysis project led by NREL to evaluate the total cost of ownership of batteries, fuel cells, and combustion engines in medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs), with varying ranges and operating conditions.4 Market segments wherein batteries were advantageous included those with shorter range (e.g., 300 miles) or flexibility with respect to available time to charge. Market segments wherein fuel cells were advantageous included those with longer range (e.g., >500 miles) or time constraints with respect to fueling.

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[1] NREL, "StoreFAST: Storage Financial Analysis Scenario Tool," accessed September 2021, https://www.nrel.gov/storage/storefast.html.

[2] Chad Hunter, Michael Penev, Evan P. Reznicek, Joshua Eichman, Neha Rustagim and Samuel F. Baldwin, "Techno-Economic Analysis of Long-Duration Energy Storage and Flexible Power Generation Technologies to Support High Variable Renewable Energy Grids," *Joule* (2020) https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3720769.

[3] Pacific Northwest National Laboratory, "User Guide: Hydrogen Energy Storage Evaluation Tool (HESET)," from *Energy Storage Evaluation Tool (ESET)* website, accessed September 2021, https://eset.pnnl.gov/document/heset.

[4] Chad Hunter, Michael Penev, Evan Reznicek, Jason Lustbader, Alicia Birky, and Chen Zhang, "Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks," NREL Technical Report NREL/TP-5400-71796, September 2021, https://www.nrel.gov/docs/fy21osti/71796.pdf.

Supply and Demand Potential for Hydrogen

In support of DOE's H2@Scale initiative, NREL, Argonne National Laboratory (ANL), Idaho National Laboratory (INL), and Lawrence Berkeley National Laboratory (LBNL) completed three comprehensive analyses of hydrogen supply and demand potential in the United States.[5] These analyses characterized the technical potential of hydrogen supply in the United States, assessed price points and market potential for hydrogen demand in eight sectors, and identified the economic growth potential for hydrogen supply and demand in five scenarios to be at least two to four times current consumption.

Other Highlights

The subprogram is also supporting the development of internationally agreed-upon methods of lifecycle analysis, working with the Hydrogen Production Analysis Task Force of the International Partnership for Hydrogen and Fuel Cells in the Economy.

Project-Level Accomplishments

Annual Technology Baseline (ATB)

The ATB provides a consistent set of technology cost and performance data (based on annual DOE analysis) that may be used as modeling input for energy analyses. In 2020, a transportation module of the ATB was launched through a collaboration between HFTO, the Strategic Analysis Team, the Vehicle Technologies Office, and the Bioenergy Technologies Office. The platform characterizes cost and emissions data for 10 different light-duty vehicle powertrains, under user-specified scenarios of technology progress and scale.[6] The 2021 update will include expansion to MDVs, HDVs, and aviation.

Hybridized Nuclear Plants Producing Hydrogen

State-of-the art analysis tools were used by NREL, INL, and ANL to estimate the value of integrating hydrogen production at two Xcel Energy nuclear power plants, given regional demands for hydrogen. Grid prices with and without hydrogen were estimated, and the operating strategy for a hybrid energy system was optimized. Future work may evaluate sensitivities of these conclusions to key assumptions, such as the cost of hydrogen storage infrastructure.

Industrial Applications for Hydrogen

ANL led analysis characterizing the potential for clean hydrogen to reduce emissions from liquid fuels and iron refining.

- Preliminary analysis indicates that hydrogen use in iron refining can reduce lifecycle emissions by 30%–50% compared to iron refining using coke or natural gas via blast furnaces or direct reduction of iron.
- Per analysis funded by the Advanced Research Projects Agency–Energy (ARPA-E), clean hydrogen use in ammonia production can reduce lifecycle emissions by over 80% compared to conventional ammonia production using natural gas without carbon capture and sequestration.
- It was determined that hydrogen and carbon dioxide synthesized into synthetic fuels can achieve over 70% lower lifecycle emissions than conventional diesel, assuming end uses that burn the fuel (e.g., vehicles, turbines).[7]

New Projects Launched FY 2020–2021

- PNNL, ANL, NREL – Updates to GCAM
- OnLocation – Development of Hydrogen Module for National Energy Modeling System

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[5] Reports available at "H2@Scale" on the DOE website (accessed September 2021): https://www.energy.gov/eere/fuelcells/h2scale.

[6] https://atb.nrel.gov/transportation/2020/index

[7] https://pubs.acs.org/doi/10.1021/acs.est.0c08237

- NREL – Annual Technology Baseline – Transportation
- ANL, NREL – Analysis of Hydrogen Export Potential
- LBNL, NREL – Advanced Network Analysis of Hydrogen Fuel Cell Automated Vehicles for Goods Delivery (ATLAS)
- NREL – Long duration energy storage cost analysis

Budget

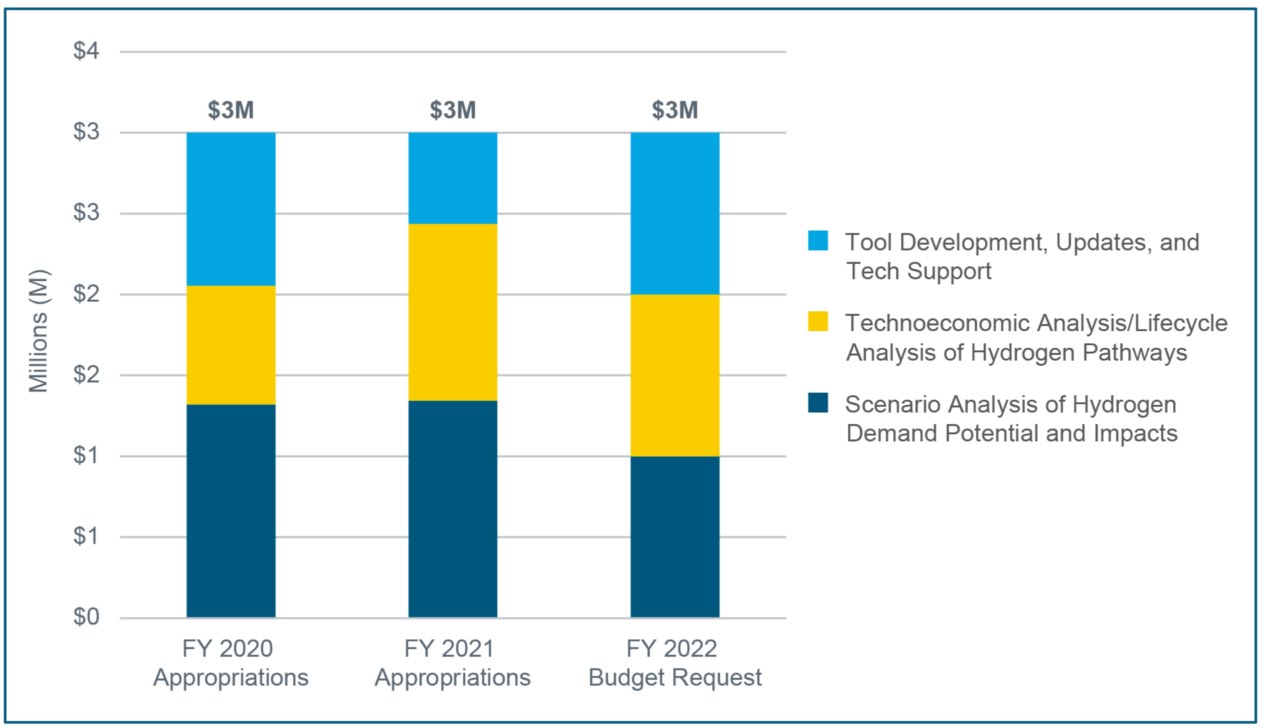
The FY 2021 appropriation for the Systems Analysis subprogram was $3 million. In FY 2021, the subprogram funded efforts in three key areas: scenario analysis of hydrogen demand potential and impacts; technoeconomic and lifecycle analysis of hydrogen pathways; and tool development, updates, and technical support.

Funding for scenario analysis focused on areas such as sustainability metrics, hydrogen market sizes in different energy system scenarios (e.g., high-renewable grids), and the value proposition of hydrogen energy storage. Technoeconomic and lifecycle analyses explored industrial applications, synthetic fuels and biofuels, and medium- and heavy-duty transportation applications. The subprogram also continues to fund annual updates to its portfolio of diverse models, while developing new tools to characterize the value proposition of hydrogen and fuel cells.

The FY 2022 budget request for the Systems Analysis subprogram is also $3 million. Activities planned for FY 2022, subject to appropriations and congressional direction, include:

- Assessment of potential large-scale deployments of hydrogen and fuel cells to address viability and benefits, such as decarbonization, sustainability, and environmental justice
- Assessment of climate impacts of hydrogen production and use
- Completion of ongoing analyses from FY 2021, such as updates to GCAM and evaluation of the total cost of ownership of fuel cells in autonomous fleets.

Systems Analysis RD&D Funding



Annual Merit Review of the Systems Analysis Subprogram

Summary of Systems Analysis Subprogram Reviewer Comments

The reviewers commended increased focus on environmental justice and the shift to considering hydrogen as a way to decarbonize carbon-intensive industries. The subprogram's ability to provide tools for analyzing hydrogen applications without actually investing in the applications, essentially testing out and de-risking ideas, was seen as invaluable to achieving the Hydrogen Energy Earthshot goal. An overall funding increase was recommended for the subprogram, reasoning that it can be essential in better guiding where research, development, and demonstration (RD&D) efforts in other subprograms should be targeted.

To better articulate HFTO's RD&D strategy, reviewers suggested use of more waterfall charts and investigations into total cost of ownership sensitivities, as well as linking these findings to the portfolio of projects. It was also suggested that multiple analyses could be integrated and some of them expanded to include additional emerging applications (e.g., mining, construction equipment, refuse trucks). Moreover, it was suggested that concepts such as sustainability, circular economy, recycling, eco-design, and just-in-time hydrogen production (producing hydrogen based on anticipated demand) could be considered.

Reviewers also pointed out that some stakeholders were interested in becoming self-sufficient in running the models but may hesitate, as they are not certain of the skill set required to run the models. Thus, reviewers suggested that an explanation conveying the level of expertise needed be added both to the models' websites and to the merit review presentations.

Market segmentation of MDVs and HDVs was seen as a comprehensive, nuanced, and insightful analysis that filled major data gaps and was informative to a variety of stakeholders, meeting needs as transportation moves toward zero-emission vehicles. Reviewers suggested that the scope could be expanded to consider infrastructure, operator perspective, factors such as dwell time and payload, and new data sets.

Technoeconomic analysis of the use of hydrogen in steelmaking and in producing synthetic fuels was regarded as an important step in reducing carbon dioxide emissions and a building block toward meeting the Hydrogen Energy Earthshot goal. Reviewers suggested that carbon utilization and capture also be evaluated.

The annual technology baseline work was commended for providing data that many stakeholders can reliably and easily find and reference. Coordination with industry and users outside of DOE was recommended as a way to validate the data.

The cradle-to-grave transportation analysis conducted by the subprogram was viewed as demonstrating tangible improvements in modeling, data, and assumptions. Industry verification and additional sensitivity analyses (for types of vehicles) were recommended.

For H2@Scale, the following were observed:

- Coordinating with state and regional entities could be a value-add for H2@Scale.
- As H2@Scale is focused on modeling, it might be worth validating findings through demonstrations.
- The technology readiness levels of various analysis components and pathways could be incorporated into the H2@Scale effort.
- There is a need to have a more nuanced understanding of the roles hydrogen can play, given the heavy interest and push toward battery technologies (i.e., more detailed information, rather than evaluation of general economic sectors).
- More clarity is needed about what it would take to build an upstream supply chain to support the vision of H2@Scale.
- Climate-change-induced droughts affect current energy systems and have sometimes led to increased use of fossil fuels, further exacerbating the issue. Perhaps H2@Scale could serve as a platform for investigating hydrogen's role in short-circuiting this kind of feedback loop.

During the 2021 Annual Merit Review, eight Systems Analysis projects were reviewed, receiving scores ranging from 3.0 to 3.8, with an average score of 3.5. Project reviewers were impressed with specific project-level highlights and accomplishments. Following this subprogram introduction are individual project reports for each of the projects reviewed. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Project Reviews

Project #SA-169: Market Segmentation Analysis of Medium- and Heavy-Duty Trucks with a Fuel Cell Emphasis

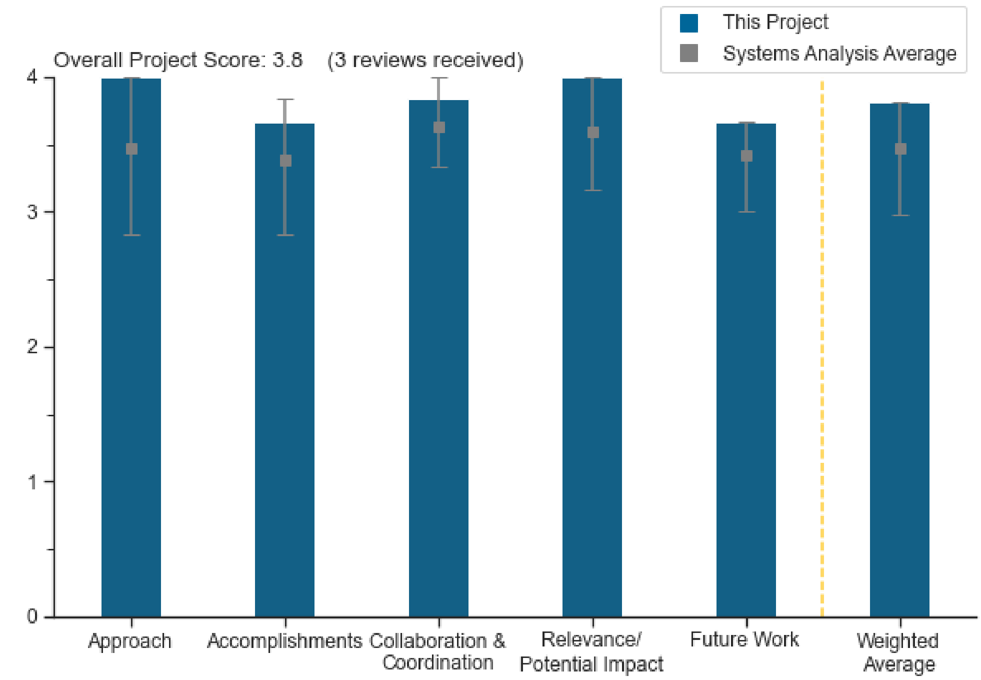
Chad Hunter, National Renewable Energy Laboratory

DOE Contract #	5.3.0.502
Start and End Dates	10/01/2018–08/30/2021
Partners/Collaborators	External peer reviewers: Argonne National Laboratory, Bosch, California Air Resources Board, Center for Transportation and the Environment, Cummins, Eaton, Energy Independence Now, FedEx, Toyota, DOE Vehicle Technologies Office
Barriers Addressed	• Future market behavior: assessing competitiveness of fuel cell medium- and heavy-duty vehicles • Inconsistent data, assumptions, and guidelines: developing a consistent modeling methodology using established U.S. Department of Energy cost/price and performance targets • Insufficient suite of models and tools: expanding spatial and temporal analysis tools to the medium- and heavy-duty vehicle sector

Project Goal and Brief Summary

This project provides stakeholders a broad assessment of medium-duty (MD) and heavy-duty (HD) fuel cell vehicle market opportunities and helps guide future U.S. Department of Energy investments in the area. As part of this effort, systems analysis models that assess cost and market barriers to fuel cell vehicle adoption will be enhanced and expanded. The tools and models used in analysis include the Future Automotive Systems Technology Simulator (FASTSim) for vehicle optimization to obtain vehicle cost, fuel economy, and weight; and the Scenario Evaluation, Regionalization, and Analysis (SERA) model for stock modeling and modeling of direct costs, opportunity costs, and other value streams. The SERA model will be used to calculate total cost of ownership (TCO) for each vehicle class and vocation by region.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Analysis projects.

Question 1: Approach to performing the work

This project was rated 4.0 for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The methodologies used in this project, leveraging the national laboratories' suite of transportation modeling tools, are comprehensive, logical, and well-designed. One of the major barriers this project aims to overcome is inconsistent data or lack of existing data, and this project provides results that will fill major data gaps. It is comprehensive in its analysis of many possible future drivetrain technologies, and it is nuanced in its evaluation of many different use cases and possible trajectories for future development.
- There is a clear understanding of the key pain points for truck operators, and the project seeks to quantify an appropriate mix of scenarios. The project leverages and improves upon existing tools and data sets as much as possible, as well. The project not only adds core TCO components (truck cost, fuel, etc.) but also accounts for the financial impact of operations to capture the full return on investment (e.g., dwell time and payload), which is especially appreciated.
- The project makes very good use of existing tools and methods to accomplish goals. Also, it is nice to see that payload capacity and dwell time are two cost components/drivers.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- It appears that much work has been done over the last year and that previous Annual Merit Review comments and peer review feedback were taken seriously and addressed. The results are starting to indicate challenges and opportunities in the zero-emission truck market.
- The results to date are very insightful. Using the market segmentation effort to help bound the Class 8 market is excellent for seeing the full picture. It will be interesting to see more.
- The project already appears to be providing several novel data points that will be informative to hydrogen and MD/HD transport stakeholders. While it is a bit outside the project's control, the continued reliance on 2002 Vehicle Inventory and Use Survey (VIUS) data is a concern. The project could have potentially sought some other alternative or even developed a new and verified data set that could have stood as

comparable to VIUS. While an updated VIUS data set is expected to be released sometime soon, it stands as a potential weakness of the project to be so reliant on this update for more accurate or up-to-date data as a critical model input.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project has engaged several relevant institutions for collaboration and review of the project, which likely provided valuable and relevant insight into project development. In addition, the incorporation of models across national laboratory teams and other projects is a core strength of this project.
- The establishment and verification of assumptions required significant coordination with industry partners, which appears to be sufficient and effective. Continuous updating and verification will be important for the rapidly changing battery and fuel cell technologies.
- There is great coordination with other groups at DOE and industry partners. The inclusion of the North American Council for Freight Efficiency is good, as it allows getting closer to the truck operators, and it is suggested that the project engage in even more direct conversations with operators to fully understand how they use the vehicles and what affects their truck purchase decisions. That may inform how to present new insights that consider the voice of the customer. Also, coordination with hydrogen infrastructure stakeholders may be somewhat out of scope, but it will help confirm assumptions on fuel cost.

Question 4: Relevance/potential impact

This project was rated **4.0** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This work is exactly the type of information and modeling that is needed today, as government agencies are starting to develop regulations and requirements of fleets to move toward zero-emission technologies. Government and industry stakeholders alike need this type of information to understand the potential impact of new and proposed requirements, as well as the most cost-effective way to meet these requirements. There is a good deal of early-stage misinformation and misunderstanding that this project can directly address with authoritative and comprehensive scientific evaluation.
- This work is critical to understanding where and how efforts should be directed to achieve commercialization for the zero-emission truck market.
- This is an extremely relevant project, both to the DOE Hydrogen Program and the broader industry. A publicly available model is highly anticipated so fleets and the industry can further explore.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- Now that the methodology, approach, and assumptions have been refined, future work must continue to include solicitation and incorporation of any assumption updates, as well as modeling of all other truck markets. The development and release of the TCO tool will be very useful for the industry but should include validation, verification, and communication activities.
- It is good to see that consideration of hydrogen station placement has been added to the scope for potential future work. However, there may also need to be some consideration of charging infrastructure to provide the kind of apples-to-apples comparison many stakeholders will expect. The project team may need to expand collaboration to complete this work.
- Sharing a published model will be a major value-add from this project. The project team seems to have a good understanding of what gaps and improvements remain, but it is not clear what will be prioritized or performed under separate projects to build from this work. Engagement with fleet operators, a deeper dive on market segmentation, and more focus on the supporting infrastructure are examples that should be explored.

Project strengths:

- There is much to like about this project, with some key strengths:
    - Relevance and value: Industry, operators, and policymakers understand how important TCO is to driving the freight movement sector to zero emissions. This work provides a great reference that compiles reputable data and modeling to inform better decision-making and quantifies the value of fuel cell electric trucks.
    - Public model: There is always value when the results do not have to be static and stakeholders can dive as deep as they please to understand scenarios and options.
    - Cost-effectiveness: This project provides a great bang for the buck. Other multiyear, multi-million-dollar initiatives have provided much less value than this project already has.
- Overall project strengths include the ability to simulate and quantify critical drivers for commercialization of the zero-emission truck market. The approach is great and provides a robust framework for building in and updating use cases and being used as a decision-making tool in the development of zero-emission vehicles and projects. Further, the planned development and release of the comprehensive reports and tools will be important to driving the use and understanding of the work.
- This project's greatest strengths are its timeliness, comprehensive nature, and the well-structured methodology that leverages multiple transportation modeling tools available across DOE and the national laboratories.

Project weaknesses:

- A wide stakeholder group will take interest in this project, given the focus on TCO in the HD space, where there is currently somewhat limited information. How this information is presented, published, shared, and expanded will be very important. It is recommended that the team connect with more stakeholders (operators, infrastructure providers, and policymakers) to ensure the team understands what stakeholders are looking for and help tailor the message to add value. There is a good deal of potential with this project, so more effort on the dissemination piece is encouraged.
- It would be good to have a better understanding of the source, conditions, and values for critical input assumptions used, such as fuel cell density by weight and volume, fuel cell cost, comprehensiveness of Fleet DNA duty cycles, electric vehicle charge times, and battery density. This understanding would give users more confidence in the results and tools, as well as increase acceptance.
- The project weaknesses are (1) the potential delay or roadblock that can occur if the VIUS data are delayed and (2) the project's current structure of not investigating sensitivity to infrastructure development.

Recommendations for additions/deletions to project scope:

- The project scope should keep expanding. Some ideas are already mentioned in previous comments, but a few thoughts are below:
  - Infrastructure: Comparing the infrastructure experience is equally important. Some of this is already captured indirectly, yet much more work could be done here.
  - Operator perspective: This would help address the question of "designing to the average." It would add more reality to the project if the team found out how much of the market would really purchase a truck for single-shift, volume-limited cargo operation. If that is not the case all of the time, it would be good to know what happens.
  - More data: It sounds like a new VIUS study is coming in a couple years, but perhaps there are ways to collect data or expand new data sets to create even better insights.
- Overall, this is fantastic work done by Chad Hunter and the team, and they should keep up the good work.
- Recognizing that a prior year's reviewer already commented about infrastructure and the project team responded that it is out of scope, this still feels like it is the largest remaining gap in the project. Given the project scope, it is appropriate to use outside projections of hydrogen price for the estimates. However, infrastructure (in addition to TCO) is a large part of the fleets' consideration regarding adopting these vehicles and of the public sector's consideration regarding the impacts of requirements or the necessary support. In addition, the project already incorporates SERA, which has more than enough capability to investigate this aspect. A full investigation with multiple sensitivity evaluations may be beyond the scope of this work, but even a case study or a small set of representative studies could be an immensely useful addition in the near term. This type of information, even just as an example or two, is a major need right now for stakeholders. It could also provide a strong basis for a future project that could be more detailed and comprehensive in its analysis.
- An addition could include tying simulations and results to various scenario inputs related to specific charging and fueling methods and/or other expected industry advancements and breakthroughs. For instance, the project might show how the results change based on liquid hydrogen (LH2) delivery versus onsite electrolysis, or with LH2 fueling, or with a battery chemistry breakthrough such as a solid-state lithium battery.

Project #SA-174: Technoeconomic and Lifecycle Analysis of Synthetic Fuels and Steelmaking

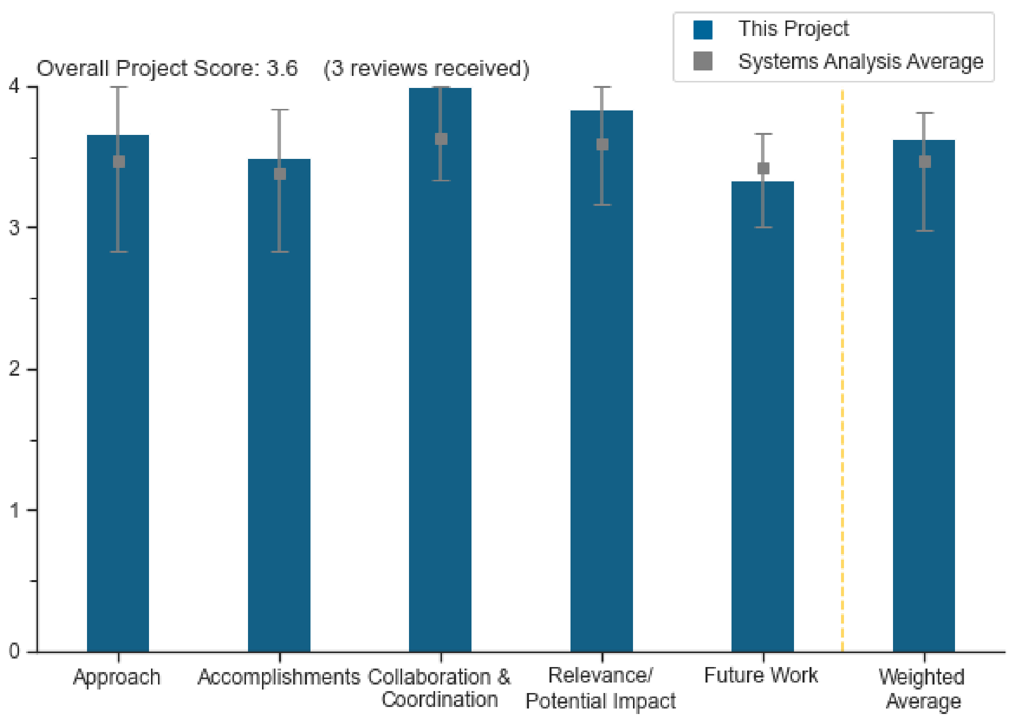
Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	5.1.0.6
Start and End Dates	10/1/2019
Partners/Collaborators	National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, University of California, Irvine
Barriers Addressed	• Future market behavior: Potential hydrogen markets beyond fuel cell vehicles • Insufficient suite of models and tools • Unplanned studies and analysis: Cost and environmental impacts of hydrogen use in new applications

Project Goal and Brief Summary

Hydrogen is being considered for new markets, including as a means of producing synthetic fuel and of manufacturing steel from iron ore using hydrogen to reduce iron oxides. This project aims to evaluate the technoeconomics and environmental implications of hydrogen use in these applications, providing estimates of associated costs and greenhouse gas (GHG) emissions. Argonne National Laboratory is collaborating on this project with the U.S. Department of Energy's (DOE's) Strategic Analysis Office, DOE's Advanced Manufacturing Office (AMO), the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (LBNL), and the University of California, Irvine (UCI).

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Analysis projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project has an excellent understanding of the problem(s) to be solved, namely balancing GHG emissions and hydrogen cost requirements (with and without incentives). It has a sound approach on how to resolve the technoeconomic barriers through the development of a technoeconomic analysis (TEA) model, interviews with key partners, and the assessment of current and new technologies.
- The project goals and barriers addressed are clearly described. The project design is well-organized, precise, and comprehensive. This work is highly relevant to advancing H2@Scale goals.
- The scope is clearly defined and addressed in the project. The scope is also manageable in the sense that it is not vague or ambiguous. Therefore, the findings can provide discrete value to the DOE Hydrogen Program.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The presentation and background material showed significant progress toward the goals and offered key conclusions. For example, the breakeven cost of hydrogen necessary to achieve low-CO2 steelmaking at $1.2/kg is consistent with other publications and the reviewer's personal (albeit much less sophisticated) evaluation. Of course, such TEA models can always be further refined with more detailed calculations, improved assumptions, and more case scenarios, but the work showed that all the building blocks are in place.
- The methodology employed in the analysis was comprehensive and yielded a good result. However, further background should be made available to provide better context of the results. For example, the steelmaking scenarios looked at various production technologies and energy sources. However, each of the technologies examined were at various levels of commercial readiness and deployment. More accurate costs for carbon capture and CO2 are available.
- The proposed work plan was completed.

Question 3: Collaboration and coordination

This project was rated **4.0** for its engagement with and coordination of project partners and interaction with other entities.

- The project has leveraged a range of expertise across DOE, national laboratories, and academia. The team also seemed to care about the end use of the product, a very important aspect in applied analysis.
- The collaboration partners—the DOE Strategic Analysis Office, DOE AMO, NREL, LBNL, and UCI—constitute a very strong team.
- The work presented displayed all the evidence of extensive collaboration with laboratories (LBNL in particular), universities (UCI), and industrial partners.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This work is a building block toward the ultimate goal of reducing CO2 emissions by using green hydrogen (from nuclear and/or renewable energy). The study aims at setting goals and necessary conditions to achieve decarbonization; however, the project is not intended to "solve" the problem but rather to indicate pathways, such as using hydrogen in ironmaking. In that respect, the project's relevance is outstanding. It is the kind of work that sets clear targets, such as the Hydrogen Energy Earthshot announced earlier in the week.

- The DOE Hydrogen Program's success turns in large part on the economic validation provided by the models, tools, analyses, and studies performed by this team. This effort is necessary for sound policy development and business decision-making. It saves substantial amounts of time and resources.
- The team has a strong understanding of the H2@Scale initiative and its goal and is receptive to input from the initiative. The growing interest in decarbonized, hard-to-abate emissions, plus the Hydrogen Energy Earthshot, makes TEA of the project's suite of technologies very important.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The lifecycle assessment (LCA) aspect of the work is fundamentally important, as accurate carbon reductions may drive newer technology forward more than economic competitiveness over the incumbent technologies. The presentation did not highlight the importance of the LCA and details (i.e., viability and economics) of the CO2 sources, CO2 capture, and CO2 infrastructure adequately. However, the future work based on the other aspects, such as steelmaking, were well-laid-out areas of logical growth.
- The proposed future work makes sense based on the earlier findings and conclusions presented. Economics of CO2 capture and transportation definitely ought to be included, but it is also suggested that "scale" be included as a consideration. The CO2 emissions from the steel industry are tremendous, and it is not clear that storage is feasible beyond a limited time before we run out of space. Decarbonization should be promoted, rather than giving the steelmakers an option to delay. Documentation, publication, and access to the model are critical to disseminating the message of this excellent work.
- Proposed future work is comprehensive and important. However, the list should be longer.

Project strengths:

- The approach and relevance are logical and of interest. The analysis is constructed in a way to provide tangible benefit for industry, DOE, and the broader research and development community. The scope is contained, and the methodology is comprehensive.
- The project's strengths are its analytical rigor, well-conceived tools, detailed analyses, relevant and useful results, and excellent outreach.
- The project's understanding of the problem areas, approach to solutions, and clear and concise results are its strengths.

Project weaknesses:

- The analysis could benefit from additional background for context, especially if these findings were to be used by a policymaker. Additional details should be provided, and consideration should be given to the carbon utilization and capture component of the project, as models such as Greenhouse Gases, Regulated Emissions and Energy use in Transportation (GREET) are not specifically designed for carbon use. Also, CO2 costs, ranging from capture to delivery costs (CO2 is not free, as there are capital expenditures and operating expenses even from compression), should be used in the analysis.
- The project's modeling can always be improved.

Recommendations for additions/deletions to project scope:

- No deletions are needed. The project's focus on steelmaking is a welcome improvement. It is only suggested that the team dive a little deeper into the TEA of building new steelmaking infrastructure and abandoning the existing one. For example, waste gases from blast furnace/basic oxygen furnace steelmaking are often used for other applications (including power/heat) that will have to be replaced. This can have a significant impact on companies and local communities.
- The project should consider adding the metric "dollars per ton of CO2e emissions avoided or offset" wherever possible. This could provide a common basis for comparison of disparate technologies and approaches.
- Overall, this is a good project and has shown good progress.

Project #SA-175: Regional Hybrid Energy Systems Technoeconomic Analysis

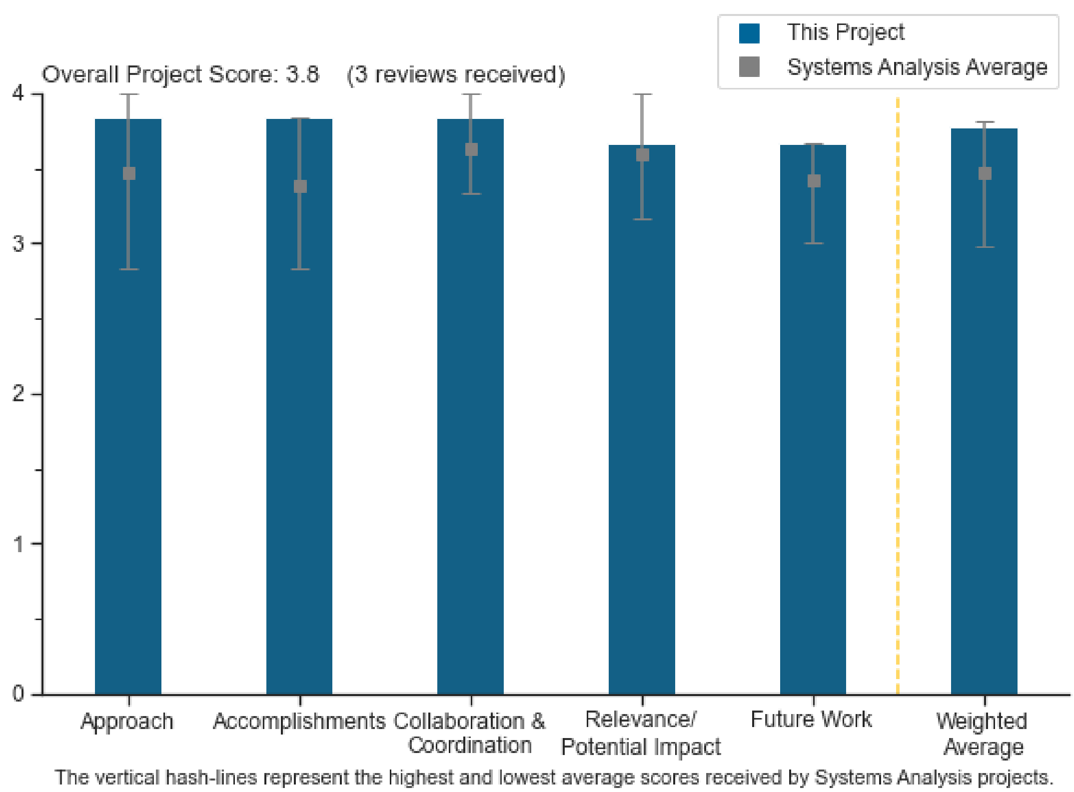
Mark Ruth, National Renewable Energy Laboratory

DOE Contract #	5.3.0.502
Start and End Dates	8/22/2019
Partners/Collaborators	Idaho National Laboratory, Argonne National Laboratory, Xcel Energy Inc., Electric Power Research Institute (EPRI)
Barriers Addressed	• Hydrogen production cost of $2/kg • Insufficient suite of models and tools

Project Goal and Brief Summary

This project aims to quantify the potential financial impact of hybridizing Xcel Energy's Prairie Island and Monticello nuclear power plants to produce hydrogen. This project will provide investment-grade information to support Xcel Energy's greenhouse gas reduction efforts, improve understanding of the potential for hybridized nuclear power plants to produce hydrogen at $2/kg or less, and develop tools and capabilities to better characterize hybridized hydrogen production on the grid so that new opportunities can be analyzed.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project team is developing a unique figure-of-merit-based approach to optimizing hydrogen production for a nuclear power plant. This approach is commercially relevant and useful for nuclear utilities.
- The capabilities of the national laboratories in complex scenario modeling are excellent, and leveraging them in concert with each other adds even more value.
- The project goals and objectives are very clear (e.g., as shown on slide 3). Barriers are identified, but how they are being addressed could be more clearly articulated in the presentation. For example, new tools are described well, but the linkage of these efforts to addressing the $2/kg barrier is not as clear. The project appears to be feasible and integrated well with both industry and government needs.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Within the scope of the project, the progress indicated shows that the goals have been addressed very well and good insights into the different market points have been provided. The existing project focuses on high-temperature electrolysis (HTE), but this approach could likely be extended to low-temperature electrolysis and hybrid systems.
- The accomplishments are consistent with the DOE H2@Scale initiative goals by enabling low-cost hydrogen produced from nuclear power for various end-use applications.
- The presentation provides an excellent display of aspects of the project (e.g., as shown on slide 10) and accomplishments for each. Preliminary results show that the project objectives are being met. Specific performance indicators are not as clear as they could be, as they read more as qualitative progress toward the outcome. The project appears to be on track to overcoming the barrier related to tools and techniques, but, as noted in Question 1, the linkage to the $2/kg barrier could be emphasized more.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project involves modeling capabilities across multiple laboratories and is grounded by industry participation and review. Having the Electric Power Research Institute (EPRI) on the project with access to multiple utilities, as well as a specific utility partner, provides both specific and general validation of the models and direction.
- The presentation shows outstanding collaboration between industry, laboratory, and government partners. In particular, the many portions of the Xcel Energy organization that are involved demonstrates the effort in this area.
- Additional input directly from hydrogen end users or industrial gas companies might be helpful.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project aligns very well with the DOE Hydrogen Program by exploring both the supply and demand sides of one means of producing hydrogen in a way that may be economical for multiple parties. As the various nuclear-related projects advance toward approval and implementation, they do have the potential to show more progress; however, at this early stage, it is difficult to say they are critical or will show significant progress.
- The project aligns very well with DOE Hydrogen Program objectives in HTE. With some additional work, the framework could also likely be very useful to other water-splitting pathways.

- The project supports the goals of the research and development subprograms and is impactful in enabling carbon-free hydrogen production from nuclear power.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- Since future work is dependent on future funding, it is not totally clear what commitments can be made. The ideas discussed toward adding additional relevant factors, analyzing different demand scenarios, and looking at co-optimization are all aligned with overcoming the barriers for deployment.
- The future work is clearly identified and impactful in quantifying the hydrogen production future compared to business as usual or flexible operations scenarios.
- The project has clearly planned its future (e.g., as shown on slide 24) and is well on its way to accomplishing each of its objectives.

Project strengths:

- The strength of the team and presenter are key attributes of the project. The potential for expansion to other scenarios and connection to other projects that touch on similar topics can provide additional value.
- This project integrates partners from multiple sectors. It advances the suite of analytical tools available. It bridges the gap between hydrogen and nuclear efforts with practical applications.
- The project is commercially relevant and impactful for the utilities thinking about hydrogen production from nuclear power and enables scale-up.

Project weaknesses:

- The project could demonstrate greater use of risk identification and mitigation. For example, the team could determine what would happen if HTE is not available when needed, if “guesses” about the demand curve (as stated in the oral presentation) turn out not to be correct, or if the dynamic functioning of the plant and electrolyzer do not operate as planned.
- The project could benefit from input from hydrogen end users.
- No major weaknesses were noted.

Recommendations for additions/deletions to project scope:

- Expanding the analysis to additional cases and technologies would help define which technologies might best fit different energy scenarios while achieving different price targets.
- The project could benefit from input from hydrogen end users such as natural gas-fired power plants. Also, next year’s presentation could include a figure on the intersection of supply and demand curves.

Project #SA-176: Annual Technology Baseline – Transportation

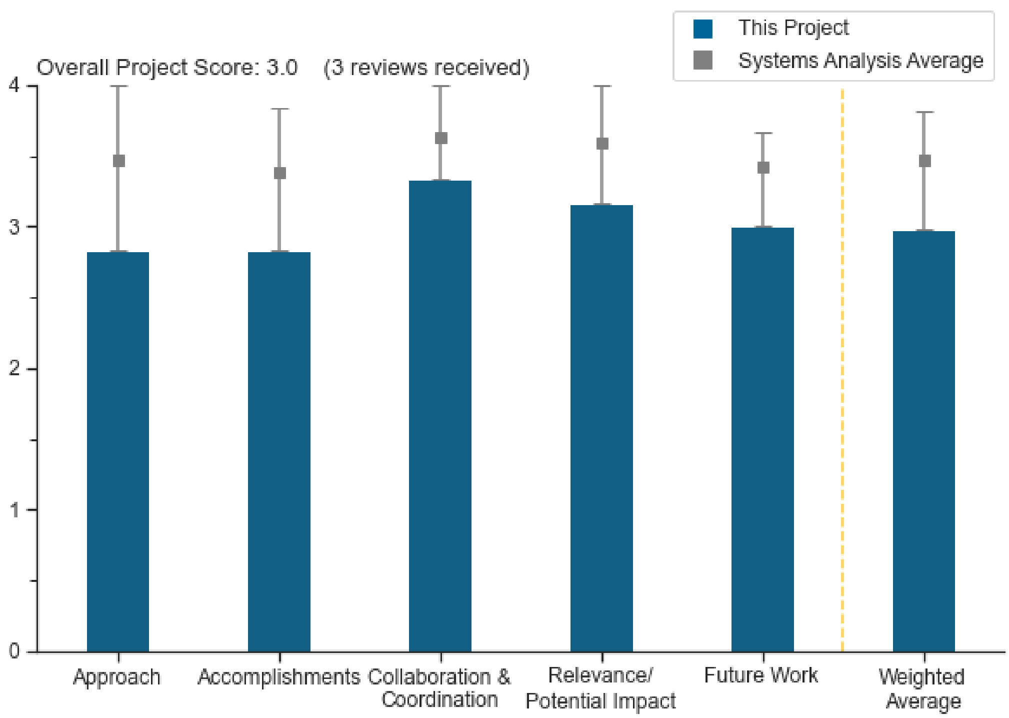
Laura Vimmerstedt, National Renewable Energy Laboratory

DOE Contract #	WBS 5.3.0.502
Start and End Dates	10/1/2017
Partners/Collaborators	U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Argonne National Laboratory
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Stove-piped/siloed analytical capability • Unplanned studies and analysis

Project Goal and Brief Summary

This project will maintain the Annual Technology Baseline (ATB), an energy analysis dataset that provides current, credible, and consistent information on technology cost and performance across energy sectors. The ATB is updated annually and reviewed for consistency. The National Renewable Energy Laboratory, the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy, and Argonne National Laboratory will work together to review data sets, online publications, and documentation.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Analysis projects.

Question 1: Approach to performing the work

This project was rated **2.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The development of the ATB vehicle portal and downloadable information seems to be very well-suited to the intended project goals. The variety of ways to access the data, with varying levels of detail and variation, is a useful aspect, as it allows the website to be useful for a wide variety of stakeholders that have different levels of need in terms of data nuance and detail. Two areas are less clear in the project. First, it is not entirely clear how the project might resolve differing data points for similar projections that come from different projects across DOE and the national laboratories. Second, the project so far includes only midsize light-duty vehicles (LDVs), and it is unclear why a larger set of vehicles was not included in the first launch of the portal, given that information is available at least for more classes of LDVs from the same resources that are used for the mid-size vehicles. It seems some modifications during early project planning could have allowed more vehicle classes to be available in the initial release.

- While the goals and objectives are clear and much needed in the industry, the input, or aggregated data, seems narrow and confusing to decipher. It appears that the input data consist solely of mined information from DOE reports that involve select, scenario-driven case studies. It is hard to figure out the cases and conditions on which the results are based. Most case studies appear to utilize DOE tools, which are great but are limited. Perhaps the tools could be used to do parametric sweeps across all conditions that could then be aggregated. There did not appear to be any empirical data that were used (only simulated projections), which would also be valuable. Also, there is no mention of the approach to how input data are validated, verified, and normalized. This is especially important, given that one of the objectives is to address inconsistent data, assumptions, and guidelines.
- There is a good deal of different information within separate DOE offices, but it is unclear exactly how much of a gap there really is and whether this project sufficiently addresses it. The approach was defined and presented in some detail, yet there were no accomplishments to show after the methodology had been presented.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project team has put together a large collection of tools so many stakeholders can easily access important transportation system data. The amount of work required to develop these several tools and formats is large, and the project team has made significant progress.
- There is good progress in publishing the results in various formats usable by the public. Some of the products could use clarification of source data, categorization of source data, explanation of parameters, and definition of units.
- The very brief accomplishments, which mentioned only publication and a couple webinars, were a bit confusing. There is potential to leverage a compiled data set to share useful insights, but this project does not currently take that step. If this really is a pure compilation of existing data, the scope and costs could be greatly reduced going forward.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The amount of coordination and collaboration appears to be well-suited to the project. The project leverages multiple DOE and national laboratory project teams. It is also good to see that the project has engaged a panel of outside reviewers to provide feedback and direction on the development of the ATB portal and data materials.
- Collaboration with internal sustainable transportation offices is good. Perhaps they are the primary consumers of this effort and tools. However, this project could benefit from coordination with outside users, researchers, and industry to better validate the usefulness and understanding of the work being produced.
- Clear collaboration has been established with the appropriate offices at DOE to compile data. Considering this does not include new modeling efforts, the role of the Technical Review Committee (TRC) is not clear since there does not appear to be any new content to review. It would also be interesting to learn who is already part of the TRC.

Question 4: Relevance/potential impact

This project was rated **3.2** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This type of resource, especially one that is as authoritative as the one this project provides, is something that stakeholders need very much right now. This project fills a gap in usable and accessible data that many stakeholders can reliably reference and find quickly and easily.
- Finding credible and consistent data is absolutely needed in the industry, and this project can provide that with the right approach.
- The idea of compiling siloed information can be a value add, but the relevance to broad stakeholders is not clear. This appears more like an internal check within DOE to ensure that analyses and targets are not misaligned.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The proposed future work will address one of the largest limitations of the current version of the ATB, namely, that results and data are currently available only for midsize LDVs. It is also extremely encouraging to see the intended scope of additions expanded beyond on-road vehicles to address the infrastructure side of zero-emission transportation.
- The project appears as though it would benefit from a focus on source data validation, normalization, characterization, and explanation.
- The scope of future work will determine the value of this project. As proposed during the presentation, it appears that more analyses will be compiled to refine the set of assumptions used to make the plots. This may increase the accuracy of the ATB without much significant change from its current state. A larger directional shift to add more insight from the data or even additional analysis of some kind is suggested.

Project strengths:

- The greatest strength of this project is its ability to provide consolidated and authoritative data via several formats that speak to many different types of stakeholders. There are many information needs across zero-emission stakeholders today, each with its own interest in levels of detail and nuance, and this resource will be useful to many of these different perspectives.
- Project strengths are the aggregation of LDV levelized costs of driving and well-to-wheels emissions that are predicted through reports created by DOE laboratories and energy offices.
- Having the awareness to leverage existing and sometimes siloed expertise is a project strength.

Project weaknesses:

- It appears that the input data consist solely of mined information from DOE reports that involve select, scenario-driven case studies. It is hard to figure out the cases and conditions on which the results are based. Most case studies appear to utilize DOE tools, which are great but limited. Also, there is no mention of the approach to how input data are validated, verified, and normalized. This is especially important given that one of the objectives is to address inconsistent data, assumptions, and guidelines. Some of the products could use clarification of source data, categorization of source data, explanation of parameters, and definition of units.
- There are a number of areas for improvement:
    - The project needs a clearer "why." It is unclear what problem is really being solved here. There are other projects that compare technologies and investigate a new problem.
    - Clarification of the scenarios is needed. The assumptions for the constant, mid, and advanced cases need more description. This project probably does not involve new analysis or assumptions, so perhaps there is a consistent reference that is used by all offices. It would be good to have more insight into what affects these curves, whether it is public policy/funding, private research and development investment, DOE investment, or a likelihood of hitting DOE targets.

  - The project is missing the punchline. This scope frames up the background for what should be a new project that builds on this information. The value is currently limited.
- So far, the project's weakness has been the limited scope of the data available through the ATB portal. However, the project team provides confidence that the scope will soon expand significantly, which will make this project much more useful.

Recommendations for additions/deletions to project scope:

- Other than improvements mentioned previously (if out of current project scope), the aggregation, normalization, and addition of historical data would be beneficial to analysts and researchers.
- Perhaps the full intent of this project is not being realized. If all this information already exists, then future projects are expected to directly reference that work as needed and build new analysis from there rather than starting from the ATB as a baseline. This project seems to be setting up the framework for an expanded scope that offers new analysis and insight of some kind. If that is not the intent, then a much simpler work scope is recommended to make sure information is shared internally with DOE offices.
- There are no recommendations other than to ensure that the proposed future expansions of scope do occur.

Project #SA-177: Analysis of Hydrogen Export Potential

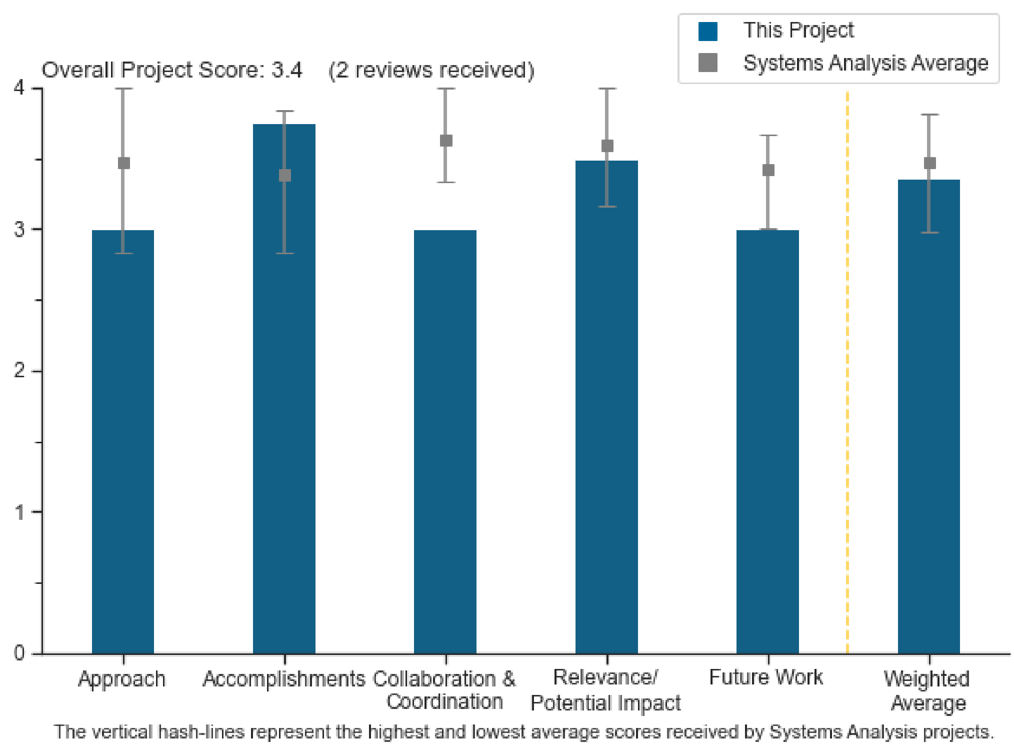
Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	5.1.0.6
Start and End Dates	10/1/2020
Partners/Collaborators	Analysis of Hydrogen Storage Options (ST-001), National Renewable Energy Laboratory
Barriers Addressed	• Insufficient suite of models and tools: Extend suite with export model • Stove-piped/siloed analytical capability for evaluating sustainability • Inconsistent data, assumptions, and guidelines: Leverage the Hydrogen Delivery Scenario Analysis Model (HDSAM) and ST-001

Project Goal and Brief Summary

Argonne National Laboratory and the National Renewable Energy Laboratory are evaluating the economic potential for liquid hydrogen (LH2) export. Team members will identify regions near ports with potential for LH2 production, work with ST-001 to determine the cost of terminals and tankers for LH2 transport, and estimate current and future global hydrogen demand. The project will provide information needed to assess the value proposition of exported hydrogen, identify technology barriers to hydrogen export by identifying cost drivers, and expand opportunities for hydrogen export.

Project Scoring



Because of late reviewer withdrawals and conflict of interest notifications, the minimum number of reviewers for a complete review panel (three reviewers) was not achieved for this project. The results are included here to inform future work and reviews, but the scores for this project are not included in the subprogram average.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach leverages external studies, as well as past U.S. Department of Energy efforts and modeling frameworks. An important aspect of the work is that the analysis specifies the assumptions in variables such as liquefaction cost across different studies so that it is clear where differences may arise (lower technology readiness level projections versus current technology, etc.). Otherwise, it is very difficult to assess the value of the different analyses.
- The current approach is reasonable but does not seem to address the costs of hydrogen distribution/ transport domestically. That is reasonable if it is assumed that the hydrogen is being produced near a port, for example, in the Gulf Coast. However, there are comments about the demand for green hydrogen in Europe, and in that scenario, there could be additional transmission costs associated with renewable hydrogen production, say, in the middle of the country, where renewables may be cheaper and more abundant. It also seems like the data gathered on current and future hydrogen demand include hydrogen as mixed gases, which does not seem relevant here. Also, it is unclear what the point of analyzing future global demand is if the study is not complemented with a supply analysis (in this project, it appears the team is actually just using projections from others). It seems the point should be identifying net importers of hydrogen, but this approach does not take it to that step.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project made substantial progress, despite a very small budget. As the shipping scenario has been discussed for a few years now, having a grounded analysis of the related costs is important. The work also lays the framework for continued analyses to compare different generation and transportation scenarios.
- The team seems to have made good progress on completing its tasks. However, the scope should be expanded so that the work better answers the question of what the potential is for the United States to export hydrogen.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- There is some collaboration with the National Renewable Energy Laboratory, but it was not discussed in detail. For a small project, there is not much room for collaboration across multiple institutions, but it would be interesting/valuable to get perspective from the stakeholder industries (Kawasaki, port authorities, shipping companies, etc.).
- More engagement with NASA would be beneficial. It seems there could also be mutual benefit to collaborating with the International Energy Agency, particularly on export/import potential.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Managing renewable hydrogen costs in areas where renewable energy costs are high is an important part of understanding the balance between transportation modes and distances versus generating at the point of use. This project starts that analysis and should help to highlight potential regulatory issues that may arise.
- The research and analysis on LH2 storage costs can be leveraged to better understand the potential role for hydrogen in maritime and commercial aviation applications.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- It is unclear whether this modeling/functionality is being added to the Hydrogen Delivery Scenario Analysis Model (HDSAM). This seems important to addressing the "insufficient suite of models and tools" barrier.
- The future work description is somewhat generic but logically comes after the current tasks.

Project strengths:

- The project's strengths include good coordination with other projects, use and extension of modeling tools, and leveraging of external studies.
- The biggest strength is that the project builds off of HDSAM.

Project weaknesses:

- Better data are needed on the scalability of LH2 storage, as well as potential for boil-off during hydrogen transfer (boil-off considerations were removed, but it appears they were based on boil-off solely during storage).
- The lack of direct industrial feedback/participation could be a weakness.

Recommendations for additions/deletions to project scope:

- Ultimately, the lowest-cost solution will be the most successful. Now that the framework has been developed, it would be valuable to compare the different segments versus geography (generation, transportation, storage) to determine the best location for electrolyzer deployment for specific geographies (whether we should be exporting hydrogen or electrolyzers, how far away from point of use electrolysis should be placed based on delta in electricity cost, etc.).
- The project should include the analysis of which countries may be net importers of hydrogen, as well as which other countries are positioned to be net exporters (e.g., Chile). HDSAM should be expanded so that there is a public tool to evaluate LH2 shipping costs.

Project #SA-178: Cradle-to-Grave Transportation Analysis

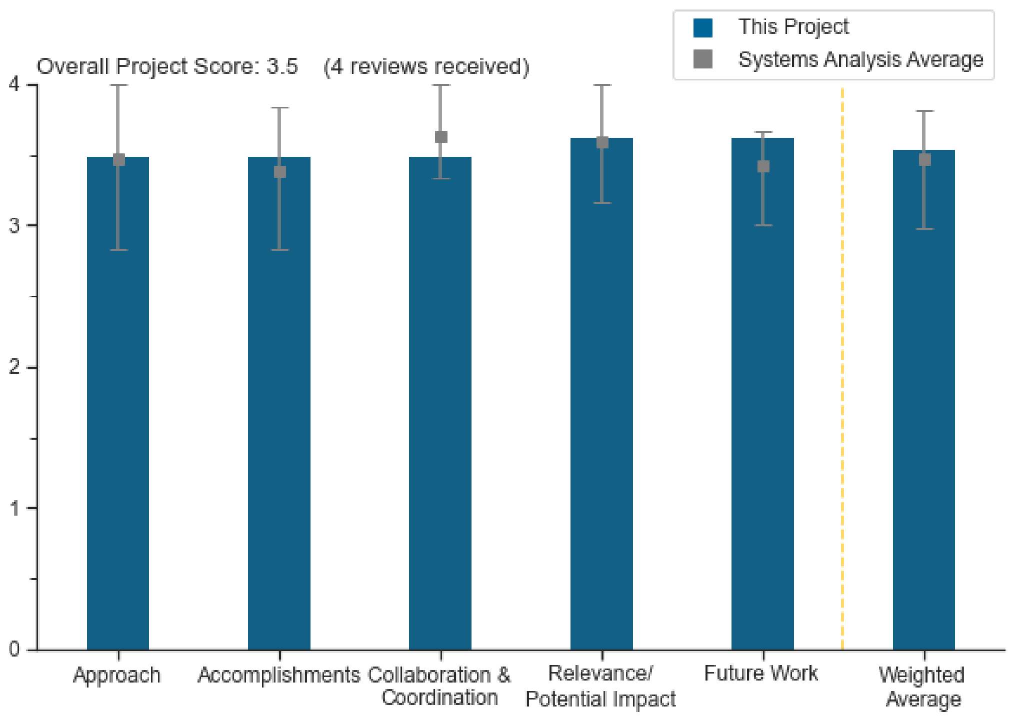
Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	5.1.0.6
Start and End Dates	10/1/2020
Partners/Collaborators	U.S. DRIVE Partnership, Integrated Systems Analysis Tech Team, Strategic Analysis, Inc., Argonne National Laboratory Autonomies Team
Barriers Addressed	• Insufficient suite of models and tools • Indicators and methodology for evaluating economic and environmental sustainability • Inconsistent data, assumptions, and guidelines

Project Goal and Brief Summary

This project will deliver information about anticipated cradle-to-grave (C2G) greenhouse gas (GHG) emissions and costs of different vehicle technology pathways. Argonne National Laboratory will employ the lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) and Autonomie modeling tools to evaluate C2G economic and environmental vehicle technology impacts. The analyses will examine fuel production, vehicle operation, and vehicle manufacturing for different vehicle classes and powertrains.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Analysis projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The comments apply only to Task 1 and Task 2, as information from Task 3 was not presented. The project seems generally well-designed for addressing the barriers and objectives identified. Some improvements to

Task 1 would include consideration of larger light-duty vehicles (LDVs). Including small sport utility vehicles (SUVs) makes sense, given their large market share, but larger light-duty (LD) trucks and SUVs may be the most difficult segments to decarbonize and would benefit from additional analysis. Duty cycles for these vehicles may also differ from those of midsize cars and small SUVs, as the former are more frequently used as commercial vehicles. For Task 1, cost sensitivity results were not presented, though the presenter indicated that such analyses are under way. It is recommended that cost sensitivities be integrated into the levelized-cost-of-driving results. This was done well on the GHG emissions impact side of the project. For Task 2, it would be useful to present updated vehicle lifecycle assessment (LCA) results in the context of existing fuel LCA estimates. In addition, fuel cell sizing sensitivities could be illustrative. This can be parsed to some extent from slide 19 results but could be more clearly presented.

- The team used a proven approach to evaluate and compare advanced vehicle concepts versus baseline concepts, and the approach focused on estimates of the key contributors to differences peculiar to specific technologies (carbon fiber impacts).
- The approach appears consistent with the needs of the industry and builds on previous model development in this area.
- The approach is illustrated in the slides, and GREET is expanded and updated to evaluate fuel and vehicle cycles. It is suggested that the appendix be used to describe the approach in more detail.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has clearly resulted in tangible improvements in DOE's ability to estimate costs and environmental impacts associated with these technologies. This includes valuable modeling improvements and improved data and assumptions useful to a wide range of applications. Significant gaps remain to be addressed by future work, but the project shows solid progress toward overcoming identified barriers. As discussed under Question 1, additional sensitivity analyses and expansions, in terms of the types of vehicles studied, would further contribute to overcoming these barriers.
- The project started in October 2020, and progress is commensurate with funding, helping DOE to achieve the goal of enabling improved technologies to contribute to national objectives. It is good that work has started on both medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs).
- The project has achieved excellent progress, with comprehensive analysis of various scenarios and significant technical accomplishments. The project could be further improved from the points of view below:
    - Comparing slides 9 and 10, the differences among midsize sedans with different types of fuels are similar to those differences among SUVs with the same types of fuels. The comparison between slides 11 and 12 also led to similar conclusions for the GHG analysis; however, should some preferences of SUVs over midsize sedans to certain types of fuels be expected, the project should review the assumption for midsize sedans and SUVs and provide some explanations.
    - In addition to slides 11 and 12, the project should show the breakdown of total GHG for midsize sedans and SUVs into vehicle manufacturing and operation, and feedstock and fuel production.
    - Slide 7 should include the explanations on the error bar.
    - It seems there is a jump from slide 12 to slide 13 on carbon fiber LCA. Some background introduction should be provided before slide 13.
- The accomplishments to date are very good. The quantitative results are clear so far, and qualitative justification make sense. The only questionable item is for the degree of hybridization being used for fuel cell medium-duty and heavy-duty trucks. Recent and near-term Class 8 fuel cell drayage truck battery sizes have been anywhere from 12 kWh up to 100 kWh. Even at the lower end, slide 18 shows that battery mass for fuel cell trucks is less than for diesel configurations.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration with the U.S. DRIVE Partnership team, Strategic Analysis, Inc. (Strategic Analysis), and another national laboratory project team (Autonomie) who have the needed expertise is excellent, as a result of prompt and thorough input provided by the collaborators.
- This project engaged several excellent partners to improve success. There is little to criticize here. One potential improvement might be to compare and contrast the impact estimates from this work with those of other groups working in this space. This might help to further illustrate where key cost and emissions impact uncertainties remain across methodologies. This is perhaps a stretch goal.
- The collaboration is good. The project could benefit from the industry/original equipment manufacturer review of assumptions and preliminary results to provide a reality check, especially for vehicle composition for both material and drivetrain configuration.
- This project has good teamwork with other partners and collaborators. It collaborated with U.S. DRIVE members on C2G analysis, with Strategic Analysis on material composition of fuel cell system and onboard hydrogen storage, and with the Autonomie team on fuel economy and vehicle cost and composition. Nonetheless, it will be better to have some auto companies included in this study to validate the assumptions on vehicle composition and cost.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- C2G economic and environmental analysis is critical to evaluating these options on the table. The project aligns well with DOE Hydrogen Program and DOE objectives, and the project has the potential to advance progress toward DOE research, development, and demonstration (RD&D) goals and objectives.
- The project aligns well with DOE RD&D objectives and has the potential to advance progress toward DOE goals and objectives because critical component costs are still a barrier in the midterm.
- This project has great information for decision-making purposes. There certainly is a need for reliable and consistent C2G economic and emissions information.
- The project clearly contributes to advancing Hydrogen Program goals and objectives. The outputs of this project would have applications across several other workstreams presented at this Annual Merit Review. This project could improve its relevance by emphasizing areas of key uncertainty in cost and emissions impacts. This would assist the Hydrogen Program and other projects by identifying important focus areas for future work.

Question 5: Proposed future work

This project was rated **3.6** for effective and logical planning.

- There is nothing to criticize here. The planned and proposed future work seems like a logical and effective path.
- The proposed activities are very logical continuations of this year’s activities.
- The proposed future work is right on track.
- The project has an effective proposed future work plan that incorporates key decision points and considers barriers. However, the following points could be considered in the future work, if not included in this or other studies: (1) evaluation of GHG emissions associated with the manufacturing of fuel cell stack and balance of plant for LDVs and SUVs; (2) evaluation of GHG emissions associated with the manufacturing of carbon fiber overwrapped tanks for 350 bar and 700 bar onboard hydrogen storage for LDVs and SUVs; and (3) cost analysis for various MDVs and HDVs.

Project strengths:

- Overall, the project demonstrated an excellent study on the C2G transportation analysis, with comprehensive analysis on various scenarios and significant technical achievements.
- The analysis topic is outstanding. There is a sound approach and a highly qualified principal investigator and partners. Progress is excellent, as are collaborations with experts.
- The overall project strengths are the focused approach and ability to build on existing methods and tools.
- The project has tangible and impactful project outputs, with highly rigorous technical work.

Project weaknesses:

- The project could be further improved from the points of view below:
  - Comparing slides 9 and 10, the differences among midsize sedans with different types of fuels are similar to those differences among SUVs with the same types of fuels. The comparison between slides 11 and 12 also led to similar conclusions for the GHG analysis; however, should some preferences of SUVs over midsize sedans to certain types of fuels be expected, the project should review the assumption for midsize sedans and SUVs and provide some explanations.
  - In addition to slides 11 and 12, the project should show the breakdown of total GHG for midsize sedans and SUVs into vehicle manufacturing and operation, and feedstock and fuel production.
  - Slide 7 should include the explanations on the error bar.
  - It seems there is a jump from slide 12 to slide 13 on carbon fiber LCA. Some background introduction should be provided before slide 13.
  - The appendix should show how the GREET model will be expanded and updated.
  - Some automotive companies should be included in this study to validate the assumptions on vehicle composition and cost.
  - Future work or other studies could consider the following: evaluation of GHG emissions associated with the manufacturing of fuel cell stack and balance of plant for LDVs and SUVs; evaluation of GHG emissions associated with the manufacturing of carbon fiber overwrapped tanks for 350 bar and 700 bar onboard hydrogen storage for LDVs and SUVs; and cost analysis for various MDVS and HDVs.
- The suite of market segments considered could be improved. More emphasis is needed on cost uncertainty and sensitivity analysis.
- The project appears to need some industry verification of assumptions and results.

Recommendations for additions/deletions to project scope:

- The project could consider larger LD SUVs and trucks. It is recommended that the project integrate Task 2 findings with existing fuel LCA literature to give a fuller context.
- Potential additions to the project could be empirical testing (where possible, related to mass and cost) to validate some of the results. Also, the development of a publicly available tool would be helpful.
- A forward-looking analytic plan developed in conjunction with partners may be useful.

Project #SA-179: Transportation Benefits Analysis

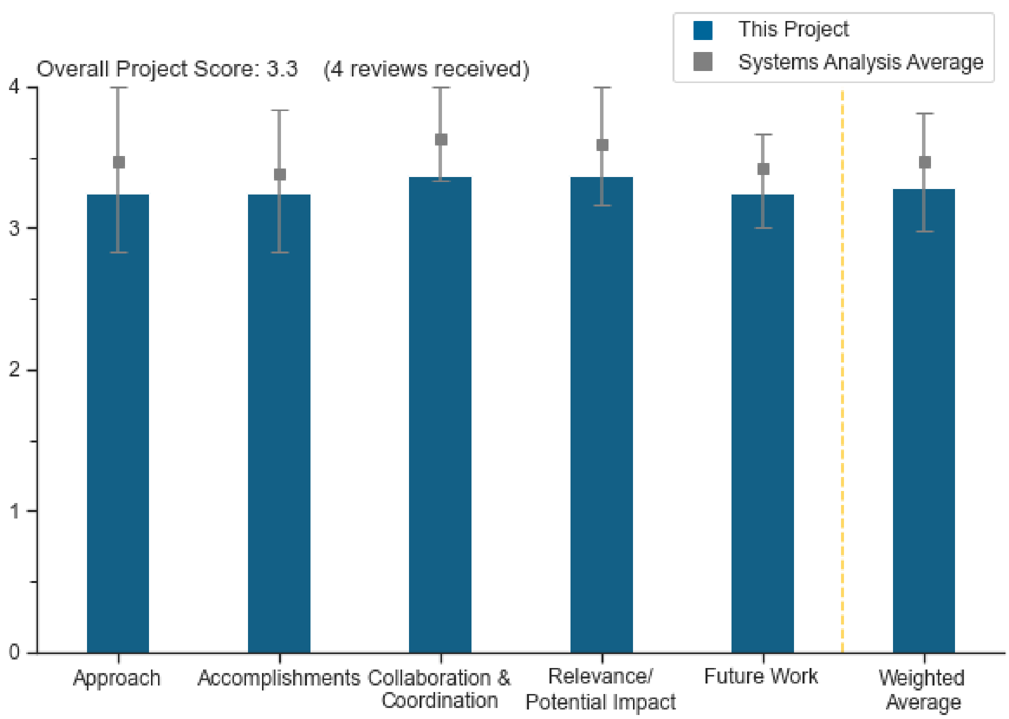
Aaron Brooker, National Renewable Energy Laboratory

DOE Contract #	5.3.0.2.502
Start and End Dates	10/1/2019
Partners/Collaborators	21st Century Truck Partnership
Barriers Addressed	• Future market behavior: Assessing impact of Hydrogen and Fuel Cell Technologies Office (HFTO) research, development, and demonstration targets on future fuel cell and battery electric vehicle adoption • Inconsistent data, assumptions, and guidelines: employ consumer choice models validated with real-world data, and coordinate across U.S. Department of Energy offices (HFTO, Vehicle Technologies Office, Bioenergy Technologies Office) and analysis efforts (Annual Technology Baseline) to use consistent data and assumptions • Insufficient suite of models and tools: expand vehicle choice models to the medium- and heavy-duty sector

Project Goal and Brief Summary

The National Renewable Energy Laboratory (NREL) is collaborating with the 21st Century Truck Partnership to quantify the benefits of U.S. Department of Energy research into alternative powertrain technologies. The project team will model future light-duty (LD), medium-duty (MD), and heavy-duty (HD) vehicle deployment and adoption, emissions reductions, and petroleum consumption reductions associated with the achievement of U.S. Department of Energy (DOE) research and development targets. Researchers will then develop cost and performance scenarios for various levels of DOE contribution. The results will help to identify key targets that drive tipping points in technology adoption.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Analysis projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The team intends to use capable models (Automotive Deployment Options Projection Tool [ADOPT], Future Automotive Systems Technology Simulator [FASTSim], and TRUCK) to analyze vehicle technologies in the Program Success Case and the No Program Case [Fiscal Year (FY)] 2020. The interface between analysis tools is sound.
- The approach appears to be good, and there is good use of existing tools and approaches to updating tools for MD/HD use. However, results are so dependent on assumptions, and there should be a little more insight into their establishment and impact. In addition to more background on how assumptions are established, it is suggested that the project perform sensitivity analyses and determine the drivers and needs for areas of focus. This may be part of future work, but that was not completely clear.
- Good efforts have been made to leverage modeling tools and data to provide useful insight. It could be greatly improved by adding more real-world adoption metrics and the impact of policy levers. This could include the impact of longer charging/fueling time, access to overnight home charging (multi-unit dwellings), impact of limited payload capacity, etc. Policy levers could include vehicle sales and purchase mandates (only zero-emission vehicles [ZEVs] become viable options in certain years), tax incentives, and different vehicle purchase incentives, to name a few.
- Using models such as ADOPT, FASTSim, TRUCK, and HDStock to help estimate the energy and emissions benefits of achieving DOE targets makes sense. However, looking at this from the perspective of what would be ideal, it seems that NREL would ideally consider ADOPT results within the context of a broader suite of analysis. It does not seem that these frameworks are capturing all of the dynamics needed to fully characterize energy and emissions benefits. There are a few critical examples of why this is the case.
    - First, the sales volumes of fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs) that would be achieved if DOE targets were met would have a substantial impact on U.S. petroleum consumption, more than enough to affect global prices.
    - Second, achievement of these goals would have substantial implications for the electricity grid, including infrastructure needs and regional and nationwide electricity prices. The price multiplier for the *Annual Energy Outlook* electricity prices helps somewhat on this front, but it does not describe how we would expect the composition of the grid to change under conditions of elevated electricity demand. It is a good start, but it could be much more robust.
    - Third, depending on how expensive or inexpensive these vehicles are relative to conventional vehicles, potentially significant changes would be expected in household and firm costs of passenger and freight transport. These impacts could also move markets, leading to changes in national passenger vehicle miles traveled and freight ton miles.
    - Ideally, NREL would be incorporating the perspective of global economic modeling in some form. This could be from technologically rich integrated assessment, partial equilibrium, or general equilibrium frameworks—but the global economic perspective should be represented in some way to get a more complete assessment of benefits.
    - Incorporating dispatch or other electricity market modeling would also improve the robustness of this methodology.
    - This is not to say that the NREL approach is subpar, only that it could be improved. Admittedly, incorporating additional large and complex modeling frameworks into this methodology may be outside the scope of what has been funded for this project. A middle ground, then, would be to conduct a robust set of sensitivity analyses that explore alternative petroleum and electricity prices for the program success scenario, as well as alternative assumptions about passenger and freight transportation service demand levels. These would at least put some bounds around how we might expect DOE transportation program benefits to vary, given uncertainty in how other markets would respond to these rather transformational changes in the transportation sector. This will be especially critical for the decarbonization scenarios the project contemplates.

  - It was noted that sensitivity analysis of this type is discussed on slide 21, but the materials do not describe the nature of this analysis or what methods would be used to conduct it. Slide 22 includes a reference to TEMPO being leveraged in FY 2022, but if this benefits analysis and decarbonization scenario work is being conducted in FY 2021, it is unclear how TEMPO will inform those results. Further, some of these sensitivity questions would seem to be outside the capabilities of TEMPO, though this reviewer's knowledge of that framework is limited.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- With the approach set up the way it is, the results make sense; they show that both BEV and FCEV penetration are very low for both LD and HD applications since adoption curves are heavily based on pure cost competitiveness. This is an extremely valuable insight, especially for policymakers that are pushing for 100% ZEVs within one to two decades. Even if the technology reaches technoeconomic targets, adoption will only start to occur many years after targets have passed. The data as presented create a good baseline to really add value for stakeholders when new adoption models (as suggested in the comments above) are explored.
- The project has been meeting its milestones, such as the March 2021 milestone, an important priorities' assessment and plan. The charts show that technology assumptions are consistent with DOE transportation program input. Legacy analysis approach improvements were discussed.
- There is good progress for a project that perhaps is more complex than originally anticipated.
- It is hard to fully evaluate progress on the updated 2021 analysis since, as the presenter noted, most of the results being presented are from the older FY 2020 analysis. That being said, the 2020 results are a useful characterization of where DOE believes technologies may penetrate U.S. markets under conditions of program success and what the benefits of this penetration might be. Updated analysis with better characterization of MD/HD vehicles should only improve this. The updates to ADOPT to handle MD/HD vehicles are well-defined and demonstrate good progress toward the project goals. These improvements seem very likely to contribute to reducing barriers to our understanding of the benefits of FCEVs once they are brought to bear to update the FY 2020 analysis. During the presentation, there was not enough time to discuss the intuition behind the FY 2020 MD/HD truck results presented on slides 16 and 17. Perhaps the report does so, but that was not noted anywhere in the presentation. Such a discussion would be perhaps the most valuable output from this project, as it would help to characterize the key drivers of expected market penetration, or the lack thereof.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- DOE connections are good, as is the 21st Century Truck Partnership. Gathering feedback—especially from key policymakers, truck operators, and LD vehicle manufacturers—would add great value for vehicle adoption assumptions and the role that policy could play. The project should look especially to California stakeholders that are setting aggressive ZEV targets that will likely be re-created in other states.
- Collaboration with the U.S. DRIVE Partnership and coordination across Office of Energy Efficiency and Renewable Energy program offices are outstanding.
- There is great collaboration and use of existing DOE groups and industry working groups. Reviewing results and drivers with industry working groups to inform and provide validation is recommended.
- The project participants seem to be making good efforts to gather the most up-to-date modeling inputs for their analyses. Gathering industry perspectives through the 21st Century Truck Partnership is good, though how applicable that perspective is to vocational vehicles is not clear. There do not appear to be any similar information-gathering efforts on the LD side of the analysis. Therefore, there seems to be room for improvement in terms of the scope of industry outreach.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is of critical importance to the DOE Hydrogen Program's goals and objectives. Characterizing the potential impacts and benefits of program success not only helps to justify the program, but also can help to guide program goals and priorities. This work helps to clarify the transportation applications in which fuel cells are most likely to succeed. The relevance of this project could be improved only by expanding the universe of estimated benefits. Work to estimate criteria emissions benefits, in addition to greenhouse gas emissions benefits, would have a strong impact. Estimating jobs impacts and impacts on overall household/firm expenditures would also be welcome.
- This project provides a method of evaluation and really good feedback on impacts of DOE funding initiatives. Also, the project can be used to set areas of focus and prioritize funding initiatives.
- The project aligns well with DOE's research, development, and demonstration objectives and has the potential to advance progress toward DOE goals and objectives in the transportation sector.
- The relevance and impact could be huge, but it is not there yet. However, there is great potential to add significant value with some of the earlier changes suggested.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Overall, the planned work for the remainder of FY 2021 seems logical and is likely to help address critical program barriers. Per comments on the approach above, a more holistic consideration of economic impacts could enhance these benefits, but the planned work is good. The project participants are right to identify market disruptions and interactions as an area of future work in FY 2022. However, it is unclear that the planned methods will fully address this need. Per comments above on TEMPO, it is unclear that this framework can address all of these types of questions. It may make sense to supplement these methods with electricity sector modeling and global economic modeling. It is encouraging to see that work in non-road and aviation sectors is under consideration for FY 2022. DOE and NREL are strongly encouraged to conduct this work. Especially in the context of fuel cells, many of the most critical applications may be in these types of non-road applications. This is work that should go forward with full funding.
- The proposed activities are very logical continuations of this year's activities. Non-road and off-road analysis would be interesting.
- The future work appears to hit all the areas in need of refinement of assumptions and tools being used.
- Proposed future work focuses a bit too much on refinement, rather than taking a step back to ensure the overall direction provides the highest value. More stakeholder engagement and inclusion of new high-level metrics will add more value than detailed refinement of assumptions at this stage.

Project strengths:

- The overall project strength is the development of a structured approach to evaluating the impacts of DOE funding. Once it is defined, then stakeholders can evaluate input assumptions to better understand funding priorities based on cost and emissions impacts.
- The scope of work is highly impactful. There is good use of collaboration to identify modeling inputs. Outputs so far contribute strongly to program goals. Plans to expand beyond on-road vehicles are taking this project in a good direction.
- The overall project is set up well to address key questions and issues for reducing the environmental impact of the transportation sector.
- There is a sound approach and a highly qualified principal investigator and partners. There is excellent progress and collaboration or coordination with DOE and external/internal experts.

Project weaknesses:

- The project weakness currently appears to be the complexity of the project and the ability to process and present the "take-aways." For instance, it is unclear how many variations in assumptions affect the results, and it is unclear which assumptions are the biggest drivers. It is unclear which inputs present the most risk for not meeting DOE goals. It is likely all there but appears to be difficult to present.
- Lack of dynamics for fuel prices and transportation service demand could limit usefulness of benefit estimates. This is especially true for transformational decarbonization scenarios that would be expected to have significant impacts on petroleum prices and the structure of the energy sector. Sensitivity analysis plans need to carefully consider how to characterize these impacts. Characterization of the intuition behind market penetration estimates could be improved. That messaging is not very clear so far, at least for the MD/HD results. The project could benefit from broader industry outreach in LD and MD/HD vocational sectors.
- Keeping a refined scope to quantifying impacts only from DOE-funded research could be a major missed opportunity. It is concerning that the project researchers do not understand their assumptions and analysis well enough to form basic insight. Even with two panelists supporting the question-and-answer session, simple questions and confirmations were met with confusion.
- There are no weaknesses.

Recommendations for additions/deletions to project scope:

- Current results have shown that much more support outside DOE is needed to accelerate ZEV adoption for on-road transportation. This should be framed as a call to action, as the typical pathway to cost competitiveness is not acceptable, given global environmental targets. The project should find ways to incorporate the voice of the customer to inform vehicle adoption and explore a number of different policy scenarios (for example, if policy support created a total cost of ownership parity tomorrow and if ZEV was the only option by a certain year). The project should take a look at policies in California for specific examples of these policy frameworks. Also, the recent proposed awards from a combined California Air Resources Board/California Energy Commission grant supporting drayage trucks in California now has public information for commercial Class 8 truck costs in about the 2023 timeframe, with multiple reference points for both battery and fuel cell trucks. A copy of the full proposals to help establish a baseline can be requested (spoiler: they are not cheap).
- The project should improve robustness of planned sensitivity analysis methods and ensure these methods include global economic modeling and electricity market modeling. For future project cycles, the team should consider expanding the scope of benefits to include criteria air pollutants and other economic metrics.
- In addition to more background on how assumptions are established, it is suggested that the project perform sensitivity analysis and determine the drivers and needs for areas of focus.

Project #SA-180: Advanced Network Analysis of Hydrogen Fuel Cell Automated Vehicles for Goods Delivery (ATLAS) – Total Cost of Ownership of Autonomous Fuel Cell Fleet Vehicles

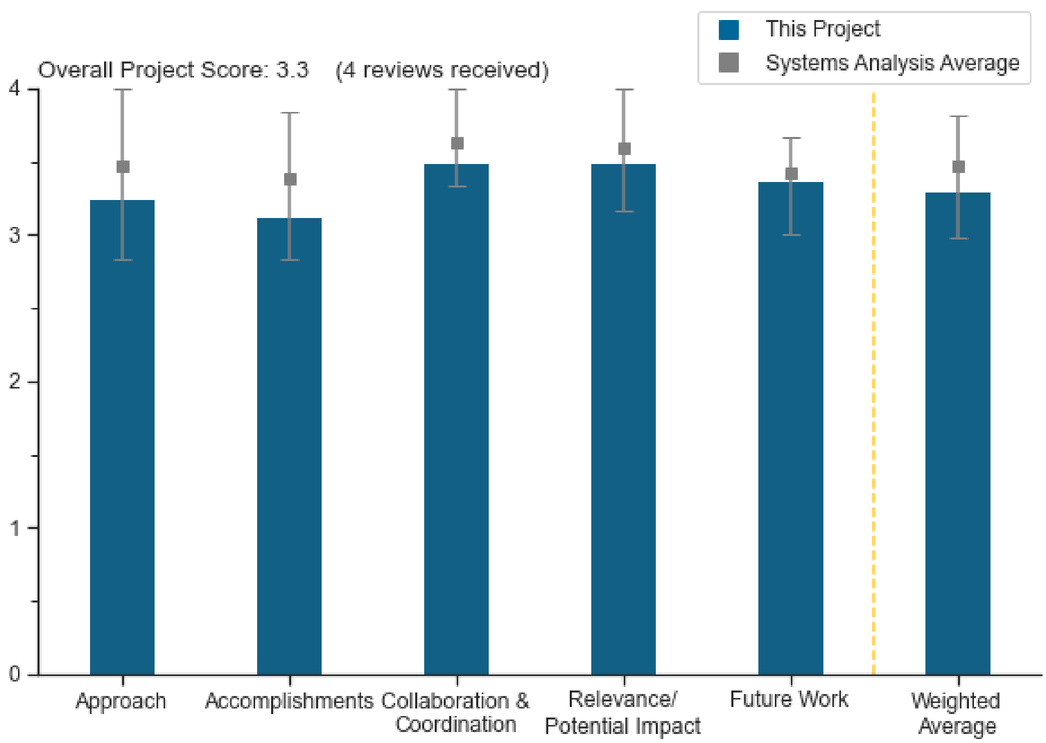
Tim Lipman, Lawrence Berkeley National Laboratory

DOE Contract #	5.3.0.2.502
Start and End Dates	9/1/2020
Partners/Collaborators	National Renewable Energy Laboratory, Center for Transportation and the Environment
Barriers Addressed	• Future Market Behavior – Economic and environmental value of FCEVs in MDV applications • Insufficient Suite of Models and Tools –MDV fleet level analysis, early adopters, H2 refueling infrastructure roll-out, economics and emissions analysis

Project Goal and Brief Summary

The Advanced neTwork anaLysis of hydrogen fuel cell Automated vehicleS (ATLAS) seeks to help directly reduce harmful emissions of both greenhouse gases (GHGs) and criteria air pollutants (CAPs) through implementation of zero-tailpipe-emission technologies. In this project, ATLAS aims to enable future regional goods delivery networks, with fleets comprising medium-duty fuel-cell-powered delivery vans and heavy-duty short-haul hydrogen trucks. The project team is developing delivery network analysis tools that will help evaluate routing optimization, vehicle duty cycles and drive-cycle dynamics, vehicle energy use, and the impacts of vehicle automation. Researchers will also calculate costs for these networks and compare them to those of conventional fuel systems.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Analysis projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The team has a thorough, systematic approach to conducting a challenging analysis involving steps such as routing and fueling facility siting. The approach is being used on an initial site. The choice of GraphHopper mapping for routing analysis is good for what this project needs to accomplish.
- This is a good approach, in theory. The project will likely run into challenges with process and need to remain flexible in finding solutions and modifying the approach. For instance, the team will likely need to complete simulations for case studies and evaluate results for effectiveness and utility before applying them broadly. The station deployment approach is unclear, i.e., it is not clear whether the project will consider only private stations that are commonly found at distribution sites or also private or shared station deployments. The distribution facility approach is also unclear, i.e., it is not clear whether the project will consider existing package distribution facilities, future unconstrained locations, or both. It will be important to accurately characterize the duty cycles for various delivery schemes, as they are unique and differ depending on whether they are commercial, residential, urban, rural, etc. Results from the study will be valuable to better understanding the benefits for a holistic approach to parcel delivery using zero-emission vehicles/fuels and autonomous technology.
- The project developed a systematic approach that combines a fuel cell delivery van and drayage truck vehicle route modeling, detailed simulation of vehicle energy use, hydrogen station planning/design trade-offs, and calculation of vehicle ownership and hydrogen fuel costs. It is suggested that the project add some more description of the use of GraphHopper, such as required input and output.
- The project aims to model the incorporation of hydrogen-powered fuel cell electric vehicles (FCEVs) in autonomous driving modes. Based on the work presented so far, there did not seem to be a clear connection in the approach to this aspect of the project goals. It is not clear how the routing behavior or the needs assessment, as presented so far, would be specific to the automated vehicle use case. In addition, it seems as though the geographic scope of modeling will necessarily be limited to smaller regions and/or smaller numbers of routes. The project approach was not clear in terms of how useful this could be in implementation or how potential future users of the project results or tools could utilize this more limited geographic result for larger or broader system considerations. It is unclear whether it would need to be piece by piece for individual regions or whether a multi-regional approach could be implemented in a single run, somewhere down the line.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has been meeting its milestones, such as demonstrating initial success with GraphHopper. Development of H2Plan, an infrastructure analysis platform, began recently, and it is not yet time to assess progress.
- The project has reached several accomplishments so far. However, there are still gaps between these accomplishments and the milestone deliverables, as shown in progress toward DOE targets or milestones. In addition, there are a few points for further improvement. On slides 12 and 13, the project should add the assumed hydrogen refueling station into the simulation map, show the number of delivery vans for the simulations, and explain how the five distinct routes are calculated with 80 van stop locations, as some routes are intertwined with each other. It is suggested that the project do some more studies to investigate the relationships between the number of vans, distinct routes, van stop locations, and number of package drops. It will be interesting to see the timeline of the delivery along the routes on the map. The project is asked to provide some explanations on how the approach could realistically reflect the actual traffic situations.
- There is good accomplishment to date. It is still early in project. The project has done good work in finding an open-source solution to routing, but it would be good to verify its effectiveness and accuracy with a parcel delivery industry representative.

- The project team has spent significant time implementing and developing a routing process that will be central to the project's overall goals; however, it is not entirely clear why this new development is necessary. Several off-the-shelf options are available, even in open-source software. The significant amount of time that was put into this routing routine could have been spent more on other, later modeling steps in the project.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The project is co-led by Lawrence Berkeley National Laboratory (LBNL) and the National Renewable Energy Laboratory (NREL), in collaboration with the Center for Transportation and the Environment (CTE). The project teams demonstrated strong expertise in modeling and analysis in past projects.
- Collaboration with CTE is a major plus, in addition to the excellent partnership between LBNL and NREL.
- Several relevant and potential collaboration and coordination opportunities have been identified. The project should also consider collaborating with other ongoing hydrogen fuel station siting activities that have been ongoing in California at the state government level and other research and education institutions. At the least, the project should coordinate with these other ongoing works for lessons learned and potentially to provide some points of comparison or identify opportunities to capitalize on the work that is being done today in terms of siting hydrogen fueling stations. There may be opportunities for co-location that should at least be evaluated.
- The collaboration is good but will benefit from having an industry partner to collaborate and verify the assumptions. It would be good to have that partner provide the requirements and operational constraints since that can be unique to logistics and parcel delivery.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is definitely timely and will provide valuable insights, based on the project goals. As the project team notes, there are already multiple demonstration projects on the ground that have similar operations, and this work could be a very valuable resource for translating those demonstration projects' findings into improved implementation for more commercial-ready projects in the next phase of deployment.
- The goal of the project is to enable future regional goods delivery networks based on hydrogen fuel and medium-duty fuel-cell-powered delivery vans and heavy-duty short-haul hydrogen trucks; the project will work toward this with a unique and detailed analysis that combines and advances hydrogen system modeling capabilities. The project aligns well with current DOE objectives.
- Depending on the effectiveness of the model, this project will be very relevant and impactful. The project can inform funding decisions, industry needs, funding program characteristics, and industry blind spots.
- The project aligns well with DOE's research, development, and demonstration (RD&D) objectives and has the potential to advance progress toward DOE goals and objectives in these segments of the transportation sector.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The proposed future expansion of scope to additional vehicle classes and use cases is a very good addition to the project. In addition, expanding the number of routes/geographic extent is necessary. It would be helpful if the project team were to provide some vision of even further expansion and what will be necessary to implement the project on an even larger scale. This question of scale will be critical for growth of commercial implementation.
- The project aligns well with DOE's RD&D objectives and has the potential to advance progress toward DOE goals and objectives in these segments of the transportation sector.
- Future work is on target. However, the project would benefit from some validation steps along the way.

- Highlighted at beginning of the presentation is the intent to help reduce GHG and CAP emissions, especially in highly impacted communities. However, the proposed future work on slide 18 did not include any GHG and CAP emission analysis for the environmental benefits of FCEV goods delivery. How the highly impacted communities are identified should also be included in the scope of the future work.

Project strengths:

- The project's strengths are its timeliness, its applicability to real-world operations and near-term demonstration or commercialization, and its structure to consider many aspects of delivery vehicle operations, including drive cycles and infrastructure development.
- The project has developed an excellent systematic approach that integrates and extends modeling capabilities developed at three national laboratories with collaboration activities. The approach is well-illustrated in the slides. The project demonstrated the successful application of GraphHopper on route simulations.
- This is an outstanding analysis topic. The project has a sound approach and a highly qualified principal investigator and partners. Progress is excellent, as is collaboration or coordination with experts.
- This is a complex project but can have some very impactful results that are both qualitative and quantitative. It will be exciting to start seeing some results.

Project weaknesses:

- The project should be further improved in terms of the following points:
  - The progress of the project seems to have fallen behind the expected milestone deliverables, possibly because of COVID-19.
  - It is suggested that the project add some more description of the use of GraphHopper, such as required input and output.
  - On slides 12 and 13, it is suggested that the project add the assumed hydrogen refueling station into the simulation map, show the number of delivery vans for the simulations, and explain how the five distinct routes are calculated with 80 van stop locations, as some routes are intertwined with each other.
  - The project should do some more studies to investigate the relationships between the number of vans, distinct routes, van stop locations, and number of package drops.
  - It will be interesting to see the timeline of the delivery along the routes on the map.
  - The project is asked to provide some explanations of how the approach could realistically reflect the actual traffic situations.
- This is a complex project that could benefit from some industry validation and verification of operational requirements constraints. There is a very broad range of possible inputs and scenarios that will need to be narrowed down and focused through industry needs in order to provide useful results.
- Currently, the project seems to be potentially narrow in its practical applicability. Also, there is not a well-defined methodology for making this work specifically applicable to the automated vehicle application.
- There are no weaknesses.

Recommendations for additions/deletions to project scope:

- The project needs either to develop a way to expand the geographic region and routes that can be modeled within this project or to develop a more complete vision and recommendations for enabling this kind of large-scale modeling in a future project. Also, the project needs to develop more concrete methodologies for application to the autonomous operation case specifically.
- GHG and CAP emissions analysis for the environmental benefits of FCEV goods delivery and the identification of the highly impacted communities should be added to the project scope.
- There are no current recommendations for additions/deletions. There is a good deal of challenging work to be done with the scope as is.

Appendix A: 2021 Hydrogen Program Review Summary

This appendix shows the results of the Hydrogen-Program-level peer review for the 2021 Annual Merit Review (AMR), including feedback from a subset of the reviewers attending the AMR. A total of 61 Program-level reviewers were invited to provide feedback, and 20 reviewers responded.

1. The Hydrogen Program has a mission and strategy that are clearly articulated and has appropriate goals and milestones, as well as quantitative metrics that are SMART (Specific, Measurable, Actionable, Relevant, and Timely).

Please comment on the overall Hydrogen Program (including activities in the U.S. Department of Energy [DOE] Hydrogen and Fuel Cell Technologies Office, Office of Fossil Energy, Office of Science, Office of Nuclear Energy, and ARPA-E), as well as each subprogram/activity area, as appropriate. (Note: The Hydrogen Technologies subprogram comprises three categories: Hydrogen Production (with HydroGEN Seedling as a sub-category), Hydrogen Infrastructure, and Hydrogen Storage.)

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

	Hydrogen Program Overall Rating	Hydrogen Technologies R&D Subprogram Rating	Fuel Cell Technologies R&D Subprogram Rating	Technology Acceleration Subprogram Rating	Safety, Codes and Standards Subprogram Rating	Systems Analysis Subprogram Rating
Average Score	9.2	9.1	9.3	8.9	9.1	9.1
Number of Responses	20	20	19	18	18	19

Comments:

- The Hydrogen Program is two things: “user friendly” and forward-looking. DOE is accessible to all, and the agency provides information on projects for all stakeholders. The Hydrogen Program is neutral and well-respected. The Program provides tools for analyzing hydrogen applications without actually investing in the applications. The ability to “test out ideas” without investing is invaluable to the goal of hydrogen available at $1/kg in one decade. The Program de-risks researchers from going ahead with their ideas. One is left with no doubt that the models are under continuous update, as are the technology validation programs. Stakeholders are under pressure to make decisions about their own projects, and the AMR provides the tools to make decisions on one’s own without divulging plans and products. I realize that an across-the-board rating of “strongly agree” may appear maniacal. In fact, the consideration took a long time, and I landed at a 10 for all. The plenary with the Energy Secretary was so impressive, I felt as though I was able to speak with her. The Program Manager’s presentation was equally remarkable, as it was full of details and data, and individuals’ names were mentioned. The agency leads’ session in the plenary was also very important for the AMR participants to hear through Zoom. Thank you for the thoughtful Program and AMR.
- The Hydrogen Program has a well-articulated mission and strategy with appropriate goals and metrics. This Program has some of the most talented researchers in the world; they should be considered an important asset for the program and the U.S. energy economy. This work provides early-stage research across several sectors, including hydrogen technology, hydrogen production, fuel cell development, technology validation, manufacturing, and market transformation. With support from the Secretary and President, the United States may continue to be in a position to increase efforts for international leadership, industry collaboration, and partnerships with resources from the national labs, academia, and state partners. With this leadership position, DOE may be in a position to increase efforts for collaboration, partnerships, and demonstrations with state and regional stakeholders. Such efforts will help to advance the research from the labs to commercial applications.

- I do not have any additional specific recommendations with respect to the mission, strategy, and goals. I feel that the goals are comprehensive and well-formulated. I have seen the goals respond to the needs of stakeholders, such as the addition of intermediate and near-term cost status and targets. The Program strategy appears to be well-designed to enable research and development (R&D) that has the potential to make progress toward the targets. The diversity of structures from individually funded projects to consortia and larger mainline efforts (such as H2@Scale) provides flexibility to the Program to address a wide variety of potential uses of Program outcomes and adjust to stakeholder needs.
- The Program is clearly a large and valued effort, judging from government spending across various offices. Efforts cover the full range, from fundamental science to loans and capital risk reduction for enabling scale-up of commercialization. There is an interesting increasing shift to hydrogen as a way to decarbonize CO_2-intensive industry (relative to the 2019 AMR). Dr. Satyapal had many special announcements; she certainly made the plenary must-see viewing.
- The overall Hydrogen Program goal among DOE offices will benefit from closer coordination among R&D activities. The Hydrogen Program plan will address collaboration among the DOE offices, and the Hydrogen Energy Earthshot initiative will drive the future targets.
- The Program is well-planned and well-managed, with each office having the appropriate focus. The Program and subprogram overviews were excellent. The increased focus on environmental justice is overdue and good to see. However, there are some gaps in the Program, and these will be discussed below.
- The use and development of metrics (goals and milestones and targets) in the Program is impressive, consistent, and forward-looking.
- The Program is very well-structured, with clear objectives and milestones. However, the Hydrogen Shot objective of $1/kg hydrogen in 1 decade will be extremely challenging.
- I am looking forward to the increased activity in all Program areas and the ability to deploy (moving past technology readiness levels [TRLs] 1–4) the goals set out by this administration, bolstering the U.S. visibility and overall activity in hydrogen.
- The Program is outstanding. It is the best R&D program worldwide.
- The Program's objectives are very clear. The synergy between the various offices is well-presented and helps focus efforts to achieve the Hydrogen and Fuel Cell Technologies Office (HFTO) objectives. The goals are consistent with the global community. However, I noticed, for instance, that work on hydrogen electrochemical compression was no longer part of the Program. It would be beneficial to indicate when an area is no longer active and the reasons why. I think it's important to learn from what works and what
- doesn't.
- I think the Program and subprograms could do a slightly better job in articulating strategy—for example, having more waterfall charts/total cost of ownership sensitivities explaining where the biggest gains can be made and then directly linking that to the portfolio of projects.
- The Hydrogen Program mission, strategy, and goals make sense. However, it is not fully clear whether the Program goals need further "revamping" to reflect the recently announced ambitions of the new administration, including the Hydrogen Earthshot.
- One of the most critical issues in the hydrogen economy scheme is large hydrogen storage. Unfortunately, from the work I have seen at the AMR, this issue has hardly been addressed, and there do not seem to be any new innovative ideas being developed. More emphasis should be given to this critical topic, including materials for hydrogen storage, with assessment of full cycle life, energy required to release hydrogen, and full thermodynamic study.
- Connections/synergies between various initiatives/consortia are not well-articulated.

2. The Hydrogen Program is well-focused and well-managed and is effectively fostering research, development, demonstration, and deployment (RDD&D) to enable innovation and advance the state of technology for hydrogen and fuel cell technologies to be competitive and achieve widespread commercialization and adoption by industry.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Average Score	9.0
Number of Responses	19

Comments:

- The Program is nicely arranged into the key areas needed to generate a hydrogen economy that functions, starting at hydrogen creation and ending with consumption, plus the steps in between and the facilitating functions such as codes. Each area can then be interrogated as to needs, and requests for proposals offered to address them. At the same time, the interfaces between areas are not ignored, and the relevant groups do discuss what it will take to be sure there is no problem going from, say, production to delivery; plus, the simulation and analysis teams also look at these issues. I am pleased to see long-term and near-term goals and planning. The individual managers seem committed personally to their areas, and Dr. Satyapal just about lives her work. This matters because it indicates the quality of effort they will put into making the Program succeed. Analysis is used to help isolate the key problems—not just as part of the R&D but as part of the management of the Program. This is another example of using a wide variety of inputs (scientists, industry, political considerations, simulation) to make well-informed and well-timed projects funded with a suitable distribution over the portfolio.
- As in prior years, I continue to find the Hydrogen Program to be well-managed and effectively operated. I do not see any faults in the work of the Program managers or DOE staff in running what is truly one of the most cutting-edge and reliable technology development programs in the world.
- The Hydrogen Program includes a vast portfolio of projects that address development of technologies from basic science to manufacturing and scale-up to demonstration of systems. The department is performing a commendable job managing the projects.
- My rating for the Program is actually 8.5, with 10 each in R&D, 8 in Demonstrations, and 6 in Deployment. The Program's R&D activities are outstanding, significantly advancing the state of the art. However, the Program has not done enough to enable deployment. Engaging more at the state and local levels and supporting education and outreach activities would help. There are still many people, including state policymakers, who are not aware of hydrogen and fuel cell technologies and their benefits. In addition, the ban of fuel cell electric vehicles (FCEVs) from the Northeast tunnels and double-deck bridges has delayed the deployment of FCEVs and hydrogen stations in the Northeast by 5–7 years. During that time, battery electric vehicles have gained in market share, and interest in light-duty FCEVs has waned. The tunnel safety studies conducted by Sandia National Laboratories were an excellent response to that issue; however, the ban should have been addressed much earlier—and those studies were completed two years ago, yet the ban is still in place.
- The Program is extremely well-focused and well-managed and has been very effective at fostering R&D. Some of the demonstration and deployment projects have been well-focused and well-managed. However, there may be value at this time to increasing demonstration and deployment to bring this technology into commercial applications with market acceptance, as are other clean energy technologies, such as solar, wind, and battery technologies.
- As it seems, the Hydrogen Program sets its targets on input from industry and the new results from the projects. In some cases, significant progress is presented by the principal investigators, and in my view, it has to be validated by at least one other lab (outside the same project) to avoid false positive outliers.
- The addition of Hydrogen from Next-generation Electrolyzers of Water (H2NEW) and Million Mile Fuel Cell Truck (M2FCT) is welcome and complementary to the other consortia. H2NEW's linkage with

HydroGEN 2 is clear as far as the line between the two. I expect H2NEW will grow to include a platform to host findings from HydroGEN that are maturing to that level in time.

- This is probably one of the best-managed office programs in DOE, with one of the best office teams.
- Excellent.
- Overall, the Program RDD&D portfolio is well-balanced and wide-reaching. However, considering the bulk of current domestic and global hydrogen supply comes from fossil fuel and is likely to stay that way for quite some time, there ought to be a more visible engagement in “greening” fossil sources of hydrogen. Because of the large scale, even incremental changes can translate into meaningful greenhouse gas reduction. Toward this goal, I suggest the Hydrogen Program more actively engage with the Office of Fossil Energy and Carbon Management to advance carbon capture, utilization, and sequestration (CCUS) and “blue hydrogen” production technologies from steam methane reformer plants or other fossil fuel sources.
- Some of the models could be updated to include new hydrogen/fuel cell applications. Also, what is needed are projects that integrate hydrogen applications, such as green steel with transportation at the hydrogen supply.
- Widespread commercialization and adoption by industry needs more effort.

3. The Hydrogen Program’s portfolio of projects is appropriately balanced across research areas to help achieve the Program’s mission and goals.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Average Score	8.6
Number of Responses	19

Comments:

- Appropriately balanced does not imply evenly balanced but, rather, employing people and funds where they are needed most in the order that makes sense. Using this definition, I feel the Program or office is in fact well-balanced. The funds seem in largest part devoted to those issues that prevent a hydrogen economy from taking hold; to science problems, such as how to force a very low-mass gas into a small enough volume to transport it; and to the accompanying engineering problems of getting said gas in and out in a reasonable time in a device that is modest in cost…but, at the same time, developing the codes and standards needed for societal acceptance and a legal framework that permits insurance that can be afforded for that storage system…and then also funding seemingly unrelated technology projects for use in what seem like niches but what are in fact the start of building the supply chain for the storage system we started considering. All these steps are needed—the science first, so you know what you are engineering, and that step is well in hand; the engineering next, in concert with the codes, which is also making good progress; and now an expanding Technology Acceleration subprogram that will bootstrap the supply chain. A good example here is that work to help implement technology to get through the valley of death, as it were, has been (appropriately) fairly low. Funds went to R&D, not to industry in the largest share. Now a great deal more is going to de-risking implementation and commercialization through facilities to validate and integrate and funds for lowering capital risk. This makes sense now, when it did not before, and the shift is an example of appropriate management response to the changing situation. All that said, I think to achieve the goals elucidated in this plenary, the funding needs to shift more toward technology acceleration.
- The Program has been well-balanced on development of polymer electrolyte membrane (PEM) fuel cells and electrolyzer technologies for a number of years. The focus has been shifted to other emerging technologies, such as solid oxide fuel cells (SOFCs) for electrolysis and energy storage. The reduction of hydrogen cost to the levels targeted by the Hydrogen Earthshot requires re-balancing the research,

development, and demonstration (RD&D) activities by prioritizing end-use demonstrations for hydrogen production.

- The portfolio is appropriately balanced across research areas and is recognized globally as world-class, with the United States in a leadership position. Increased efforts for demonstration and deployment, consistent with local and state and regional stakeholder engagement coupled with educational initiatives, may provide additional value for commercialization and market acceptance.
- The Program is very responsive to stakeholder recommendations.
- The balance of projects is excellent.
- I am concerned about the recent shift in focus in the Program toward medium-duty (MD) and heavy-duty (HD) applications. I do agree that this area needed to grow for the DOE's portfolio of projects, but I am concerned that the shift is looking to be too strong toward these focus areas and away from the light-duty applications. While there has been significant stakeholder interest in MD and HD applications in the last couple of years, my opinion is that this has been due to misunderstanding of technology capabilities and the current readiness of commercial products in these sectors. Several stakeholders are still looking to hydrogen and fuel cell technologies being an important part of the light-duty sector in addition to other sectors. What these stakeholders need help with is not only advancing the MD and HD market but also data, research, and demonstration that provide further insight and additional examples of how FCEVs continue to have a role to play in the future of light-duty transportation as well, especially for aggressive targets of full change-over to zero-emission options in the coming one to two decades. In addition, much of the HD fuel cell work appears to be considering the needs of HD as completely different from light-duty when, in reality, they are the same focus areas (cost, durability). Even if HD targets may be more aggressive, it doesn't seem logical that technologies to meet those targets have to be treated separately. It would seem that technology transfer would logically be immediate, just as it has been in the opposite direction so far (as we see examples today of light-duty fuel cell systems being applicable to HD vehicles.
- The Program should consider boosting projects aimed at "hard-to-decarbonize" industries such as iron, steel, concrete, etc., both in number and effort level. Given the growing desire and urgency to decarbonize these industries, as well as the inherent advantage in hydrogen quality and cost compared to fuel cell applications, this space could be an opportunity for early large-scale hydrogen market entry. The recently announced HyBlend project is one example that can potentially advance this approach.
- In the areas of "deployment," one of the more impressive portfolios of projects were presented by federal/ state agencies that were not from DOE, because the review of the applications showed successful use of hydrogen over a relatively long time. The emphasis on fuel cell research and hydrogen (vessels) stored on board vehicles is very much needed.
- There should be more funding for systems analysis, which can be essential in guiding where R&D efforts in other subprograms should be targeted.
- Given the lack of awareness of hydrogen and fuel cell technologies, the Program should increase education and outreach activities, particularly at the state and local levels.
- More emphasis should be given to hydrogen storage and hydrogen production.
- Having better defined priorities in various research areas is suggested.

4. The Hydrogen Program is collaborating with appropriate groups of stakeholders.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Average Score	8.4
Number of Responses	18

Comments:

- Working with Vehicle Technologies Office (VTO) truck groups is a good idea and very appropriate, given both groups' goals. Working with the Advanced Manufacturing Office is appropriate for getting new technologies in production. In addition, there is a great deal of work across offices and agencies in the hydrogen area, which seems to be counted as collaboration and, I suppose, is at the budget level. Within programs, there are many examples of significant collaboration at the project level. Where true collaboration occurs, it is a benefit to HFTO goals. I would like to see more U.S. Department of Defense collaboration, especially on implementation.
- The breadth and depth of collaboration with the various domestic entities are strong and encouraging.
- The key stakeholders are involved in every subprogram.
- The Office of Energy Efficiency and Renewable Energy (EERE) has been the de facto pioneer of the hydrogen economy and infrastructure over the years. The current trend is growing collaboration between DOE offices for implementing a coherent hydrogen plan. EERE can play a great role to re-focus the efforts in other offices, such as ARPA-E, on critical technology needs.
- The Program seems to have its own pull of research groups and stakeholders. To innovate and bring in new ideas, it has to refresh its ranks. In my personal view, each large consortium should include a certain percentage of newcomers with new ideas, tools, and perspectives. These need to be research groups from academia and companies that have not participated in the consortia before (or for several years). Also, there has been great advancement in the field outside the United States, especially on topics such as hydrogen production, which the U.S. consortia can leverage. Inviting international partners can contribute significantly to the advancement of the U.S. programs in areas where they are lagging.
- Overall, the involvement of the various stakeholders in the United States is quite good. It would be good to clearly see effort with other countries, especially on harmonization of codes and standards. Specifically, tight coordination with Canada, which shares a border, would be important when it comes to hydrogen blending in natural gas and infrastructure for cross-border transport, to name a few. As Canada has expressed clear intentions to promote the hydrogen sector through its new strategy, joint funding opportunities, at least coordinated, in areas of common interests would be a very good idea.
- Collaboration has always been a strength of the DOE Program and the projects it funds. I did not find any significant lack of necessary collaboration. The only area that could potentially be improved is for some individual projects related to hydrogen fueling infrastructure that provide analysis of needs in California from a carte blanche perspective. This is obviously not the case. I don't expect those projects to fundamentally alter their approach, but at the least they should address the ongoing development on the ground. They can engage with the California stakeholders and either look for opportunities to leverage ongoing development with respect to their own projects (either for tools in their projects or in terms of how their project outcomes can interface or build alongside current development).
- Collaboration with the public sector is excellent. Collaboration with industry needs to be increased.
- Stakeholder participation has been somewhat limited, with a focus on early-stage research. This is an area that at this time may be increased with collaboration from stakeholders, including state and regional authorities. With additional funding, demonstrations could be developed through state and regional stakeholder engagement with execution of planning documents that are now being developed in several states, including California and the Northeast states.
- Outside of DOE, perhaps more state governments can be included. Here, I mark off a "9." Perhaps, if there is no action in a zero-emission vehicle state, it would be possible for a status to be given, even as "no action." We need help with planning. As far as collaboration within the Program, the message of "we will work together" was conveyed, but given the newness of the administration, any accomplishments were premature.
- The Program should increase engagement with state and local decision-makers.
- Optically, the Program tends to rely more on national laboratories.

5. The Hydrogen Program's RDD&D aligns well with industry and stakeholder needs and is appropriate given complementary private-sector, state, and other non-DOE investments.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

	Hydrogen Program Overall Rating	Hydrogen Technologies R&D Subprogram Rating	Fuel Cell Technologies R&D Subprogram Rating	Technology Acceleration Subprogram Rating	Safety, Codes and Standards Subprogram Rating	Systems Analysis Subprogram Rating
Average Score	9.0	8.8	9.1	8.8	8.9	8.6
Number of Responses	18	18	18	17	17	17

Comments:

- The use of the "tech team" concept helps ensure a good alignment between industry needs and Program goals. My understanding is that offices with these teams do much better than those who do not use the concept, and certainly, here that seems true. The overall aim is, of course, a government value—a technically sophisticated clean energy system that creates valuable jobs and avoids pollution. But after that, the teams clearly have provided the needs seen by industry, and they also provide feedback to at least some of the researchers. In some of the projects, they are involved directly in the work and clearly will only propose work they value. The Program could improve by giving Technology Acceleration a tech team or perhaps a more useful equivalent, such as a consulting group of major industry reps.
- With industry, the alignment seems very good in terms of participation in DOE-funded projects or working with national labs on specific projects relying on competencies developed through DOE-funded projects. The alignment with states is dependent on the states themselves, and I'm not too familiar with that dimension. The increased collaboration between the labs seems to provide a much greater opportunity to align with stakeholders.
- The key to reducing hydrogen cost to below $1/kg by 2030 includes accelerated R&D, demonstration and deployment, and scale-up of mature technologies (PEMs and SOFCs). The less-developed and low-TRL technologies will need a longer horizon to achieve the Hydrogen Earthshot goals.
- There is good alignment with industry and stakeholder needs.
- Industry and stakeholder involvement has been achieved at every level.
- One of the reasons the overall Hydrogen Program and sub-areas are aligned well with industry and stakeholder needs is "we all are watching the costs." The competing technologies and systems are low-cost, by comparison, and the "cost drivers" and "focus areas" presented by Ned Stetson clearly explain the intent of researchers and projects to reduce the electrical energy costs and capital costs, along with the overall hydrogen refueling station costs. The stakeholder community, in general, has the same intent. Storage, as Ned Stetson explained, is another area (on land and on board)—again, another area where cost reduction is needed. All of that said, perhaps the presenters from the subprograms could be directed to address these cost drivers and focus areas for hydrogen. Perhaps, indirectly, they all work along these lines, but perhaps the presenters could directly speak to these imperatives at future AMRs. It may not have been possible because of the scope of work of the projects and the timing of when presentations are considered and due, but the Zoom platform showed how Ned Stetson's cost drivers could be threaded throughout the presentation and unambiguously described as such. Stakeholders are driven primarily by cost reductions (short- and long-term), and they are often required to articulate cost reductions. Perhaps the projects can be focused on economies of scale and also describe their cost metrics and how they will evaluate success from a cost-reduction point of view. Some of the models describe cost reduction, but maybe the output can be augmented with cost-reduction goals that support self-sufficiency (for some applications).
- Although the Program research aligns well with industry research, the Hydrogen Earthshot would be well-served with execution of plans for market commercialization and demonstration programs to accelerate state and regional deployment efforts.

- My main issue here is the hard shift to focus on MD and HD. It may have just been an issue of how the focus was presented or communicated and conveyed, but from the experience I had at the AMR and from speaking with other attendees, the change in focus was very strong and noticeable. I think, so far, the messaging does leave many with the impression that the light-duty effort is simply not moving forward through DOE's Program or is not considered a focus area anymore. This seemed most noticeable in the Fuel Cell Technologies and Systems Analysis subprograms, given the suite of projects. If this really is the intent, I strongly encourage reconsideration. If not, then perhaps the messaging simply needs an adjustment.
- The Program has good alignment with industry needs but is not aligned so well with other non-DOE investments.
- The Program should consider prioritizing advanced R&D effort for hydrogen sources from fossil fuels, including renewable natural gas. Given the sheer scale of current hydrogen supply, even incremental improvements to existing technologies can result in significant lower-carbon hydrogen volumes.
- The Program should do more to enable deployment in general of both mobile and stationary fuel cell systems and hydrogen infrastructure. Also, it is premature to abandon the light-duty vehicle application.

6. The Hydrogen Program is funding high-impact projects that have the potential to significantly advance the state of technology for the hydrogen and fuel cells industry.

	Hydrogen Program Overall Rating	Hydrogen Technologies R&D Subprogram Rating	Fuel Cell Technologies R&D Subprogram Rating	Technology Acceleration Subprogram Rating	Safety, Codes and Standards Subprogram Rating	Systems Analysis Subprogram Rating
Average Score	9.0	8.7	9.1	9.2	8.9	8.9
Number of Responses	18	18	17	16	17	17

Please respond for any subprogram/activity area as appropriate (e.g., hydrogen production, hydrogen storage, hydrogen infrastructure, fuel cells, technology acceleration, safety, codes and standards, solid oxide, ARPA-E, Basic Science, etc.).

Comments:

- First of all, if all the work were high-impact, then the Program portfolio does not have nearly the risk we should expect from government-sponsored research. Thus, a well-chosen portfolio will have projects with low impact. Secondly, in any R&D portfolio that has meaningful risk, there needs to be multiple paths forward at the same time so that when, inevitably, one route fails to bear fruit, the Program does not flounder. Inherently, this means some will be higher-impact than others. With that perspective, I would rate the Program well overall for picking projects that have the potential for high impact if successful, which I feel is the true "figure of merit" here. The outcomes highlighted in the afternoon (life of electrolyzer, >25,000-hour fuel cells, bringing up ARIES [Advanced Research on Integrated Energy Systems]) are good examples. Expanding the scope to non-transport uses offers many more opportunities for high impact, such as adding hydrogen to CH_4 for a fast increase in renewable content and to use in cement- and steel-making, which are big sources of stationary CO_2 production (and thus logical targets for abatement). Expanding fuel cell targets to HD trucks and rail and ship use likewise opens up many new high impacts, e.g., ship engines use the nastiest fuel imaginable and have huge engines running at below idle in port. With so much of world commerce moving by ship, this is a huge opportunity to decarbonize using hydrogen. The Energy Secretary's announcement of $1/kg hydrogen production within 10 years is an example of a potential high-impact area of work. If you want more impact, it makes sense to move funds out of highest-risk early TRLs and into technology acceleration.
- Given their high cost, the emphasis on electrolyzer and hydrogen storage technologies is appropriate. There has been excellent progress in reducing PEM fuel cell cost. At first glance, more stringent durability targets

for MD/HD vehicle fuel cells seems to be a major challenge, but perhaps not, when one considers that fuel cell electric buses (FCEBs) have demonstrated reasonable durability.

- The significant achievements of the Hydrogen Program include reduction in cost of PEM fuel cell stacks to <\$80/kW and hydrogen production cost of \$5–\$6/kg. These achievements are significant milestones along the path to H2@Scale.
- The Program has an excellent selection of high-impact projects. It is the best way to advance the frontiers of hydrogen technology.
- The presenters at the plenary explained the deliberate coordination and collaboration with the national laboratories, private-sector companies, and universities. The presenters clearly explained the collaboration in hydrogen and fuel cells, technology validation, projects that explain the technical and economic impacts of MD and HD FCEVs, codes and standards, and overall systems analysis. The presentations clearly showed the accomplishments. In the future, perhaps an effort could be made to lengthen a few of the presentations so the topics can be presented in more detail. And finally, perhaps these presentations could be “linked” together by a high-level expert.
- The Program is indeed funding high-impact projects. However, there may be value in increasing the number of these projects consistent with state and regional stakeholder collaboration.
- In some cases, such as in the case of the Fuel Cell Technologies subprogram, most of the funds go to exploration of materials and technologies that are not fully developed. In the case of the Fuel Cell Technologies subprogram, this is the development of platinum-group-metal-free oxygen reduction reaction catalysts. It is wise and important to invest in the development of fuel cells based on earth-abundant materials, but one also needs to reassess the possible applications every once in a while. One application that has been on the rise in the past few years is anion exchange membrane fuel cells, which can use these materials as very efficient catalysts, but the Fuel Cell Technologies subprogram almost completely neglects this technology. It is not clear why. Another example is the growing need from industry for fuel cells for aviation. There are large companies such as Airbus and Plug Power that are in need of scientific support that the Hydrogen Program can supply. These emerging areas should be given the necessary attention.
- I did appreciate that the office has taken another look at the fuel cell systems’ durability target that not only considers advances in material development but also looks more at the system-wide design possibilities. I think this will end up being an important piece of the strategy that fuel cell and vehicle providers choose to pursue in the future to meet the needed durability and cost targets. I also do appreciate the amount of effort that has gone into trying to develop more materials-based approaches. However, this area continues to appear to be elusive through the Program’s efforts. It does leave the impression that there may be some opportunity for consolidation of efforts. Consortia approaches to advance the basic science knowledge and provide guidance for viable paths of further development seem to have been bearing fruit, but even that method appears slow. It appears that this is an area where perhaps DOE could benefit from a more critical view of funded projects and have stricter requirements for funded projects. Incremental improvements don’t seem to be making enough headway, so perhaps the funded projects in this Program need more incentive to get beyond incremental development.
- The H2NEW and M2FCT consortia definitely provide a great platform for high-impact projects. The work on fuel cells is good, but I’m not too clear that materials R&D is a priority at the moment compared to industrialization R&D, like the work on high-volume manufacturing and quality control. International collaboration in those areas is also an opportunity to seize further.
- The Hydrogen Program could build a stronger engagement with the Office of Fossil Energy and Carbon Management to create some sort of a joint program effort around CCUS/hydrogen production from other fossil fuel sources. The refinery and petrochemical industry are likely to support such efforts.
- I believe that high-impact projects are being funded within the funding limitations.
- It is not clear whether all the funded projects are “high-impact.”

7. Research Consortia Approach (including Energy Materials Network Consortia and others): Do you have any comments or recommendations on the Hydrogen Program's consortia approach for conducting laboratory-supported research (e.g., HydroGEN, H2NEW, HyMARC, ElectroCat, H-Mat, and M2FCT)? Please state what is working effectively and areas that may benefit from further improvement.

Comments:

- I believe that the consortium approach is generally working to make necessary advances toward DOE's goals. I was happy to see the consolidation that occurred within the Hydrogen Materials Advanced Research Consortium (HyMARC) and its merging with the Hydrogen Storage Characterization Optimization Research Effort (HySCORE). I believe that one of the most valuable outcomes of a consortium approach is to start with many threads of research with potential for success so that they can be investigated and developed in parallel and in coordination with one another. However, that coordination should also enable easier narrowing down and focusing of efforts into the threads that have the highest potential as those projects progress. The consortium effort should enable this kind of re-focusing easier and faster than funding structures where every individual project has its own timeline and budget that must be carried through to completion. I was glad to see this kind of action take place as it was described with HyMARC, and I recommend that this philosophy be carried over to the other consortia whenever and as much as possible.
- The consortium approach has great potential. It focuses the human expertise spread across academia and the national labs and gets them to work together on solving groups of difficult and important problems. When this works, it is great—when it generates collaborations that are truly intertwined and could not succeed without such joint work. When it merely binds a bunch of individual projects under a loose leadership with monthly or quarterly Zoom calls, it really adds no further value. Certainly, the EERE consortia always promote cooperation; actual collaboration is harder and not always achieved. To be clear, this is nothing specific to DOE or EERE or the Hydrogen Program; this happens everywhere in government and industry and academia. The best way to get better collaboration is a line-item veto of projects at the solicitation phase so that only projects that require multiple groups working together are actually funded by this mechanism. It appears the consortia already do a good job of including only projects that make sense together in the same sub-portfolio.
- The research consortia approach appears to have increased collaboration among the national labs and created a synergistic work environment, resulting in significant progress toward technical targets. The devil is in the details, however. The Program might consider having this research model independently evaluated for effectiveness. I attended the following consortia overviews:
  - M2FCT, which had a well-organized and articulated presentation, outstanding leadership team, well-formulated projects goals, and excellent systems analysis to guide R&D. The accelerated stress test (AST) and investigation of degradation mechanisms are exactly the kind of work the national labs should be doing to inform industry development efforts, including vehicle operating and control strategies. Providing discretionary funding to support new concepts adds flexibility to the consortium approach.
  - H2NEW, which has an outstanding leadership team, excellent presentation, strong systems analysis guiding cell operating strategies, materials development, and AST.
- The research consortia approach seems to be valuable in leveraging and streamlining access to national laboratory capabilities and expertise. It seems that increased involvement from industries would be a better utilization of the consortia crosscutting research activities. The consortia agenda is well-defined, with focused technology area targets. The HydroGEN consortium can benefit from a focused program on limited specific technologies in lieu of scattered projects.
- The research consortia are very appropriate for guidance needed for early-stage research. Linkage of these consortia with state and regional stakeholders through market-based planning efforts could increase value and accelerate the pathway for development of policy and effective commercialization with market-based deployment.
- Separating HydroGEN 2.0 from H2NEW based on current TRL levels is a good idea. That way, HydroGEN 2.0 focuses on low-TRL R&D areas, given that low-temperature PEM electrolyzers are far more advanced than other advanced water-splitting routes. One benefit of the consortia approach is the

continuation of maintaining expertise and developing new talent around hydrogen science and technology through the core lab systems and academia.

- The materials science research in the consortia is excellent (the Hydrogen Materials Consortium [H-Mat] and HyMARC). Many use the outcomes of these groups.
- Consortia make remarkable use of people and labs, in particular national labs. Consortia make very powerful research teams.
- The HydroGEN network of nodes is an excellent example of cooperation between industry, national labs, and universities.
- The approach proposed appears excellent to enable the best experts to work together in a medium-term vision and to provide new results for further complementary R&D activities.
- Collaboration is going well. The avoidance of duplication of research effort at the national labs is being achieved.
- The approach is solid.
- The consortia approach is great for generating competencies and capabilities for industry to tap into for specific, more proprietary topics but also to tackle pre-competitive topics. A case in point would be quality control R&D, presenting a challenge to bring industry to a level of maturity to recognize where the pre-competitive aspects are and to exchange them more freely, both for fuel cells and electrolysis. The consortia should add more emphasis to bringing an even more dynamic dialogue between competitors on those topics and elevate their readiness to seriously compete globally where appropriate.
- The Electrocatalysis Consortium (ElectroCat) and M2FCT are well-developed and backed by well-experienced researchers and companies. HyMARC, HydroGEN, and H-Mat could benefit from better SMART goals, better collaboration, and more influence from industry to strengthen their management, ideas, and innovation.
- More focus on working with industry can be considered.
- An advisory board/committee may be needed to review consortia approaches/projects and progress.

8. H2@Scale: What are the strengths and weaknesses of the H2@Scale initiative? Do you have any recommendations for other H2@Scale analysis, research topics, or demonstrations to enable the scale-up and value proposition of hydrogen and fuel cell technologies (e.g., a region with low electricity prices, excess curtailment, and hydrogen supply opportunity along with a co-located demand for hydrogen, etc.)? Please provide any other recommendations on H2@Scale.

Comments:

- I whole-heartedly support the H2@Scale effort and believe this is the exact type of full-picture analysis and information-generating effort that we see is needed even in regions that are generally supportive of hydrogen industry development. The program’s strength really is its ability to develop the types of information resources that policy makers and business decision makers need in order to develop a future hydrogen energy system. Some issues that I think H2@Scale could help address through research include the following:
    - Acknowledging the heavy interest and push toward electrification (specifically batteries) in many end uses; there is increasing need to have more nuanced understanding of the roles hydrogen can play. H2@Scale can help answer questions more fully about the specific applications and use cases in which hydrogen will be preferable and maybe even necessary. More detailed information than evaluation of general economic sectors is needed—for example, specifically about multi-unit dwelling residents or power needs in remote and protected locations. This may end up being a set of hyper-specific case studies, but that type of focused information is still needed by policy makers today.
    - There needs to be far more clarity about what it would take to build up a whole upstream supply chain to support the vision of H2@Scale. Even with all the development in hydrogen production, distribution, and dispensing going on today, it’s still nothing compared to the volumes of a vision like H2@Scale, and there is not much good information available today about how that growth can practically occur, what its costs will be, what the potential societal impacts will be (again, with an eye toward localized analysis here), and what might become the bottlenecks. H2@Scale could help scope all this out and define the risks that should be avoided in this massive energy transition.

  - Climate change is a general and foundational motivating factor of H2@Scale. However, the effects are already being felt today and cause operational changes in our energy system today. For example, recent reporting has highlighted California's drought, leading to increased dependence on fossil fuels for the state's power needs, further exacerbating the issue. H2@Scale could also serve as a platform for studying hydrogen's potential role in short-circuiting this kind of feedback loop. This could be an immensely powerful piece of information.
- H2@Scale enables large-scale hydrogen production, storage, and utilization across different sectors of the economy. H2@Scale addresses many environmental and energy issues and provides for the transition to a net-zero-emissions economy.
- The Program should consider accelerating deployment by enabling approaches that have already been successful in one region to be pursued in other locations/regions. For example, what the Stark Area Regional Transit Authority did with FCEBs in Canton, Ohio, should easily work in many other cities.
- I don't have much to add on this, as I think the challenges along the hydrogen value chain are numerous already. The work done in this initiative is impressive already.
- Regarding the strengths and weaknesses of hydrogen at scale, a clear strength is that this expands the funding and technology readiness level (TRL) scope, which, of course, will drive progress. There seem to be many, many projects making progress. The leaders seem to have a high-level awareness of what the other offices are doing. It is very exciting to see expansion to uses such as agriculture (NH_3 generation for crops). All the projects sound exciting, though I am not in a position to appraise them from an economic viability perspective from what was discussed. While not a strength in the usual science or engineering sense, the emphasis the participants put on diversity, communities left behind, and environmental justice should help the end products to find societal acceptance, sustainability, and stability. A weakness I see is that collaboration seems to be defined as working on the same area, not working together. What I did not see is a clear method of making sure there is not duplication of effort and that the other offices are getting and valuing the guidance from industry that HFTO possesses. It may well be that there is sharing of this "intelligence" on what would matter if it were accomplished, and even what industry sees as industry-competitive areas that government should stay out of, but if so, it was not clear. It would be preferable if there were a clear leadership structure at a level above the offices involved that was driving this in a "peer-reviewed" direction, and that could be administrative peers as well as science peers. It is also critical that this effort not defund the existing work. At the very least, one might model this effort's organization on the counsel of battery research funding offices in VTO, EERE, ARPA-E, etc. that tried to make sure the massive efforts in the Obama administration on battery science, engineering, and commercialization were consistent, coordinated, and logical. Better yet, that model could be used as a base and improved upon based on where that effort succeeded and where it did not and where it was okay but might have been better.
- Since its inception, the H2@Scale initiative has generally been a success, both in terms of realizing actual projects and from the perspective of motivating the broader hydrogen community to think big, beyond transportation and the possibility of integration with broader industry sectors. However, maybe as a result of the understandable objective of simplifying a complex concept, H2@Scale appears to have sacrificed the critical parameters of technology readiness. It would be immensely helpful to incorporate the TRLs of the various components that make up the initiative. For example, a more meaningful representation of the petrochemical industry, transportation, and synthetic fuels can be added to the famous slide. Perhaps the Program can come up with a creative way to introduce current TRLs and hydrogen consumption volumes of the different opportunities. It might be useful to create different versions of the H2@Scale master slide, including one based on TRL, current and future market potential (energy or cost basis/year), greenhouse gas reduction potential, etc. That way, there are more realistic expectations and minimal room for misinterpretation by policy makers or non-technical stakeholders.
- The strengths are an excellent market-based approach to the research topics. The one aspect that is missing that I think could be improved is making a stronger connection to more fundamental research being supported by agencies such as the National Science Foundation and DOE's Basic Energy Sciences. I feel this could be a mutually beneficial link that is currently missing.
- H2@Scale is an important initiative to promote the application of hydrogen and fuel cell technologies. Better interaction between this initiative and the other consortia can result in more advanced solutions and technology assessments and overcoming scientific and engineering hurdles, which will help achieve the targets much faster.

- H2@Scale is a perfect example of a thoughtful approach to improving scale to reduce cost for market deployment. This approach could find additional value if coordinated with state and regional entities.
- It would be useful to add a "fourth dimension" that describes projects in just-in-time hydrogen production, i.e., a plant produces fuel based on the anticipated demand for the fuel.
- H2@Scale was focusing on mapping and modeling activities. It might be interesting to validate it through H2@Scale demonstrations.
- This is an important cornerstone that must form a stronger alliance with solar energy.
- H2@Scale is an excellent program to prepare massive deployment. It will not be sufficient to open the hydrogen market. The support of a strong U.S. policy, industry, and investors will be needed.
- The Hydrogen Program's analysis should be expanded to include additional emerging applications, such as mining and construction equipment as well as refuse trucks.

9. International Collaboration: The Hydrogen Program collaborates through a number of international partnerships. For example, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is an international partnership to coordinate activities on hydrogen and fuel cells across 20 countries and the European Commission. Additional international collaboration initiatives with U.S. participation addressing hydrogen include the Clean Energy and Hydrogen Ministerials, Mission Innovation, the International Energy Agency, and others. Please comment on actions DOE can undertake in conjunction with these international activities that can effectively accelerate progress in hydrogen and fuel cell technologies.

Comments:

- DOE international collaborations and partnerships in hydrogen R&D are important and successful. One expects a strong comeback of the United States at the end of the year in the 2021 United Nations Climate Change Conference (COP26).
- The extent of involvement in important international entities such as IPHE is paying off for all parties involved. Communication allows for peaceful, more rapid, coordinated efforts.
- International collaboration is key to accelerating hydrogen deployment. Any DOE action to foster international collaboration is thus fully supported. IPHE is the right partnership with which to exchange on regulations, codes, standards, and safety activities and may also facilitate some R&D collaborations. Direct connections to other R&D programs, such as the second generation of the European Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU) or the new upcoming Clean Hydrogen JU, could be used to continue international collaborations.
- These are great initiatives globally. I would recommend coordinating closely with Canada on topics related to codes and standards harmonization and cross-border issues such as vehicle infrastructure, hydrogen blends in natural gas, and so on. Coordinated funding for R&D with Natural Resources Canada would be very productive. There have been informal collaborations on the topics of quality control and membrane manufacturing, but it would be more productive and impactful if joint/coordinated funding were considered.
- One area of international collaboration that DOE could help with is standardization of reporting and progress methods. It is notoriously difficult to catalog, evaluate, and understand how different regions' hydrogen-specific plans, funding, targets, and progress compare to one another. An immediate example that comes to mind is comparing progress in terms of station network development. Countries, states, and regions count stations differently (based on type of access [private, public, behind-the-fence], permanent versus temporary/mobile locations, and other metrics). It has been very difficult to ascertain progress and competitiveness of the United States and its constituent states as compared to international efforts. At many times, this has led to the perception that no other country is making progress on hydrogen and that the United States or specific states "are going it alone." While this misconception can be corrected with available information, it is still very difficult to convey in a useful manner since all the regions' reporting is on different bases. The more that DOE can work with international partners to standardize the accounting and communication and make updating and publication a regular activity, the better.
- While there are many cited partners, the actual shared research or shared projects seem limited, and, given that U.S. tax dollars are being spent here, it is difficult to have true international collaboration that includes funding. Still, there is DOE representation on international boards and harmonization groups. It would be

nice if there were a more deeply international approach to all this, like R&D, but I understand that the U.S. economy depends on intellectual property, so that will not happen to the extent it could. The leadership certainly sees the need for a world approach, so the degree and kind of international joint projects are not from lack of interest. The EERE approach is certainly sufficient and about as good as one can hope for under the circumstances. I think the coordination internationally is good.

- The Hydrogen Program's international collaboration looks good. However, the collaboration level may need to constantly be updated to catch up with the fast-growing focus and funding in international hydrogen activities (especially the European Union, China, and Japan) and ensure that DOE-funded researchers are appropriately engaged.
- International collaboration is highly recommended. Higher levels of transparency and participation by U.S. industry in international collaborations are encouraged. U.S. industry involvement in European fuel cell and hydrogen collaborative projects needs to be facilitated.
- Collaboration with international partnerships is of value in raising global awareness and increasing opportunities for global development. Resource-sharing could improve research productivity and reduce cost; however, there will be a need for protection of intellectual property.
- The international collaboration is mission-critical for the stakeholder community, comprising global nationals and researchers with global viewpoints. There should be a way to garner information about the amount of past, present, and future (planned) investments in hydrogen refueling infrastructure from the IPHE members.
- So far, it seems the international collaboration is very limited to the different organizations stated above and to participation in their meetings. There is virtually no scientific cooperation such as joint research or work with international companies, although up until a few years ago, the U.S. hydrogen program was the world leader in its field. Since then, many countries have invested in facilities and experienced researchers who have made significant advancements that can contribute to the U.S. effort. Stronger research collaborations should be formed with international members. In addition, there are parallel research consortia, mainly in the European Union. The Hydrogen Program should try to formalize the collaboration between its consortia and the international ones.
- International workshops should be held periodically.

10. Prizes: Agencies have shown interest in implementing prizes and competitions as a mechanism to complement the conventional grant process. Examples include the H-Prize (H2Refuel) for a small-scale hydrogen fueling appliance that complements large retail stations. Please provide comments on the prize/competition approach and provide any suggestions for future prizes or competitions that would align with the goal of accelerating the widespread success of hydrogen and fuel cell technologies.

Comments:

- The prize and competitions do successfully complement the conventional grant process. The H2Refuel is a unique station, an architecture unlike any other. Had DOE not provided a competition for this unique plant, the company may not have been successful in competitive solicitations for larger refueling capacity requirements. The AMR presentation explained this correctly.
- Prizes and competitions have always been good motivators. I recommend continuing the existing programs.
- The right number of prizes is helping to hold interest and educate and grow stakeholders.
- This tends to be very single-goal-focused with little spillover. I would suggest the Defense Advanced Research Projects Agency/ARPA-E model would be better. The advantage of a prize is you do not need to pay out till someone "wins." However, you also do not get progress on really tough problems because the odds and timelines are too long. If DOE will use this, it should be used as part of the Program's implementation acceleration, and the Program should make absolutely sure this is a highly desired outcome and one the industry would not do without the prize. Finally, the prize should not be given out for good effort; that voids the value of the technique. As for ideas, DOE can just look at its tech team goal sets and pick one team's set of goals and make that the challenge—or make a meaningful subset of the goal set with limits on the other parameters that make the challenge target, if accomplished, sufficient to start some adoption on a wide enough scale to start up the development of a supply chain for a bigger hydrogen economy in time.

- I think prizes are a good idea but should be fairly limited in the size of the award and thus the scope. Prizes would be best for applications in which the technologies already exist and it's just the application or integration that is novel.
- Prizes and competitions may be an interesting and valuable mechanism for scholastic and academic competitions. However, acceleration of deployment to increase clean energy deployment might be best served with improved education and public demonstrations with state and regional partnerships.
- I'm not sure such prizes or competition would accelerate widespread success of hydrogen and fuel cell technologies.

11. Please comment on the overall strengths and weakness of the Hydrogen Program and its portfolio of projects. Please provide strengths and weaknesses for each subprogram as appropriate. On which technology areas should the Hydrogen Program put more or less focus for future activities?

Comments:

- I believe that the Hydrogen Program is generally well-balanced. The Program clearly delivers progress in technology development and key information to demonstrate the utility of hydrogen and fuel cell technology. The sheer volume of reliable and authoritative data and information that comes from the Program is its greatest strength. Especially in recent years, the Program has also demonstrated significant flexibility in the structure and goals of its funding program and projects, especially to provide timely information and results relevant to the evolving state of the hydrogen and fuel cell industry. It appears that Program activities looking forward could begin to add more focus to demonstration and perhaps even market development efforts that has been missing in recent years. I believe this has been a major lack in prior years of the Program and that, if it can actually be expanded going forward, it will prove to be a powerful engine of change and success for the hydrogen and fuel cell industry.
- Everything I might say is covered above. In summary, the management system, the involvement of industry, the breadth of effort across many TRLs and all aspects of a hydrogen economy, the expansion from a transportation focus to an economic focus, and the people's passion and expertise are strengths in what is no doubt the best hydrogen program on earth. The increasing emphasis on engaging industry past goal-setting to partners in technology implementation is appropriate at this point. The harmonization of standards internationally can only help. This is not a weakness but a place where improvement might occur: coordination and true collaboration on projects across the offices and agencies working in this area. The more understanding and coordination there is between funding units, the more efficiently everything will work. The same could be said internationally, especially if it is true research collaboration, working as if you were in the same lab, on the same project, talking all the time. It is clear there is economic risk that Congress would not accept in higher-TRL work, but perhaps the Office of Science and HFTO, for the lower-TRL work, could try to partner with the very best researchers in the world, with DOE funding our researchers in the partnership and the various European Union and national science agencies funding their top researchers in the partnership on a specific project.
- The Hydrogen Program is encouraged to address the most urgent and high-value uses of hydrogen, including fertilizer, steel industries, and refineries. Those are the industries that use energy and need hydrogen the most. The key to success for H2@Scale is the scale-up and demonstration of the technologies that are close to maturity by integrating different sectors and users that can benefit from hydrogen, leading to an increased role of the Technology Acceleration subprogram.
- The Hydrogen Program has clear objectives described in a very detailed manner, with associated quantitative key performance indicators. The projects appear well-structured and -monitored by the DOE team. The research consortia approach is a real strength of the Program, as it ensures a mid-term action enabling the best U.S. experts to work together on a specific critical item. Collaboration with other agencies has been improving, but it might be enhanced with more inter-agency projects. As the hydrogen technologies should significantly increase in the next decade, a stronger effort in considering sustainability, circular economy, recycling, and eco-design could be considered.
- The Program office is strong at all levels and should be used as a benchmark for other DOE offices.
- The Program has enabled outstanding R&D progress, significantly advancing the state of the art. That is the Program's strength. That progress stems from an outstanding leadership team and staff with significant

experience in program planning and execution, as well as scientists and engineers with in-depth technical expertise. The Program's weakness is enabling deployment and raising awareness of hydrogen and fuel cell technologies at the state and local levels.

- Overall, this is a strong program with a strong funding base. Building relationship with industries is needed to accelerate some of the key technology development.
- No doubt, the Program has made significant progress in technology RD&D and cost reduction of key performance indicators over the years, as clearly shown in Dr. Satyapal's presentation (slide 15). However, the same slide also appears to indicate an asymptotic plateauing of those key parameters in recent years and that they are still far from 2030 targets, namely costs for hydrogen production (PEM electrolyzers), auto PEM fuel cells, and onboard storage. This observation may suggest that those Program strategies with incremental changes may not be enough to achieve the ambitious DOE goals. Perhaps it is time for the Program to bet big on new ideas with potential for transformational changes.
- The biggest weakness the Program has is the lack of a formal route to validate results. This must be corrected. In some cases, the testing, parameters, and goals are not well-defined (H-Mat, HyMARC, HydroGEN). International collaboration has to be improved. The Program is the longest-lasting hydrogen and fuel cells program in the world. As such, it has the longest institutional memory, which must be cherished. Although it invests quite a bit in catalyst development, it has almost completely erased the Pt research programs. The Program has to maintain this research area, even at a low level, to keep the institutional memory and the top researchers in the field, which is now also becoming relevant for hydrogen production. In addition, not enough attention is given to development of advanced electrode materials (not catalysts) that can endure harsh conditions in fuel cell and electrolyzer operation. It is worth mentioning the M2FCT call for proposals, which is open to all U.S.-based universities (opening this to international participants as well should be considered). This program will allow bringing in new ideas that were not necessarily considered by the consortium or that can help the consortium mitigate some issue it faced.
- The Hydrogen Technologies subprogram and the Fuel Cell Technologies subprogram, which were the only subprograms I sat through and reviewed, are led by knowledgeable and goal-driven leaders within DOE. The programs they support at various companies and universities work very well in collaboration among themselves and the national labs. The weakness is the lack of a direct connection with basic science research being supported by the National Science Foundation and DOE Basic Energy Sciences program. While I understand that these programs have to be necessarily focused on applied research, a stronger connection with basic research being supported by other agencies will strengthen the programs.
- Overall, the Program strengths include the quality of its early-stage research; weaknesses include a need for more state and regional collaboration, with stakeholder engagement and cooperative partnerships; opportunities include advancement of hydrogen and fuel cell deployment with other initiatives, including offshore wind and energy storage, in support of climate protection and energy reliability; and threats include unproductive competition with other industries, such as battery technology that is better understood by the public and sometimes favored simply because of a better public understanding of the technology when compared with hydrogen fuel cell technology.
- The R&D program is outstanding, but it needs a strong link with U.S. energy policy to have an impact on climate change. DOE's announcement of the Hydrogen Energy Earthshot goal to achieve $1/kg hydrogen production in one decade could give the impression that one has to wait ten years to start deploying hydrogen. One has to start now to develop the hydrogen market to achieve net-zero goals.
- The international perspective is needed. The future or the planned exportation/importation of hydrogen is very important to global businesses, albeit just starting. A session should be added on the integration of hydrogen systems as expressed in H2@Scale: how the various processes and subprocesses work together.
- It is hard to tell where to drop focus. However, topics that are dropped, such as electrochemical hydrogen compression, should be identified in the overview of the Program and subprograms, with some justifications as to contribute to the collective learning.

12. Do you have any other comments or suggestions to improve the overall effectiveness of the Hydrogen Program or any of its specific subprograms?

Comments:

- This Program is well-planned, well-organized, and well-managed in every aspect listed above. All Program managers are very professional and dedicated. The virtual meeting agenda for this year of 2021 is organized nicely and moderated accurately. It is very convenient for the reviewers and principal investigators to attend the different presentations seamlessly. To further perfect this Program, the reviewer has the following suggestions for the Program to consider:
    - The deliverability of the large research projects, such as those led by the industry and national labs, could be monitored more closely, especially when they proposed to deliver the products to the market.
    - More investment in the smaller research projects led by universities (with much lower cost to this Program than those led by national labs) can be very beneficial in many aspects, including the training of the workforce and building the sustainable infrastructure for the hydrogen economy for the years to come.
    - The peer review process for the selected projects is very interesting. To make this review process more effective, a blind review is suggested. With the incorporation of the virtual activities, the blind review could be done by having the reviewer and panelist submit the questions/comments anonymously to the moderator. To ensure the success of the projects and to make the review more beneficial and constructive to the project that is being reviewed, the reviewer could have the option to provide both critiques and constructive suggestions/approaches to better the projects.
- Overall, the Program is technically effective, based on very high-quality, early-stage research and collaboration between academia and the national labs. Effectiveness may be improved with state and regional planning for demonstration and deployment to increase public education, public acceptance, and commercial market-based deployment. Other themes that were discussed during the plenary sessions that appear to be of high value and should be emphasized in program planning for the Earthshot include the need to move from the labs to the markets. There are collaboration gaps, and collaboration will be essential to reducing costs. National policy will be supportive of decarbonizing, providing energy storage, and increasing export opportunities. Interagency working groups will provide valuable federal coordination. Community engagement will be needed to get stakeholders comfortable. Stakeholder engagement will be needed to help determine which technology should be demonstrated, what the best end uses are, and what the best markets and applications are. System crosscutting to reduce costs is of value. Hydrogen opens up integrated pathways. These comments and themes are all consistent with an overall emphasis on increasing stakeholder engagement at the state and regional levels to accelerate application of R&D.
- Thank you for inviting me to comment on the Program. This is always a great event of which to be a part. I am looking forward to next year.
- It would be nice if reviewers could go over a copy of the plenary presentations for the Program beforehand, just as reviewers of the individual projects are able to go over a copy of the presentation and past presentations. I get that the Energy Secretary's announcement or Director Satyapal's announcements can't be released beforehand, as that would ruin the surprise. However, the subprograms are just the facts and could be available to reviewers to read and think about what we most need to focus on as the talk is given. I do appreciate the chance to see them afterward, at least. Standard DOE slides have several times more information than can be assimilated in the time typically given each one, and the fonts are concomitantly too small. And yet so many concepts or areas are covered per slide; there is seldom enough information to verify the results; listeners just have to trust the presenter. The result is a talk that is hard to listen to, and it is hard to focus on any particular take-away value. I know these slides get reused many times, and by covering everything possible, one avoids having to get more slide decks approved, but the Program is asked to consider focusing on what you really most need to tell this AMR audience and make clear simple slides for those issues, then provide electronic "handout slides" with all the expanded information (like the current slides) or even supporting proof. Finally, and definitely a comment on the AMR process rather than the Program, just as in an in-person AMR, there is much more time to interrogate the details of posters (30-minute question-and-answer [Q&A] window, plus you can stop and repeat the smooth, recorded presentation, if desired), which are generally regarded as the less critical project evaluations relative to the

oral presentations (10 minutes of Q&A and a live presentation with occasional small technical issues and often rushed endings as the speakers see they are over time). The Program is asked about reversing that.

- For the environmental/economic modeling projects, perhaps front matter can be added to the presentations and sites that conveys the level of expertise needed to run the models independently. Some stakeholders are interested in becoming self-sufficient in running the models, but without the knowledge of the required skill sets, they hesitate.
- Strong government support to the development of the hydrogen market is needed. The Program needs to develop links with industry, investors, and R&D programs of the European Union, Japan, etc. The AMR would need the input of these sectors to give a good vision of the hydrogen future.
- The awards ceremony is a great moment of the AMR. Awards are very useful for recognizing young people and significant progress.

Appendix B: 2021 Hydrogen Program Attendee List

Last Name	First Name	Organization
Abbasi	Reza	University of Delaware
Abdel-Baset	Tarek	Stellantis
Abdelrahman	Mohamed	Carnegie Mellon University
Abdul Sater	Hassan	Creative Power Solutions
Abild-Pedersen	Frank	SLAC National Accelerator Laboratory
Abozaid	Omar	Tharwat Investment Holding
Abramowitz	Mark	Community Environmental Services
Abruña	Héctor	Cornell University
Acevedo	Yaset	Strategic Analysis, Inc.
Achtelik	Gerhard	California Air Resources Board (retired)
Adam	Raghad	Middle East Technical University
Adams	Jesse	U.S. Department of Energy
Adkins-Ferber	Verda	Oak Ridge Institute for Science and Education (ORISE)/Oak Ridge Associated Universities
Aghazadeh	Anita	Iran University of Science and Technology
Agrawal	Khantesh	Indian Institute of Science
Agrios	Alexander	University of Connecticut
Ahluwalia	Rajesh	Argonne National Laboratory
Ahn	Channing	California Institute of Technology
Ahuja	Punkaj	The Lubrizol Corporation
Ainscough	Chris	Dorsey & Whitney LLP
Ainsworth	Richard	European Marine Energy Centre
Akiba	Etsuo	Kyushu University
Alahmadi	Aljazzy	Aramco Americas
Albertus	Paul	University of Maryland
Aldas	Rizaldo	California Energy Commission
Aldrich	Robert	Aldrich Energy & Environment Company
Alexander	Fan	Northern Illinois University
Alia	Shaun	National Renewable Energy Laboratory

Last Name	First Name	Organization
Alink	Robert	Aerostack GmbH
Allen	Jeff	Leidos
Allendorf	Mark	Sandia National Laboratories
Almuarifi	Yaser	Avium, LLC
Alpert	Grant	
Amaro	Robert	Advanced Materials Testing & Technologies
Ambrosini	Andrea	Sandia National Laboratories
Ancipink	Jake	GenH2
Anderson	Brian	U.S. Department of Energy/National Energy Technology Laboratory
Anderson	Matthew	Cummins Inc.
Anderson	Michele	Office of Naval Research
Ando	Masato	Japan Atomic Energy Agency
Angst	Mike	Kohler Co.
Antoni	Laurent	Commissariat à l'énergie atomique et aux énergies alternatives (CEA, French Atomic Energy Commission)
Aochi	Joji	Toyota Motor North America
Aoki	Naoya	Ishifuku Metal Industry Co., Ltd.
Aquino	Sarah	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
Archambault	Michel	Cummins Inc.
Ardo	Shane	University of California, Irvine
Arges	Christopher	Louisiana State University
Arjona	Vanessa	U.S. Department of Energy
Arkenberg	Gene	Nexceris, LLC
Armstrong	Daniel	ABB Ltd.
Armstrong	Haley	AJW, Inc.
Arthur	David	U.S. Department of Transportation, Volpe Center
Arunagiri	Karthik	Louisiana State University
Arvind	Ramya vyas	Cummins Inc.
Aryal	Utsav Raj	University of Delaware
Asano	Masamichi	Mitsubishi Heavy Industries America

Last Name	First Name	Organization
Asato	Richard	Honda R&D Americas, Inc.
Asazawa	Koichiro	Panasonic
Atanasiu	Mirela	Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
Atkins	Charles	Ramaco Carbon, LLC
Autrey	Tom	Pacific Northwest National Laboratory
Ayers	Katherine	Nel Hydrogen
Ayub	Muhammad Saad	Princeton University
Ba	Chaoyi	Honeywell International Inc.
Badrinarayanan	Paravastu	Halliburton Company
Bae	Chulsung	Rensselaer Polytechnic Institute
Bafana	Adarsh	Argonne National Laboratory
Bahar	Bamdad	Xergy Inc.
Baker	Andrew	Nikola Motor Company
Baker	Jim	W. L. Gore and Associates, Inc.
Baker	R. R.	Retired
Bakhtian	Noel	Lawrence Berkeley National Laboratory
Bala Chandran	Rohini	University of Michigan
Balderas-Xicohtencatl	Rafael	Oak Ridge National Laboratory
Balema	Viktor	Ames Laboratory
Bambula	Michael	Gamma Technologies, LLC
Banga	Winkle	PricewaterhouseCoopers
Banner	Claudia	American Electric Power
Banner	Jane	Plug Power Inc.
Barbosa	Nicholas	National Institute of Standards and Technology
Barclay	John	Pacific Northwest National Laboratory
Barforoush	Joseph	Avium, LLC
Barilo	Nick	Pacific Northwest National Laboratory
Barker	Eric	Government of Canada
Barnes	Ted	Gas Technology Institute
Barnett	Scott	Northwestern University

Last Name	First Name	Organization
Baronas	Jean	California Energy Commission
Barroeta	Magaly	ExxonMobil
Barta	Allen	Rolls-Royce North America
Bashyam	Rajesh	Hyzon Motors Inc.
Basurrah	Assem	University of Arkansas at Little Rock
Bates	Steven	
Batten	William	Energetics Incorporated
Baturina	Olga	U.S. Naval Research Laboratory
Bayer	Armin	Greenerity GmbH
Bayer	Matt	McDermott, CB&I Storage Solutions
Bazzi	Tony	DTE Energy
Beagle	Emily	Rocky Mountain Institute
Beaumont	Robert	Exelon Generation
Beck	Fredric	California Public Utilities Commission
Becker	Juergen	Oerlikon Balzers
Beckner	Matt	General Motors Company
Belami	Debora	Manchester Metropolitan University
Beliaev	Alexander	Pacific Northwest National Laboratory
Bell	Robert	National Renewable Energy Laboratory
Bellerive	Julie	Ballard Power Systems
Beltran	Diana	Carnegie Mellon University
Benard	Pierre	Université du Québec à Trois-Rivières
Bender	Guido	National Renewable Energy Laboratory
Benichou	Pierre	Air Liquide
Benson	Adam	PowerCell Sweden AB
Benson	Eric	AquaHydrex, Inc.
Bera	Bapi	University of Tennessee
Berbeco	Minda	Bay Area Air Quality Management District
Bergeron	Greg	
Berner	Jane	California Energy Commission
Berova	Viktoriya	Freudenberg Sealing Technologies GmbH & Co. KG

Last Name	First Name	Organization
Berteletti	Dan	Boston Government Services, LLC
Berube	Michael	U.S. Department of Energy
Besser	Ronald	ExoCell Power
Best	Kevin	RealEnergy
Beutel	Alex	pH Matter, LLC
Biddle	Mike	Evok Innovations
Biebuyck	Bart	Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
Binkley	Steve	U.S. Department of Energy
Binny	Dustin	Ballard Power Systems
Birky	Alicia	National Renewable Energy Laboratory
Biro	Patrick	INERGIO Technologies SA
Bisaka	Toru	Toyota Industries Corporation
Bishop	Sean	Sandia National Laboratories
Blackburn	Bryan	Redox Power Systems, LLC
Blanchet	Scott	Origen Hydrogen
Blanco	Herib	International Renewable Energy Agency
Blank	Hermann	
Blekhman	David	California State University, Los Angeles
Bliznakov	Stoyan	University of Connecticut
Bloch	Eric	University of Delaware
Block	Joseph	Crown Consulting Inc.
Block	Ryan	U.S. Department of Energy, Office of the General Counsel
Blom	Rogier	General Electric Company Global Research Center
Blount	James	
Boardman	Richard	Idaho National Laboratory
Bock	Sebastian	Graz University of Technology
Bodner	Merit	Graz University of Technology
Boettcher	Shannon	University of Oregon
Bonnema	Michael	TDA Research, Inc.
Bonner	George	North Carolina State University

Last Name	First Name	Organization
Boonstra	Eric	
Booras	George	Electric Power Research Institute
Borgerson	Scott	
Boriboonchatuporn	Suphattarin	Marine Steel Technologies, Inc.
Borole	Abhijeet	Electro-Active Technologies Inc.
Borup	Rodney	Los Alamos National Laboratory
Bouchard	Jessey	Aramco Americas
Boulanov	Dmitri	ArcelorMittal
Boulet	Andre	V3 Consulting Engineering
Bouwkamp	Nico	Frontier Energy
Bouwman	Peter	Schaeffler Technologies AG & Co. KG
Bove	A.	Ren Energy
Bowden	Mark	Pacific Northwest National Laboratory
Braaten	Jonathan	Robert Bosch LLC
Bragg-Sitton	Shannon	Idaho National Laboratory
Brahmbhatt	Amit	HydroStar Energy LLC
Braun	Christopher	GKN Powder Metallurgy
Braunecker	Wade	National Renewable Energy Laboratory
Bredemeier	Ethan	Sargent & Lundy, L.L.C.
Breunig	Hanna	Lawrence Berkeley National Laboratory
Brewer	Erik	Center for Transportation and the Environment (CTE)
Bridges	Jonathan	JobsOhio
Briem	Musashi	Rensselaer Polytechnic Institute
Britton	Benjamin	Ionomr Innovations Inc.
Broderick	Joseph	Toyota Boshoku Corporation
Broerman	Andrew	Forge Nano
Broerman	Eugene	Southwest Research Institute
Brooker	Paul	Orlando Utilities Commission
Brooks	Christopher	Honda Development and Manufacturing of America, LLC
Brooks	Kriston	Pacific Northwest National Laboratory

Last Name	First Name	Organization
Brown Redwine	Grace	National Renewable Energy Laboratory
Brown	George	The Chemours Company
Brown	Jeffrey	Arizona Public Service (APS)
Bruderly	David	Retired professional engineer and clean energy advocate
Bui	Ngoc	The University of Oklahoma
Bullock	Morris	Pacific Northwest National Laboratory
Burke	Patcharin	U.S. Department of Energy/National Energy Technology Laboratory
Burleson	Don	
Burns	James	University of Virginia
Burye	Theodore	U.S. Army, Ground Vehicle Systems Center
Butler	Tom	Tennessee Valley Authority
Buttner	William	National Renewable Energy Laboratory
Byron	Makini	Linde plc
Byvik	Charles	iPi
Caceres Gonzalez	Rodrigo	Georgia Institute of Technology
Cai	Wei	General Electric Company Global Research Center
Calabrese Barton	Scott	Michigan State University
Calabria	Scott	Merchant si
Caldwell	Walter	Engineering & Terminal Services, LP
Callahan	Patrick	Center for Transportation and the Environment (CTE)
Calloway	Bond	University of South Carolina
Campbell	Doug	FTB Energy Solutions
Capuano	Chris	Nel Hydrogen
Carmichael	James	Berenberg Capital Markets LLC
Carter	Michael	U.S. Department of Transportation, Maritime Administration
Casados	Tyler	Sargent & Lundy, L.L.C.
Cassidy	Chris	U.S. Department of Agriculture
Castano	Geovanni	Dominion Energy
Casteel	Micah	Idaho National Laboratory

Last Name	First Name	Organization
Castro	Michael	University of the Philippines Diliman
Casuccio	John	NGK Spark Plugs USA, Inc.
Ceballos	Bianca	Los Alamos National Laboratory
Celestine	Asha-Dee	U.S. Department of Energy/Oak Ridge Institute for Science and Education (ORISE)
Celestine-Browne	Kizi	American Electric Power
Centeck	Kevin	U.S. Army, Tank Automotive Research, Development and Engineering Center (TARDEC)
Chagas	Mauricio	Florida State University
Chakraborty	Romit	University of California, Berkeley
Chalk	Steve	Strategic Marketing Innovations
Champ	Theodore	University of Colorado Boulder
Chan	Megan	NASA
Chan	Shuk Han	Hawaiian Electric Company, Inc.
Chapman	Bryan	Exxon Mobil Corporation
Charles	Ricardo	Federal Energy Regulatory Commission
Chase	Jeffrey	Southern California Gas Company
Cheekatamarla	Praveen	Oak Ridge National Laboratory
Chen	Annie	Ballard Power Systems
Chen	Dejun	Georgetown University
Chen	Fanglin (Frank)	University of South Carolina
Chen	Jixin	Ford Motor Company
Chen	Kate	Los Alamos National Laboratory
Chen	Peter	California Energy Commission
Chen	Qingzhe	NGK Spark Plugs USA, Inc.
Chen	Shin-Juh	Physical Sciences Inc.
Chen	Yingying	National Renewable Energy Laboratory
Chen	Zejie	University of California, Irvine
Chen	Zijie	University of Michigan, Ann Arbor
Cheng	Yingwen	Northern Illinois University
Chenitz	Regis	National Research Council Canada
Chesshire	William	Hydrogen Development Corporation

Last Name	First Name	Organization
Cheung	Kerry	U.S. Department of Energy, U.S. Embassy in Seoul, South Korea
Chevrier	Vincent	Form Energy, Inc.
Chhiba	Priya	ENERCON
Chikhliwala	Edul	EcoChem Analytics
Childers	Dylan	Volvo Trucks Corporation
Choi	Won Jae	Hyundai Motors
Chou	Katherine	National Renewable Energy Laboratory
Choudhury	Biswajit	E. I. du Pont de Nemours and Company (DuPont)
Chow	Eugene	Palo Alto Research Center (PARC), a Xerox Company
Chow	Yachun	California Air Resources Board
Christian	Jon	Global America Business Institute (GABI)
Chu	Gina	AVL Fuel Cell Canada
Chun	Charlie	Exxon Mobil Corporation
Chung	Mark	National Renewable Energy Laboratory
Chung	Mike	The Pennsylvania State University
Chuy	Carmen	Unilia (Canada) Fuel Cells, Inc.
Cierpik-Gold	Kim	Boston Government Services, LLC
Ciferno	Jared	National Energy Technology Laboratory
Cimenti	Max	AVL Fuel Cell Canada
Clark	Lesley	E&E News
Clark	Theresa	U.S. Nuclear Regulatory Commission
Click	Tammy	Oak Ridge Institute for Science and Education (ORISE)/Oak Ridge Associated Universities
Clifford	Caro	Capstone DC
Cohen	Joseph	Air Products and Chemicals, Inc.
Colella	Whitney	Gaia Energy Research Institute
Collins	Stephanie	University of California, Berkeley
Collins	William	WPCSOL, LLC
Colombo	Elena	Politecnico di Milano
Compton	David	Sea Power Systems

Last Name	First Name	Organization
Coms	Frank	General Motors Company
Conley	Don	Sandia National Laboratories
Connelly	Elizabeth	International Energy Agency
Connolly	Matthew	National Institute of Standards and Technology
Connors	Dan	American Electric Power
Conrad	Lawrence James	UiT (the Arctic University of Norway), Tromsø
Contrino	Domenic	C12 Environmental Services
Cook	David	U.S. Navy, Naval Facilities Engineering and Expeditionary Warfare Center
Cook	Will	Plug Power Inc.
Cooper	Nathanial	University of Maryland
Correa Jullian	Camila	University of California, Los Angeles
Correal	Jaime	McDermott International, Ltd
Correll	Helen	National Renewable Energy Laboratory
Corrigan	Thomas	The Lubrizol Corporation
Costa	Stephen	U.S. Department of Transportation, Volpe Center
Cotton	Chip	General Electric Company Global Research Center
Couto de Andrade	Alexandre	Airbus S.A.S.
Cox	Christopher	W. L. Gore and Associates, Inc.
Cox-Galhotra	Rosemary	Booz Allen Hamilton/U.S. Department of Energy, Advanced Research Projects Agency–Energy (ARPA-E)
Crain	Patrick	3M Company
Crawford	Clark	GKN Hydrogen
Creel	Erin	Oak Ridge National Laboratory
Crockett	Russell	Aeon Blue Technologies
Cronin	Aidan	Siemens Gamesa Renewable Energy
Crosbie	Gary	Lawrence Technological University
Crowell	Miki	California Energy Commission
Cullen	David	Oak Ridge National Laboratory
Curtin	Dennis	Fuel Cell Consultant
da Cruz	Flavio	Southern California Gas Company

Last Name	First Name	Organization
Dahl	Kevin	Ballard Power Systems
Daimon	Hideo	Doshisha University
Daloz	Will	BASF
Daly	Christopher	The Chemours Company
Dambacher	Jesse	Valvoline Inc.
Damle	Ashok	Techverse, Inc.
Daniels	Christina	California Department of Food and Agriculture, Division of Measurement Standards
Daniels	Jessica	U.S. Environmental Protection Agency
Danilovic	Nemanja	Lawrence Berkeley National Laboratory
Darling	Rob	Raytheon Technologies
Das	Tanya	U.S. Department of Energy
Dash	Gordon	DasH2energy
Dashkowitz	Paul	Hyundai Motor America
Dass	Sasha	Analog Devices, Inc.
Daugherty	Mark	Avium, LLC
Davenport	Tim	Raytheon Technologies
Davies	Rich	Oak Ridge National Laboratory
Davis	Julian	Georgetown University
Dawson	Richard	Berenberg
De Castro	Emory	Advent Technologies, Inc.
De Haan	Foppe	Ministry of Economic Affairs and Climate (Netherlands)
De Santiago	Hector	West Virginia University
de Valladares	Mary Rose	MRS Enterprises L.L.C.
Dean	Mark	H2@Scale
DeCuollo	Gerald	TreadStone Technologies, Inc.
DeFrancesco	Gina	American Gas Association
Deibel	Angela	West Virginia University
del Rosario	Julie Anne	University of the Philippines Diliman
Delsol	Kevin	GE Power Conversion
Deutsch	Todd	National Renewable Energy Laboratory

Last Name	First Name	Organization
Devlin	Pete	U.S. Department of Energy
Dickmeyer	Jim	Electrum Power & Technology, Inc.
Dickson	David	Crane Aerospace & Electronics
Didinger	Dennis	Harvard University
Ding	Dong	Idaho National Laboratory
Ding	Hanping	Idaho National Laboratory
Ding	Lei	University of Tennessee
Ding	Yi	U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC)
Dinh	Huyen	National Renewable Energy Laboratory
Dirschka	Eric	NASA
Dismukes	Charles	Rutgers University
DiStefano	Jennifer	Energy Futures Initiative (EFI)
Divekar	Ashutosh	Origen Hydrogen
Dixon	Derek	Pacific Northwest National Laboratory
Do	Quoc Cuong	Korea Research Institute of Chemical Technology
Do	Robert	SGH2 Energy Global, LLC
Dobbins	Tabbetha	Rowan University
Dogdibegovic	Emir	Nexceris, LLC
Dolci	Francesco	European Commission Joint Research Centre
Dombrovskis	Johanna	PowerCell Sweden AB
Dominguez	Jesus	Jacobs Technology, NASA Marshall Space Flight Center Group
Donahue	Chancellor	Tennessee Technological University
Dong	Cunhai (Josh)	Dongyue Group Co., Ltd
Dornheim	Martin	Helmholtz-Zentrum Hereon
Dorobantu	Mihai	Eaton Vehicle Group
Doshi	Jayesh	eSpin Technologies, Inc.
Dou	Jian	North Carolina State University
Dow	Eric	
Dowd	Jeff	U.S. Department of Energy
Downing	Julia	The Building People

Last Name	First Name	Organization
Dietl	Elisabeth	NOW GmbH (National Organisation for Hydrogen and Fuel Cell Technology)
Duan	Chuancheng	Kansas State University
Duan	Hui	University of Delaware
Duanghathaipornsuk	Surachet	University of Toledo
Duarte	Kimberley	Plug Power Inc.
Dubel	Zachary	Federation of Electric Power Companies of Japan
Duggal	Anil	General Electric Company Global Research Center
Duggan	Conor	First Mode
Duh	Steve	Toyota Motor North America
Duimering	Doug	Next Hydrogen
Dull	Samuel	Stanford University
Dunbar	Zachary	Edwards Vacuum
Dunsmore	Lisa	Versogen
Dunteman	Katie	Caterpillar Inc.
Duraisamy	Arun	Cummins Inc.
Dutta	Monica	Ballard Power Systems
Eaglesham	David	Electric Hydrogen Co.
Eastcott	Jennie	Hydrogenics (Cummins Inc.)
Echten	Sanne	Netherlands Embassy in Washington, DC
Ehrhart	Brian	Sandia National Laboratories
Eisman	Glenn	Eisman Technology Consultants, LLC
Ekblad	Oskar	PowerCell Sweden AB
Elbaz	Lior	Bar-Ilan University
Elgammal	Ramez	University of Tennessee
Elgowainy	Amgad	Argonne National Laboratory
Elliott	Paul	
Elrick	William	California Fuel Cell Partnership
Emori	Sakuma	Toyota Motor North America
Enyekwe	Innocent	Baylor University
Epting	William	National Energy Technology Laboratory

Last Name	First Name	Organization
Erb	Anthony	U.S. Environmental Protection Agency
Erb	Bryan	De Nora S.p.A.
Ergul	Busra	University of Arkansas at Little Rock
Ermanoski	Ivan	Arizona State University
Erne	Frank	Freudenberg Sealing Technologies GmbH & Co. KG
Ernst	Felix	PowerCell Sweden AB
Escalona	Marisabel	Global Integral Supply
Esposito	Daniel	Columbia University
Eudy	Leslie	National Renewable Energy Laboratory
Evgenev	Gleb	Moscow State Automobile and Road Technical University
Fairlie	Matt	Next Hydrogen
Fan	Wenqiang	ABB Ltd.
Farese	David	Air Products and Chemicals, Inc.
Farha	Omar	Northwestern University
Faria	Gerard	CommGFA
Farmer	Rick	
Feaver	Aaron	Washington State University, Joint Center for Deployment and Research in Earth Abundant Materials, Consortium for Hydrogen and Renewably Generated E-Fuels
Fecko	Chris	U.S. Department of Energy, Basic Energy Sciences Program
Feher	Peter	General Electric Company
Feiner	Kalli	C5 Pro-Solutions
Feise	Hermann	BASF SE
Feng	Zhili	Oak Ridge National Laboratory
Fenton	James	University of Central Florida
Ferguson	Clayton	U.S. Army Environmental Command
Ferguson	Jason	RBN Energy, LLC
Ferguson	Lance	JTEKT North America Corporation
Fernandez	Beatriz	bp p.l.c.
Fesmire	James	Energy Evolution LLC

Last Name	First Name	Organization
Figoli	Ignacio	Ministry of Industry, Energy and Mining, Uruguay
Findley	Kip	Colorado School of Mines
Fisher	Paul	Fuel Cell Enabling Technologies, Inc.
Fitzgerald	Margaret	Colorado School of Mines
Flanagan	Jordan	AJW, Inc.
Flowers	Dan	Lawrence Livermore National Laboratory
Foister	Shane	University of Tennessee
Fomby	Kerri	Oak Ridge Associated Universities
Fornaciari	Julie	University of California, Berkeley/Lawrence Berkeley National Laboratory
Forni	Adam	Google LLC
Forrest	Kate	University of California, Irvine
Forrester	Nicole	Commonwealth Scientific and Industrial Research Organization (CSIRO)
Foster	Jayson	Colorado School of Mines
Fox	Melissa	Los Alamos National Laboratory
Francis	Martin	ArcelorMittal
Frank	Ed	Argonne National Laboratory
Frank	Silke	Mission Hydrogen GmbH
Frazier	Tim	Cummins Inc.
Freitag	Douglas	Bayside Materials Technology
Freyermuth	Vincent	Argonne National Laboratory
Fritz	Katrina	California Stationary Fuel Cell Collaborative
Fritzler	Gene	Fritzler Resources, Inc
Frois	Bernard	Commissariat à l'énergie atomique et aux énergies alternatives (CEA, French Atomic Energy Commission)
Fronk	Matthew	Matt Fronk & Associates LLC
Frost	Mary	Self-Employed
Frye	Evan	U.S. Department of Energy
Fu	Jian	U.S. Department of Energy
Fuchs	Alice	Great Lakes Hydrogen LLC
Fujimoto	Cy	Sandia National Laboratories

Last Name	First Name	Organization
Fujimoto	David	Port of Seattle
Fujino	Yuzo	ENEOS Research Institute, Ltd.
Fujita	Mitsumasa	Japan Atomic Power Company
Funk	John	RTO Insider, LLC
Furukawa	Hiroyasu	University of California, Berkeley
Furukawa	Takatoshi	Hino Motors Manufacturing U.S.A., Inc.
Furusawa	Koichiro	Honda R&D Co., Ltd.
Gagliardino	Maura	Long Ridge Energy Terminal
Gaikwad	Amit	General Electric Company
Gaillard	Nicolas	University of Hawaii
Gaitor	Jamie	Carnegie Mellon University
Gallo	Jean-Baptiste	Cummins Inc.
Gandhi	Harsh	Yosa
Gandy	Kelly	Sargent & Lundy, L.L.C.
Gangavarapu	Pranathi	University of Tennessee
Gangi	Jennifer	Fuel Cell & Hydrogen Energy Association (FCHEA)
Gangloff	John	Raytheon Technologies Corporation
Ganser	Markus	Robert Bosch GmbH
Gant	Simon	Health and Safety Executive (United Kingdom)
Gao	Jun	Clemson University
Gao	Siyuan	Northern Illinois University
Gao	Yong	Southern Illinois University
Garcia	Julio	New Energy Coalition
Gardiner	Monterey	Nikola Motor Company
Garfunkel	Eric	Rutgers University
Garg	Samay	Lawrence Berkeley National Laboratory
Garland	Nancy	Retired
Garlock	Sarah	Bennett Pump Company
Garrison	Andrew	Health and Safety Executive (United Kingdom)
Garsany	Yannick	EXCET, Inc./U.S. Naval Research Laboratory
Garzon	Fernando	University of New Mexico

Last Name	First Name	Organization
Gebauer	Christian	Heraeus Deutschland GmbH & Co. KG
Gebert	Matthias	Solvay Specialty Polymers
Gemmen	Randall	U.S. Department of Energy/National Energy Technology Laboratory
Gennett	Tom	National Renewable Energy Laboratory
Gerard	David	Groupe Renault
Gerbes	Ryan	University of Maryland
Gervasio	Dominic Francis (Don)	University of Arizona
Ghavidel	Reza	Hydrogenics (Cummins Inc.)
Gheewala	Sapna	American Gas Association
Ghezel-Ayagh	Hossein	FuelCell Energy, Inc.
Ghosh	Chuni	Fuceltech Inc.
Gibbons	William	U.S. Department of Energy
Giesler	Gretchen	Sargent & Lundy, L.L.C.
Giles	Lauren	Energetics Incorporated
Gilleon	Spencer	National Renewable Energy Laboratory
Giltinan	Brian	Faurecia
Ginley	David	National Renewable Energy Laboratory
Ginter	David	Caterpillar Inc.
Girard	Claire	Air Liquide
Girard	François	National Research Council Canada
Gittleman	Craig	General Motors Company
Glaser	Paul	GE Gas Power
Goble	W. David	Consultant
Gobran	David	3M Company
Goenaga	Gabriel	University of Tennessee
Goldman	Alexander	National Renewable Energy Laboratory
Goldmeer	Jeffrey	GE Gas Power
Gómez-Villarreal	Hernán	Universidad de Castilla–La Mancha
Goodarzi	Abas	US Hybrid Corporation
Goodbody	Leslie	California Air Resources Board

Last Name	First Name	Organization
Goode	Eric	Federal Energy Regulatory Commission
Gopal	Ritu	Invenergy
Gopalan	Srikanth	Boston University
Gordon	John	Los Alamos National Laboratory
Gordon	Jon	Universal Hydrogen
Gore	Colin	Redox Power Systems, LLC
Goto	Risei	AP Ventures
Gould	Benjamin	U.S. Naval Research Laboratory
Gowin	Dan	Electrum Power & Technology, Inc.
Gracida	Jonathan	Toyota North America
Graetz	Jason	HRL Laboratories, LLC
Grams	Dana	Converge Midstream LLC
Granholm	Jennifer M.	U.S. Department of Energy
Grantham	David	RedwoodAdaptive
Grassilli	Leo	Consultant
Graves	Harry H.	Global Energy, LLC
Graziano	Frank	Chromis Technologies
Greaves	Austin	Plug Power Inc.
Green	Brian	National Renewable Energy Laboratory
Green	Malcolm	Taconic
Green	Zachary	Plug Power Inc.
Greenbaum	Elias	GTA, Inc.
Greenberg	Elizabeth	Lawrence Berkeley National Laboratory
Greene	Maxwell	Plug Power Inc.
Greenfield	Carl	International Technology and Trade Associates, Inc.
Gregory	Melissa	ONEOK, Inc.
Gretz	Daren	Aon plc
Gridin	Vladislav	Technical University of Darmstadt
Grimaldi	Amedeo	Politecnico di Milano
Groenewold	Gary	Idaho National Laboratory
Groos	Ulf	Fraunhofer Institute for Solar Energy Systems ISE

Last Name	First Name	Organization
Gross	Karl	H2 Technology Consulting, LLC
Gross	Kyle	Air Products and Chemicals, Inc.
Grot	Stephen	Ion Power, Inc.
Groth	Katrina	University of Maryland
Grubel	Katarzyna (Kat)	Pacific Northwest National Laboratory
Gu	Hengfei	Rutgers University
Guan	Panpan	Shanghai Jiao Tong University
Guerrero Nacif	Marco	NASA
Gump	Jerry	ColdStream Energy, LLC
Gundlapally	Santhosh	Gamma Technologies, LLC
Guo	Qunhui	PPG Industries Ohio, Inc.
Gurau	Marc	The Chemours Company
Guss	Adam	Oak Ridge National Laboratory
Guthrie	Barry	Prime Mover International, LLC
Gutierrez-Tinoco	Oliver	Pacific Northwest National Laboratory
Ha	Phuc	3M Company
Haberlin	George	Ionomr Innovations Inc.
Hackett	Gregory	National Energy Technology Laboratory
Hadjeres	Hichem	U.S. Department of Energy
Hafiz	Hasnain	Los Alamos National Laboratory
Haggard	Jason	
Haggi	Hamed	University of Central Florida
Hahn	Alison	U.S. Department of Energy
Hahn	Michael	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Halliday	Devin	Gas Technology Institute
Hamdan	Monjid	Plug Power Inc.
Hamilton	Jennifer	California Fuel Cell Partnership
Han	Tao	NGK Spark Plugs, Inc.
Hanauer	Matthias	Robert Bosch GmbH
Hancock	Kurtus	Airbus S.A.S.

Last Name	First Name	Organization
Hanek	Kathleen	Perma Pure LLC
Hanlin	Jason	Center for Transportation and the Environment (CTE)
Hanna	Tavis	National Renewable Energy Laboratory
Hansen	Lukas	PowerCell Sweden AB
Hanvey	Stephan	HS Diversified Solutions, LLC
Hardis	Jonathan	National Institute of Standards and Technology
Hardy	Bruce	Savannah River National Laboratory
Harenbrock	Michael	MANN+HUMMEL
Harinath	Arvind	Cummins Inc.
Harrell	Emily	National Renewable Energy Laboratory
Harris	Alexander	Brookhaven National Laboratory
Harris	Dale	Tennessee Valley Authority
Harris	Kevin	Hexagon Purus
Harris	Linda	W. L. Gore and Associates, Inc.
Harris	Tim	Southern Company
Harrison	William	NanoSonic, Inc.
Hart	David	E4tech
Harting	Karen	Boston Government Services, LLC
Hartmann	Kevin	National Renewable Energy Laboratory
Hartvigsen	Jeremy	Idaho National Laboratory
Hashimoto	Noboru	Panasonic Corporation
Hatanaka	Tatsuya	Toyota Tsusho Corporation
Hauck	Jessica	University of Colorado Boulder
Haug	Andrew	3M Company
Haungs	David	The Lubrizol Corporation
Havig	Sara	National Renewable Energy Laboratory
Hawley	Douglas	American Hydrogen Association
Hayes	Robin	U.S. Department of Energy, Basic Energy Sciences Program
Hayman	Nicholas	The University of Oklahoma/Oklahoma Geological Survey
Haynes	Daniel	National Energy Technology Laboratory

Last Name	First Name	Organization
He	Cheng	National Renewable Energy Laboratory
He	Keping	Ballard Power Systems
He	Pingan	Mitsubishi Motors R&D of America, Inc.
He	Xin	Aramco Americas
He	Yanghua	Los Alamos National Laboratory
Hecht	Ethan	Sandia National Laboratories
Hedges	Michael	Hedges Hydrogen Advisors LLC
Hedlund	Jay	Ariel Corporation
Helft	Matthieu	Solvay Specialty Polymers
Helm	Darrin	Xcel Energy Inc.
Henckel	Danielle	National Renewable Energy Laboratory
Hennebury	Michaela	Princeton University
Henrichsen	Lars	Cummins Inc.
Hensley	Erin	National Renewable Energy Laboratory
Heo	Su Jeong	National Renewable Energy Laboratory
Heo	Tae Wook	Lawrence Livermore National Laboratory
Heppe	Nils	Technical University of Darmstadt
Hering	Martin	Robert Bosch LLC
Herman	Steve	SAHEnergy
Hernandez	Diana	Simulex Limited
Hershey	Robert	Robert L. Hershey, P.E.
Hershkowitz	Frank	ExxonMobil (retired)
Hertz	Kristin	Sandia National Laboratories
Hery	Travis	Power to Hydrogen
Heske	Clemens	University of Nevada, Las Vegas
Hess	Richard	Idaho National Laboratory
Hewitt	Christopher	BASF
Heyboer	Eric	Boston Government Services, LLC
Heydorn	Barbara	Horizon Views
Heywood	Peter	Allegheny Science & Technology (contractor to U.S. Department of Energy, Office of Technology Transitions)

Last Name	First Name	Organization
Hibbs	Michael	Sandia National Laboratories
Hickey	Darren	Cummins Inc.
Hickner	Michael	The Pennsylvania State University
Hidai	Shoichi	Toshiba Energy Systems & Solutions Corporation
Hill	David	Plastic Omnium
Hill	Laura	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Hill	Michael	Federal Energy Regulatory Commission
Hillebrand	Don	Argonne National Laboratory
Hillen	Huub	Shell
Hilmi	Abdelkader	FuelCell Energy, Inc.
Hines	Spencer	Bennett Pump Company
Hirai	Masato	Federation of Electric Power Companies of Japan
Hiraiwa	Hiro	Sumitomo Electric
Hirano	Shinichi	Hyzon Motors Inc.
Hirata	Yuko	Daiwa Institute of Research Ltd.
Hitchcock	Dale	Savannah River National Laboratory
Ho	Christina	U.S. Department of Energy
Ho	Donna	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Hoagland	William	Element One, Inc.
Hodne	Taylor	3M Company
Hoffman	Andrew	General Electric Company Global Research Center
Hoffman	Beau	U.S. Department of Energy, Bioenergy Technologies Office
Holby	Edward	Los Alamos National Laboratory
Holder	Aaron	U.S. Department of Energy, Office of Sciences, Basic Energy Sciences Program
Holladay	Jamie	Pacific Northwest National Laboratory
Hollenbeck	Bruce	Black Point Holdings
Hollens	David	Maryland Environmental Service
Holtje	Glenn	Cryogenic Fuels, Inc.
Honjo	Shintaro	Mitsubishi Heavy Industries America

Last Name	First Name	Organization
Hopkin	Sarah	Shell
Hopkins	Tim	The Chemours Company
Horita	Teruhisa	National Institute of Advanced Industrial Science and Technology (AIST)
Horky	Ales	Ballard Power Systems
Horton	Linda	U.S. Department of Energy, Office of Science
Hosseinpour	Pegah	Compagnie de Saint-Gobain S.A.
Hotta	Yoshihiro	Toyota Central R&D Labs, Inc.
Hou	Deyang	QuantLogic Corporation
Houchins	Cassidy	Strategic Analysis, Inc.
Houghtalen	Natalie	ClearPath
Houle	Frances	Lawrence Berkeley National Laboratory
Houtman	Jim	Butte County Fire Safe Council
Hovsapian	Rob	National Renewable Energy Laboratory
How	Jake	Gamma Technologies, LLC
Howard	Zeon	Toyota
Howart	Michael	DTE Energy
Howe	Marisa	National Renewable Energy Laboratory
Hsieh	Eric	U.S. Department of Energy
Hu	Jingwei	Ballard Power Systems
Hu	John	West Virginia University Research Corporation
Hu	Leiming	Carnegie Mellon University
Hu	Zhendong	Toyota Research Institute
Huang	Hansong	Pine Energy
Huang	Jin	University of California, Los Angeles
Huang	Kevin	University of South Carolina
Hubert	McKenzie	Stanford University
Hubler	Mija	University of Colorado Boulder
Huddleston	Denay	Phillips 66 Company
Huerta	Rosalba	University of Wisconsin–Milwaukee
Huff	Kathryn	U.S. Department of Energy

Last Name	First Name	Organization
Hughes	Michael	GE Power
Hui	Linda	Bay Area Air Quality Management District
Hulvey	Zeric	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Hunter	Brian	U.S. Department of Energy
Hunter	Chad	National Renewable Energy Laboratory
Hurlebaus	Tara	Blue Blaze Associates, LLC
Hurst	Katherine	National Renewable Energy Laboratory
Hurst	Rachel	National Renewable Energy Laboratory
Hussey	Daniel	National Institute of Standards and Technology
Hussey	John	
Huya-Kouadio	Jennie	Strategic Analysis, Inc.
Hwang	James	Fetch Rewards, Inc.
Hwang	Monica	
Iaconangelo	David	E&E News
Ieda	Yoshiaki	Japan Atomic Energy Agency
Igarashi	Hiroshi	N.E. CHEMCAT Corporation
Ingram	David	Phillips 66 Company
Intihar	Gabby	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
Intikhab	Saad	National Renewable Energy Laboratory
Irwin	Levi	Contractor to U.S. Department of Energy
Isaac	Raphael	Energetics Incorporated
Ishida	Takanobu	Ishifuku Metal Industry Co., Ltd.
Ishikawa	Katsuya	KAWASAKI Heavy Industries, Ltd.
Ishimura	Darren	Hawaiian Electric
Islam	Ehsan	Argonne National Laboratory
Islamogly	Timur	Northwestern University
Iturbe-García	Jose Luis	Instituto Nacional de Investigaciones Nucleares (Mexico)
Iyer	Narayan	Laminar Scientific LLC
Iyer	Nisha	pH Matter, LLC

Last Name	First Name	Organization
Jacob	Tabeel	Lawrence Berkeley National Laboratory
Jacobson	David	National Institute of Standards and Technology
Jafry	Adil	ARJ
Jakubowski	Beth	American Center for Mobility
Jakupca	Ian	NASA, Glenn Research Center
James	Brian	Strategic Analysis, Inc.
James	Charles	Savannah River National Laboratory
Janarthanan	Rajeswari	De Nora S.p.A.
Jang	Ji-Hoon	Hyundai Motor Company
Jang	Yosep	Rensselaer Polytechnic Institute
Jankovic	Jasna	University of Connecticut
Jansto	Steven	Research and Development Resources
Jaramillo	David	University of California, Berkeley
Jaramillo	Thomas	Stanford University, Department of Chemical Engineering
Jayne	Lee	Hephas Energy Corporation
Jedenmalm	Anneli	ABB Ltd.
Jelen	Deborah	Electricore, Inc.
Jennings	Jon	EWI
Jensen	Craig	University of Hawaii
Jensen	Mark	Phillips 66 Company
Jia	Hongfei	Toyota Motor North America
Jia	Qingying	Northeastern University
Jiang	Changle	West Virginia University
Jiang	Ruichun	General Motors Company
Jiao	Li	Northeastern University
Jihad	Muhammad	Springreens
Jin	Xinfang	University of Massachusetts Lowell
Johnson	Alan	H Quest Vanguard, Inc.
Johnson	Joe	Signature Stairs, LLC
Johnson	Kenneth	Retired chemical engineer

Last Name	First Name	Organization
Johnson	Mark	California Energy Commission
Johnson	Nancy	U.S. Department of Energy, Office of Oil and Natural Gas
Johnson	Robert	ExxonMobil Research and Engineering Company
Johnston	Stephen	San Diego Gas & Electric
Jokinen	Kristian	CALSTART
Jones	Ayaka	U.S. Department of Energy
Jones	Jones	General Electric Company
Jorgensen	Scott	SBC Global Alliance
Jorgenson	Scott	Hyrax Intercontinental LLC
Joseck	Frederick	FJoseck Consulting LLC
Josefik	Nicholas	U.S. Army Corps of Engineers, Construction Engineering Research Laboratory
Joshi	Vijay	Greenko Group
Jourde	Camille	Solvay Specialty Polymers
Jurzinsky	Tilman	Freudenberg Sealing Technologies GmbH & Co. KG
Kabir	Pooyan	McDermott International, Ltd.
Kabir	Sadia	Giner, Inc.
Kadylak	David	Loop Energy
Kaelin	Jacob	Northern Illinois University
Kahlon	Navdeep	Progressive Energy
Kaida	Yuriko	AGC Business Development Americas
Kakimoto	Seizo	Nissan Chemical Corporation
Kamepalli	Smuruthi	General Motors Company
Kanaujia	Kamal	Nokia Corporation
Kaneko	Fumitoshi	Osaka University
Kanesaka	Hiroyuki	FC-Cubic TRA
Kang	ShinYoung	Lawrence Livermore National Laboratory
Kapoor	Harpal	Omni Strategy, LLC
Karabacak	Tansel	University of Arkansas at Little Rock
Karatay	Elif	Palo Alto Research Center (PARC), a Xerox Company

Last Name	First Name	Organization
Kariuki	Nancy	Argonne National Laboratory
Kariya	Natsuki	Mizuho Research & Technologies, Ltd.
Karlsson	Patrik	PowerCell Sweden AB
Karlsson	Tim	International Partnership for Hydrogen and Fuel Cells in the Economy
Kashiwamura	Eric	Hawaiian Electric
Kashuba	Michael	California Governor's Office of Business and Economic Development
Kast	James	Toyota Motor North America
Katakura	Hiroyuki	Seika Corporation
Katzenberg	Adlai	Lawrence Berkeley National Laboratory
Kaur	Tavleen	U.S. Department of Energy
Kawamura	Atsuhiro	Toppan Printing Co., Ltd.
Kaymak	Didem	ALDO Energy
Kazempoor	Pejman	The University of Oklahoma
Keairns	Dale	Deloitte Consulting LLP
Keane	Alex	Proton Energy Systems
Keefer	Randall	American Electric Power
Keller	Jay	Zero Carbon Energy Solutions
Kelley	Patty	New Day Hydrogen, LLC
Kelly	Jarod	Argonne National Laboratory
Kempler	Paul	Oregon Center for Electrochemistry
Kent	Andrew	WGL/AltaGas Ltd.
Kent	Ron	Southern California Gas Company
Keough	Laura	W. L. Gore and Associates, Inc.
Khedekar	Kaustubh	University of California, Irvine
Killingsworth	Nick	Lawrence Livermore National Laboratory
Kim	Hyungyup	Global America Business Institute (GABI)
Kim	Jae Jin	Argonne National Laboratory
Kim	Jai-woh	U.S. Department of Energy
Kim	Jung Ho	Kolon Industries
Kim	Namdoo	Argonne National Laboratory

Last Name	First Name	Organization
Kim	Si-Won	Hyundai Motor Company
Kim	Yu Seung	Los Alamos National Laboratory
King	Brent	
King	Laurie	Manchester Metropolitan University
Kinoshita	Shinji	AGC Inc.
Kinsinger	Nichola	U.S. Department of Energy
Kirschbaum	Asher	National Renewable Energy Laboratory
Kiser	Lee-Ann	Oak Ridge Institute for Science and Education (ORISE)
Klaassen	Trevor	The University of Oklahoma
Klebanoff	Lennie	Sandia National Laboratories
Kleen	Greg	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Klein	Ryan	National Renewable Energy Laboratory
Kloos	Steve	True North Venture Partners
Klopfenstein	Jessica	Plug Power Inc.
Knights	Shanna	Ballard Power Systems
Kobayashi	Ryo	Sumitomo Corporation of Americas
Kobayashi	Takashi	Yamanashi Industrial Technology Center
Kocha	Shyam	Shyam Kocha Consulting
Kodali	Mounika	De Nora S.p.A.
Koehr	John	Koehr Consulting Group, LLC
Koeppel	Brian	Pacific Northwest National Laboratory
Kohl	Paul	Georgia Institute of Technology
Koka	Jona	U.S. House Committee on Science, Space and Technology
Koleva	Mariya	U.S. Department of Energy
Kolla	Praveen	Skyre, Inc.
Komini Babu	Siddharth	Los Alamos National Laboratory
Kondo	Shoichi	Nissan Chemical Corporation
Kong	Szelim	U.S. Department of Energy, Naval Nuclear Laboratory
Kongkanand	Anusorn	General Motors Company

Last Name	First Name	Organization
Kopasz	John	Argonne National Laboratory
Kota	V. M. K. Kireeti	University of Waterloo
Kotake	Shoji	Japan Atomic Energy Agency
Kothandaraman	Jothi	Pacific Northwest National Laboratory
Koti	Archit	Cummins Inc.
Kramm	Ulrike	Technical University of Darmstadt
Kratschmar	Ken	Ekona Power Inc.
Kratz	Sven-Erik	SEK Strategy Consulting GmbH
Krause	Theodore	Argonne National Laboratory
Krauss	Natalie	Faurecia Clean Mobility
Kreutzer	Cory	National Renewable Energy Laboratory
Kriplani	Ushma	Argonne National Laboratory
Krogstad	Jessica	University of Illinois at Urbana–Champaign
Kropman	Susie	Embassy of Australia
Kuang	Wenbin	Pacific Northwest National Laboratory
Kübler	Markus	Technical University of Darmstadt
Kuehn	Ryan	National Energy Technology Laboratory
Kuhnert	Eveline	Graz University of Technology
Kulkarni	Devashish	University of California, Irvine
Kulkarni	Shank	Pacific Northwest National Laboratory
Kumar	Amishi	U.S. Department of Energy, Office of Fossil Energy
Kumar	Ashok	Cummins Inc.
Kumar	Yashwanth	Fusion Minds Technologies Pvt. Ltd.
Kumaraguru	Swami	General Motors Company
Kung	Bryan	Ballard Power Systems
Kuppa	Shashi	U.S. Department of Transportation
Kuribayashi	Takaki	Toyoda Gosei Co., Ltd.
Kuriyama	Nobuhiro	National Institute of Advanced Industrial Science and Technology (AIST)
Kuroki	Taichi	National Renewable Energy Laboratory
Kushner	Douglas	Lawrence Berkeley National Laboratory

Last Name	First Name	Organization
Kusoglu	Ahmet	Lawrence Berkeley National Laboratory
Kuttiyiel	Kurian	Brookhaven National Laboratory
Kutty	Shyam	Embedded Design Studio
Kwak	Dahee	Hyundai Motor Group
Kwan	May	Southern California Gas Company
Kylhammar	Lisa	PowerCell Sweden AB
Laffen	Melissa	Energetics Incorporated
LaFleur	Chris	Sandia National Laboratories
Lai	Kalok	Ithaca College
Laibson	Larry	
Lakeman	Charles	SCHOTT North America, Inc.
Lam	Steven	Tennessee Technological University
Landin	Niko	Caterpillar Inc./Colorado State University
Lane	Blake	University of California, Irvine, Advanced Power and Energy Program
Lane	Erin	Cascade Associates
Lane	Jonathan	Linde, PLC
Lang	Alan	GKN Powder Metallurgy
Lara-Curzio	Edgar	Oak Ridge National Laboratory
Larson	Amanda	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office/The Building People
Larson	Tim	Avium, LLC
Lasher	Stephen	National Grid
Lau	Thomas	Manchester Metropolitan University
Laughlin	Timothy	GKN Powder Metallurgy
Laursen	Anders	Rutgers University
Law	Sandra	Energy Development Consultants
Lawler	John	Plug Power Inc.
Lawson	Jeremy	Northern California Power Agency
Lawson	William	General Electric Company
Le	Tay Son	University of Melbourne
Le	Thien An	Korea Research Institute of Chemical Technology

Last Name	First Name	Organization
Leachman	Jacob	Washington State University
Leavitt	Mark	General Motors Company
Lederer	Klaus	H2-Industries, Inc.
Lee	Bryan	CALSTART
Lee	ChungHyuk	Los Alamos National Laboratory
Lee	Heonjoong	Cummins Inc.
Lee	Jason	Nikola Motor Company
Lee	Keonhag	Lawrence Berkeley National Laboratory
Lee	Michael	Southern California Gas Company
Lee	Myoungseok	De Nora S.p.A.
Lee	Stanley	
Lee	Stephen	Northern California Power Agency
Lee	Stephen	AVL Fuel Cell Canada
Lee	Yunsu	Hyundai Motor Group
Lehmann	Michelle	University of Tennessee/Oak Ridge National Laboratory
Lehner	William	Independence Hydrogen
Leick	Noemi	National Renewable Energy Laboratory
Leighton	Daniel	National Renewable Energy Laboratory
Leighton	Delisa	IGX Group
Leighty	William	The Leighty Foundation
Leiva	Emilce	
Leonard	Daniel	Los Alamos National Laboratory
Leonard	Mallary	
Leonard	Nathaniel	General Motors Company
Leveneur	Jerome	GNS Science
Lewinski	Krzysztof	3M Company
Lewis	Alex	Electro-Active Technologies Inc.
Lewis	Michael	Komatsu
Lewis	Michael	University of Texas at Austin
Li	Bomin	Argonne National Laboratory

Last Name	First Name	Organization
Li	Chenzhao	Indiana University–Purdue University Indianapolis
Li	Xianglin	University of Kansas
Li	Evan	Toyota Boshoku Corporation
Li	Gong Liang	NGK Spark Plugs USA, Inc.
Li	Jian	Volvo Group
Li	Jingkun	Centre National de la Recherche Scientifique (France)
Li	Jun	Kansas State University
Li	Kui	University of Tennessee
Li	Linfei	University of Colorado Boulder
Li	Shuyun	Pacific Northwest National Laboratory
Li	Sichi	Lawrence Livermore National Laboratory
Li	Ted	Air Liquide
Li	Wenyuan	West Virginia University
Li	Xianguo	University of Waterloo
Li	Xun	Northern Illinois University
Li	Yifei	Rutgers University
Liberman	Bruce	
Lidicker	Jeff	California Air Resources Board
Lie	Sharyn	U.S. Environmental Protection Agency
Lima	Elizabeth	The Ohio State University
Lin	Haiqing	State University of New York at Buffalo
Lin	Hongfei	Washington State University
Lin	Honghong	Toyota Research Institute, North America
Lindaas	Jakob	U.S. Congress
Lindell	Matthew	3M Company
Lindholm	Simon	PowerCell Sweden AB
Lindquist	Grace	University of Oregon
Ling	Yansong	University of California, Los Angeles
Linton	Bill	Linton Consulting
Lipman	Timothy	University of California, Berkeley/Lawrence Berkeley National Laboratory

Last Name	First Name	Organization
Lipp	Ludwig	T2M Global
Litster	Shawn	Carnegie Mellon University
Litynski	John	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
Litzelman	Scott	U.S. Department of Energy, Advanced Research Projects Agency–Energy (ARPA-E)
Liu	Anne	Massachusetts Institute of Technology
Liu	Di-Jia	Argonne National Laboratory
Liu	Ershuai	Northeastern University
Liu	Hanshuo	National Research Council Canada
Liu	Hong	Oregon State University
Liu	Jiangjin	Lawrence Berkeley National Laboratory
Liu	Jiawei	Carnegie Mellon University
Liu	Meilin	Georgia Institute of Technology
Liu	Mingfei	Phillips 66 Company
Liu	Ru-Fen	CDTi Advanced Materials, Inc.
Liu	Xingbo	West Virginia University
Liu	Xinyu	Argonne National Laboratory
Liu	Ying	Phillips 66 Company
Liu	Yun	Hong Kong Polytechnic University
Liu	Zeyan	University of California, Los Angeles
Liu	Zheng	Weichai America Corp.
Liyanage	Wipula	Los Alamos National Laboratory
Lloyd	Alan	University of Texas at Austin
Lloyd	Robert	Private investor
Loaiza	Luis	LUV
Lochner	John	New York State Energy Research and Development Authority (NYSERDA)
Long	Hai	National Renewable Energy Laboratory
Long	Jeffrey	Lawrence Berkeley National Laboratory
Longcore	Gregory	Hines Corporation
Longman	Douglas	Argonne National Laboratory

Last Name	First Name	Organization
López	Dora	The MITRE Corporation
Lopez-Ruiz	Juan	Pacific Northwest National Laboratory
Lord	Nathan	Shale Crescent USA
Lott	Nathan	American Institute of Chemical Engineers, Center for Hydrogen Safety
Loughrin	Casey	Sargent & Lundy, L.L.C.
Love	Darren	Evok Innovations
Love	Michelle	Oak Ridge Associated Universities
LoweLee	Florence	Global America Business Institute (GABI)
Luangdilok	Wison	H2Technology LLC
Lubawy	Andrea	Toyota Motor North America
Lucier	Ashley	DTE Energy
Ludlow	Daryl	Ludlow Electrochemical Hardware
Ludwig	Dan	Xcel Energy Inc.
Lueddecke	Bernhardt	Continental/Vitesco Technologies
Luo	Jessica	Ballard Power Systems
Luo	Jian	University of California, San Diego
Luo	Jinyong	Cummins Inc.
Luo	Yusheng	Idaho National Laboratory
Luong	Staffan	Volvo Group
Lustbader	Jason	National Renewable Energy Laboratory
Ly	Vy	Naval Sea Systems Command
Lyons	George	Self-Employed
Lyubovsky	Maxim	Booz Allen Hamilton
Ma	Kai	Zhejiang University
Ma	Shengqian	University of North Texas
Ma	Zhiwen	National Renewable Energy Laboratory
Macauley	Natalia	Giner, Inc.
MacIntire	Ian	U.S. Department of Transportation
MacLeod	Bill	Emerald Advisory LLC
Maddalena	Kevin	Bennett Pump Company

Last Name	First Name	Organization
Madkour	Sherif	BASF SE
Madongo	Leroy	
Maes	Miguel	NASA, White Sands Test Facility
Mallinson	Eric	Hawaii Solar & Wind, LLC
Mamazza	Robert	Impact Coatings AB
Mangan	Andrew	United States Business Council for Sustainable Development
Männikkö	Marika	PowerCell Sweden AB
Maranville	Alex	Energy Futures Initiative (EFI)
Marcinkoski	Jason	U.S. Department of Energy
Marechaux	Toni	Booz Allen Hamilton
Maric	Radenka	University of Connecticut
Maric	Robert	Heraeus Deutschland GmbH & Co. KG
Marie	Gigi	Marie, Inc.
Marina	Olga	Pacific Northwest National Laboratory
Markiwicz	Matthew	Ballard Power Systems
Martin	Cameron	Westinghouse Electric Company LLC
Martin	Josh	National Renewable Energy Laboratory
Martin	May	National Institute of Standards and Technology
Martineau	Rebecca	National Renewable Energy Laboratory
Martinez	Alex	Johnson Matthey
Martinez	Andrew	California Air Resources Board
Martz	Thomas	Electric Power Research Institute
Maruta	Akiteru	Technova Inc.
Marxen	Sara	CSA Group
Maserumule	Rebecca	Department of Science and Innovation (South Africa)
Mason	Chad	Advanced Ionics
Masten	David	General Motors Company
Mastropasqua	Luca	University of California, Irvine
Masuda	Junichi	Toray Industries, Inc.
Matlack	Ralph	bp ventures

Last Name	First Name	Organization
Matsuda	Yoshiyuki	Japan Automobile Research Institute
Matsui	Kazuma	Toray Industries, Inc.
Matsuki	Shogo	NGK Spark Plugs USA, Inc.
Matsumura	Michiaki	Japan Electric Power Information Center
Matsunaga	Atsushi	
Matsuzawa	Kazuyuki	Japan Electrical Manufacturers' Association
Matter	Paul	pH Matter, LLC
Matthews	Michael	Solaris Management Consultants Inc.
Mattsson	Joel	PowerCell Sweden AB
Matz	Stephanie	University of Delaware
Mauger	Scott	National Renewable Energy Laboratory
Maurya	Sandip	Los Alamos National Laboratory
Mayer	Kurt	Graz University of Technology
Mayer	Matt	ExoCell Power
McCool	Geoffrey	Pajarito Powder, LLC
McCoy	Britney	U.S. Environmental Protection Agency
McDaniel	Anthony	Sandia National Laboratories
McDonald	Nikkia	U.S. Department of Energy
McDougle	Stephen	MEI Technologies, Inc.
McDowell	Robert	MCG, LLC
McFarland	Eric	University of California, Santa Barbara
McGaughy	Tom	EWI
McGibbon	Timothy	Interstate Hydrogen
McGuirk	Mike	Colorado School of Mines
McNamara	Kevin	Strategic Analysis, Inc.
McQueen	Shawna	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
McRobie	Jordan	National Institute of Clean and Low-Carbon Energy (NICE) America Research Inc.
McWhorter	Scott	Savannah River National Laboratory
Mearns	James	Northern California Power Agency
Medina	Samantha	Colorado School of Mines

Last Name	First Name	Organization
Meekins	Ben	University of South Carolina
Meeks	Noah	Southern Company Services, Inc.
Mehta	Darius	Garrett Advancing Motion
Mehta	Maunil	Rolls-Royce
Mehta	Vishal	National Renewable Energy Laboratory/Ohio Northern University
Melaina	Marc	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Melis	Eric	H2One Hydrogen
Menon	Nalini	Sandia National Laboratories
Mercer	Michael	Bedrock Gas Solutions
Merchan-Merchan	Wilson	The University of Oklahoma
Mergel	Juergen	Consultant
Mesa	Juan	Carnegie Mellon University
Mesrobian	Christopher	Monolith Materials
Messina	Pete	
Messner	Josh	U.S. Department of Energy, Bioenergy Technologies Office
Metzger	Katherine	University of New Hampshire
Metzroth	Lucy	National Renewable Energy Laboratory
Meunier	Paul	
Meyers	Joao	U.S. Geological Survey
Mi	Zetian	University of Michigan
Michael	Aaron	Florida Power & Light Company
Michael	Austin	Idaho National Laboratory
Migliarese Caputi	Michele Vincenzo	Sapienza Universita di Roma, Dipartimento di Engegneria Meccanica e Aerospaziale (DIMA)
Mikulin	John	U.S. Environmental Protection Agency
Miles	Larry	Pacific Coast Renewable Energy LLC
Miller	B.	
Miller	Eric	U.S. Department of Energy
Miller	Paul	Energy Transition Analytics Group
Milliken	JoAnn	New Jersey Fuel Cell Coalition

Last Name	First Name	Organization
Mills	Patrick	Confederated Tribes of the Umatilla Indian Reservation
Min	Byunghyun	Phillips 66 Company
Minami	Reiko	Daiwa Institute of Research Ltd.
Minamibayashi	Kenta	Toray Industries, Inc.
Miner	Dillon	California Air Resources Board
Minh	Nguyen	University of California, San Diego
Miranda	Raul	U.S. Department of Energy, Basic Energy Sciences Program
Mirisola	Lisa	South Coast Air Quality Management District
Mitchell	George	U.S. Environmental Protection Agency
Mittelsteadt	Cortney	Plug Power Inc.
Miura	Shinichi	Kobe Steel, Ltd.
Mizutani	Yasunobu	National Institute of Advanced Industrial Science and Technology (AIST)
Moen	Chris	Sandia National Laboratories
Mohite	Aditya D.	Rice University
Mohr	Jeffrey	National Renewable Energy Laboratory
Mohtadi	Rana	Toyota Motor North America
Mojica	Felipe	Versogen
Mokrini	Asmae	National Research Council Canada
Montgomery	David	Caterpillar Inc.
Moon	Hwan	Doosan Fuel Cell America
Moore	Jared	Thermal Hydrogen Industries
Moore	Richard	Connected DMV
Moran	David	Energy Field Security, Inc.
More	Karren	Oak Ridge National Laboratory
Moreland	Greg	General Dynamics Information Technology (contractor to Oak Ridge National Laboratory)
Moretto	Pietro	European Commission
Morgan	Jason	AvCarb Material Solutions
Morgan	Robert	H Cycle, LLC
Mori	Daigoro	Toyota Motor Corporation

Last Name	First Name	Organization
Mori	Yuto	Mitsubishi International Corporation
Morimoto	Yu	Doshisha University
Morioka	Hiroyuki	Toppan Technical Research Institute
Moriyama	Koji	American Honda Motor Co., Inc.
Morris	Ashley	University of Kentucky, Center for Applied Energy Research
Morris	William	NuMat Technologies
Morrison	Suzanne	National Research Council Canada
Mosdale	Renaut	Pragma Industries
Mosser	Chris	Bennett Pump Company
Motz	Andrew	Nel Hydrogen
Mouli	Nandini	eSai LLC
Moulia	Thomas	Corporate Value Associates
Mount	Jerry	Fair Horizon Energy Capital, LLC
Mousa	Ahmed	Public Service Electric and Gas Co. (PSE&G)
Mow	Rachel	National Renewable Energy Laboratory
Muisener	Richard	Evonik Industries
Mukerjee	Sanjeev	Northeastern University
Mukundan	Rangachary	Los Alamos National Laboratory
Muley	Arun	Boeing Research & Technology
Murase	Hideaki	Panasonic Corporation
Murata	Hajime	Toyota Central R&D Labs, Inc.
Muromoto	Nobuyoshi	Honda Motor Co., Ltd.
Murphy	Brian	Strategic Analysis, Inc.
Murray	Bill	Advanced Ionics
Murthi	Vivek	Nikola Motor Company
Murthy	Mahesh	Thermax Ltd
Musgrave	Charles	University of Colorado Boulder
Mustain	William	University of South Carolina
Myers	Charles	General Dynamics Information Technology
Myers	Deborah	Argonne National Laboratory

Last Name	First Name	Organization
Naddaf	Soubhi	NITCO
Nagai	Tomoyki	Toyota Central R&D Labs., Inc.
Nagamori	Kiyotaka	N.E. CHEMCAT Corporation
Nagasawa	Kazunori	National Renewable Energy Laboratory
Naghavi	Hossein	General Electric Company
Naik	Adarsh Ajith	Indian Institute of Science
Nakamura	Naoki	Toyota Motor Corporation
Nakazawa	Taichi	Nissan Chemical Corporation
Nanninga	Nicholas	Secat, Inc.
Narayan	Sri	University of Southern California
Nathan	Todd	
Navaei Alvar	Esmaeil	Ballard Power Systems
Nelakurthi	Mahesh Babu	Texas A&M University–Kingsville
Nelson	Amy	AVL Fuel Cell Canada
Neriya	Rashmi	
Nestor	Sean	
Newell	Pania	The University of Utah
Newhouse	Norman	Newhouse Technology, LLC
Neyerlin	Kenneth	National Renewable Energy Laboratory
Nguyen	Hien	Hahn Schickard Society for Applied Research
Nguyen	Kestar	The Green Solutions
Nguyen	Phuc	Advanced Ionics
Nguyen	Tien	Retired
Nibur	Kevin	Hy-Performance Materials Testing LLC
Nichols	Marshall	National Petroleum Council
Niedzwiecki	Allison	Nel Hydrogen US
Nielander	Adam	Stanford University
Nipp	Terry	AEGIS, Ltd.
Nishimura	Shin	Kyushu University
Nitsche	Rolf	Self-Employed
Noland	Brian	Plug Power Inc.

Last Name	First Name	Organization
Nortier	Marine	Commissariat à l'énergie atomique et aux énergies alternatives (CEA, French Atomic Energy Commission)
Noto	Mayumi	Oerlikon Balzers
Nowak	Robert	
Nummy	Amanda	Hyundai–Kia
Öberg	Elisabeth	PowerCell Sweden AB
Ocampo	Minette	pH Matter, LLC
Ochs	Markus	Vitesco Technologies
Odom	Sara	Electricore, Inc.
Odufuwa	Esther	California Energy Commission
Ogden	Joan	University of California, Davis
Ogitsu	Tadashi	Lawrence Livermore National Laboratory
Oh	Jae Won	Princeton University
Oh	Songi	Hyundai Motor Company
Ohira	Junko	Toyota Boshoku Corporation
Ohnuma	Akira	Toyota Boshoku Corporation
Okamoto	Yohei	Toyota Motor North America
Okazaki	Ken	Tokyo Institute of Technology
Okumura	Ryota	DENSO International America, Inc.
Oliveira	Alexandra	University of Delaware
Oliver	Martha	U.S. Department of Energy
Olsen	Charles	American Electric Power
Olson	Gregory	General Dynamics Information Technology (contractor to U.S. Department of Energy)
Omura	Takeo	Daiwa Institute of Research Ltd.
O'Neill	John	Sikorsky Helicopter, a Lockheed Martin company
Ong	Gary	Celadyne Technologies
Onorato	Shaun	National Renewable Energy Laboratory
Ordonez	Juan	Florida A&M University and Florida State University (FAMU-FSU) College of Engineering
O'Shaughnessy	W. Shannan	GVD Corporation

Last Name	First Name	Organization
Osmieri	Luigi	Los Alamos National Laboratory
Ota	Shingo	Toyota Motor North America
Otgonbaatar	Uuganbayar	Exelon Corporation
Otilingam Sivakumar	Premanand	University of Delaware
Ott	Kevin	Los Alamos National Laboratory (retired)
Owejan	Jon	Plug Power Inc.
Paczkowski	Ben	U.S. Army Ground Vehicle System Center
Padgett	Elliot	National Renewable Energy Laboratory
Paffhausen	Chad	Bennett Pump Company
Pagels	Michael	Rensselaer Polytechnic Institute
Palies	Paul	University of Tennessee Space Institute, Department of Mechanical, Aerospace, and Biomedical Engineering
Pallan	Madhavan	IBM Thomas J. Watson Research Center
Pandey	Maneesh	Baker Hughes
Panwar	Mayank	National Renewable Energy Laboratory
Papadias	Dionissios	Argonne National Laboratory
Papageorgopoulos	Dimitrios	U.S. Department of Energy
Papavassiliou	Dimitrios	The University of Oklahoma
Parilla	Philip	National Renewable Energy Laboratory
Park	Andrew	The Chemours Company
Park	Chanmi	Kolon Industries
Park	David	California Fuel Cell Partnership
Park	Dongnyeok	Hyundai Motor Group
Park	Gu-Gon	Korea Institute of Energy Research
Park	Heemin	Rensselaer Polytechnic Institute
Park	Hwun	Hanwha Aerospace
Park	Hyounmyung	Hyundai Motor Company
Park	Jae Hyung	Argonne National Laboratory
Park	Sarah Eun Joo	Los Alamos National Laboratory
Parkan	John Michael	Providence Entertainment
Parker	Eric	U.S. Department of Energy

Last Name	First Name	Organization
Parker	Kendall	University of Florida
Parks	George	FuelScience, LLC
Pasaogullari	Ugur	University of Connecticut
Patch	Keith D.	Self-Employed
Patel	Pinakin	T2M Global
Paterson	Jack	City and County of Denver
Paterson	Jessica	Cummins Inc.
Patil	Kailash	Xerion Advanced Battery Corp
Patrie	Mitch	U.S. Environmental Protection Agency
Paul	Devproshad	Ballard Power Systems
Paulsson	Bjorn	Paulsson, Inc.
Paxson	Adam	Plug Power Inc.
Payne	Grant	National Renewable Energy Laboratory
Pearman	David	National Renewable Energy Laboratory
Pearson	Karolina	Plug Power Inc.
Pekarek	Christian	
Peltier	Jesse	University of California, Berkeley
Penev	Michael	National Renewable Energy Laboratory
Peng	Bosi	University of California, Los Angeles
Peng	JuiKun	Argonne National Laboratory
Peng	Peng	Lawrence Berkeley National Laboratory
Penn	Roger	AVL Fuel Cell Canada
Pérez Gil	Rodrigo	ARIEMA Energía y Medioambiente S.L.
Perry	Mike	Largo Clean Energy
Perry	Robert	Synergistic Solutions
Petek	Tyler	The Lubrizol Corporation
Peters	Michael	National Renewable Energy Laboratory
Peterson	David	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Pettersen	Jostein	Equinor
Phanse	Gautam	Chevron Corporation

Last Name	First Name	Organization
Pien	Michael	Giner, Inc.
Pierce	Benjamin	EN Engineering
Pierre	Veronica	VPB Associated, Inc.
Pietras	John	Compagnie de Saint-Gobain S.A.
Pinson	Mark	General Electric Company
Pintauro	Peter	Vanderbilt University
Pivovar	Bryan	National Renewable Energy Laboratory
Podkaminer	Kara	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
Polevaya	Olga	Nuvera Fuel Cells, LLC
Polyzos	Georgios	Oak Ridge National Laboratory
Pomerantz	Mike	Bennett Pump Company
Pomone	Thomas	Manchester Metropolitan University
Pontau	Arthur	
Posen	David	DTP Associates
Post	Matthew	National Renewable Energy Laboratory
Pottow	Victor	GCP Capital Partners LLC
Pour	Azadeh	Dalhousie University
Powell	Joseph	ChemePD LLC
Pozniak	Robert	Investor
Prabhakaran	Venkateshkumar	Pacific Northwest National Laboratory
Prager	McKinley	University of Hawaii at Manoa
Prakash	Alvin	National Institute of Clean and Low-Carbon Energy (NICE) America Research Inc.
Prasse	Marc	Sargent & Lundy, L.L.C.
Prendergast	David	Lawrence Berkeley National Laboratory
Price	David	1898 & Co.
Procter	Michael	cellcentric Canada
Prohaska	Robert	Pratt Miller
Pylypenko	Svitlana	Colorado School of Mines
Qian	Xin	Georgia Institute of Technology
Qiao	Xiaoxiao	Los Alamos National Laboratory

Last Name	First Name	Organization
Qiu	Yang	Pacific Northwest National Laboratory
Qiu	Yun	Enviro & Productio Solutions Inc.
Qu	Wei	National Research Council Canada
Quackenbush	Karen	Fuel Cell & Hydrogen Energy Association (FCHEA)
Quiles-Galarza	Genesis	The University of Pennsylvania
Quine	Cullen	California Institute of Technology
Quintus	Martin	Aerostack GmbH
Quong	Spencer	Electricore, Inc.
Rafelski	Lauren	U.S. Environmental Protection Agency
Ragsdale	Adam	DTE Energy
Rahman	Fahim	Los Alamos National Laboratory
Rahman	Md Anisur	Oak Ridge National Laboratory
Raiford	Michael	The Chemours Company
Raj	Phani	U.S. Department of Transportation, Federal Railroad Administration
Ramani	Dilip	Ballard Power Systems
Ramani	Vijay	Washington University in St. Louis
Ramaswamy	Nagappan	General Motors Company
Rambach	Glenn	Third Orbit Power Systems, Inc.
Ramig	Christopher	U.S. Environmental Protection Agency
Ramirez-Cuesta	Anibal (Timmy)	Oak Ridge National Laboratory
Ramotowski	Michael	Solar Turbines Incorporated
Randazzo	Ryan	DTE Energy
Randolph	Katie	U.S. Department of Energy
Ransdell	Tim	Sempra Utilities
Rao	Prady	Weichai America Corp.
Rasik	Christopher	The Lubrizol Corporation
Rasmussen	Janessa	The Chemours Company
Rath	John	New York Geothermal Energy Organization
Ravesteijn	Elizabeth	Air Products and Chemicals, Inc.
Ravi Ganesh	Priya	Battelle Memorial Institute

Last Name	First Name	Organization
Rawinski	Tomasz	North South Logistics & Transport Cluster
Ray	Keith	Lawrence Livermore National Laboratory
Razavi	Sepideh	The University of Oklahoma
Reddi	Krishna	Argonne National Laboratory
Regmi	Yagya	Manchester Metropolitan University
Reinhardt	Tim	U.S. Department of Energy
Remkiewicz	Timothy	Plug Power Inc.
Ren	Z. Jason	Princeton University
Ren	Ning	Valvoline Inc.
Ren	Shouxian	Weichai America Corp.
Renard	Nic	HiiROC Limited
Resasco	Daniel	The University of Oklahoma
Reshetenko	Tatyana	Hawaii Natural Energy Institute
Respondek	Zoe	Energetics Incorporated
Retnanandan	Raj	Energy Management & Regulatory Consulting, Ltd.
Revers	Ed	De Nora S.p.A.
Rey	Brendan	Stevens Institute of Technology
Reyes	Ilse	NASA, White Sands Test Facility
Reyna	Alfonso	Southern California Gas Company
Reznicek	Evan	National Renewable Energy Laboratory
Rice	Brian	University of Dayton Research Institute
Rice	Cynthia	Tennessee Technological University
Richards	Andrew	U.S. Department of Energy, Office of Nuclear Energy
Richards	Mark	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Rinebold	Joel	Connecticut Center for Advanced Technology, Inc.
Ringle	Erik	National Renewable Energy Laboratory
Rios	Edward	U.S. Department of Energy
Riscica	Phillip	Plug Power Inc.
Rivkin	Carl	Nikola Motor Company
Robb	Gary	Hyzon Motors Inc.

Last Name	First Name	Organization
Roberts	George	TechScale Solutions, LLC
Roberts	Holly	Akoya
Roberts	Joy	Unilia (Canada) Fuel Cells, Inc.
Rockstroh	Toby	Argonne National Laboratory
Rockward	Tommy	Los Alamos National Laboratory
Rodezno	Eva	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
Rodriguez	George	ARGENI LLC
Roemer	Andy	Nel Hydrogen
Rogers	Bernice	Retired
Rohatgi	Aashish	Pacific Northwest National Laboratory
Rojas	Jimmy	Stanford University
Rojas-Carbonell	Santiago	Versogen
Ronevich	Joseph	Sandia National Laboratories
Ropchock	Keith	National Renewable Energy Laboratory
Ross	Keeton	Evok Innovations
Rossi	Ruggero	The Pennsylvania State University
Roth	Kevan	
Rotz	Derek	Daimler Trucks North America
Rousseau	Aymeric	Argonne National Laboratory
Roy Chowdhury	Bikram	Air Liquide
Roy	Anirban	University of Tennessee
Roy	Molly	U.S. Department of Energy
Roychoudhury	Subir	Precision Combustion, Inc.
Rubbers	Etienne	Renew-e
Rufael	Tecle	Chevron Corporation
Ruiz	Antonio	Nikola Motor Company
Ruple	Matt	National Renewable Energy Laboratory
Rupnowski	Peter	National Renewable Energy Laboratory
Ruschke	Charlie	University of Illinois at Urbana–Champaign

Last Name	First Name	Organization
Russell-Parks	Glory	Colorado School of Mines/National Renewable Energy Laboratory/Hydrogen Materials Advanced Research Consortium (HyMARC)
Rustagi	Narendra	Howard University
Rustagi	Neha	U.S. Department of Energy
Rustagi	Suman	The Catholic University of America
Ruth	Mark	National Renewable Energy Laboratory
Rutkevicius	Marius	ABB Ltd.
Ryan	Amy	Toyota Motor North America
Ryan	Liam	Toyota Motor North America
Saadi	Fadl	C-Zero
Saafi	Mohamed Ali	Aramco Americas
Sackin	Gary	BD
Saddler	Kylie	National Renewable Energy Laboratory
Safran	Stephanie	
Saha	Prantik	National Renewable Energy Laboratory
Sahin	Olcay	Argonne National Laboratory
Saito	Tomonori	Oak Ridge National Laboratory
Saito	Tomotaka	Toyota Boshoku Corporation
Saito	Yasuhiro	Toyota Boshoku Corporation
Saitoh	Kenichiro	ENEOS Research Institute, Ltd.
Salahshoor	Shadi	Gas Technology Institute
Salas	Francisca	New Energy Events
Salehi	Saeed	The University of Oklahoma
Salzman	Joel	Apex Clean Energy
San Marchi	Chris	Sandia National Laboratories
Sanborn	Scott	Sandia National Laboratories
Sanders	Michael	Colorado School of Mines
Sapochak	Linda	National Science Foundation
Sapon	William	Essential Utilities
Sari	Rafael	Universitat Politècnica de València
Sasaki	Kotaro	Brookhaven National Laboratory

Last Name	First Name	Organization
Sastri	Bhima	U.S. Department of Energy
Sata	Andrew	Toyota Motor North America, Research and Development
Satomi	Tomohide	Fuel Cell Commercialization Conference of Japan
Satyapal	Sunita	U.S. Department of Energy
Saur	Genevieve	National Renewable Energy Laboratory
Sauter	Ulrich	Robert Bosch GmbH
Sayler	Todd	The Chemours Company
Scarcella	Sue	National Grid
Scarpino	Mike	U.S. Department of Transportation, Volpe Center
Scheffe	Jonathan	University of Florida
Schimming	Mark	EWI
Schlegel	Andrew	International Trade Administration, Office of Energy and Environmental Industries
Schlueter	Debbie	IRD Fuel Cells, LLC
Schlueter	John	National Science Foundation
Schmitt	Tobias	Robert Bosch GmbH
Schmitz	Michael	ReCarbon, Inc.
Schneider	Annie	The University of Utah
Schnepp	Kevin	California Department of Food and Agriculture, Division of Measurement Standards
Schoenung	Susan	Longitude 122 West, Inc.
Schrecengost	Robert	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
Schroeder	Benjamin	Sandia National Laboratories
Schubak	Gary	Ekona Power Inc.
Schuler	Tobias	National Renewable Energy Laboratory
Schultz	Paul	Los Angeles Department of Water and Power
Schulz	Robert	Hydro-Québec
Schwartz	David	Palo Alto Research Center (PARC), a Xerox Company
Schwenzer	Birgit	National Science Foundation
Sculley	Daniel	American Electric Power

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Sculley	Julian	Hawaiian Electric
Seenumani	Gayathri	General Electric Company
Seetharaman	Sridhar	Arizona State University
Seki	Yasuhiro	N.E. CHEMCAT Corporation
Seliavski	Yaroslav	Mühlbauer Group
Sellers	Zachary	Idaho National Laboratory
Selman	Nancy	Skyre, Inc.
Senior	Constance	National Institute of Clean and Low-Carbon Energy (NICE) America Research Inc.
Serov	Alexey	Pajarito Powder, LLC
Serrato	Sebastian	California Energy Commission
Serre-Combe	Pierre	Commissariat à l'énergie atomique et aux énergies alternatives (CEA, French Atomic Energy Commission)
Severa	Godwin	Hawaii Natural Energy Institute
Severs	Linda	Oak Ridge Associated Universities
Shah	Arth	Perma Pure LLC
Shah	Shailesh	U.S. Army Combat Capabilities Development Command, Command, Control, Communications, Computers, Cyber, Intelligence, Surveillance and Reconnaissance (C5ISR) Center
Shao	Yuyan	Pacific Northwest National Laboratory
Sharma	Jaswinder	Oak Ridge National Laboratory
Sharma	Preetam	University of Tennessee
Sharman	Jonathan	Johnson Matthey
Shaw	Robert	Arete Venture Management
Sheehan	Mike	Financial
Sheel	Tushar	Wilo
Sheibley	Nate	National Research Council Canada
Shelton	Walter	U.S. Department of Energy/National Energy Technology Laboratory
Sherk	Peter	Wabash Valley Resources
Sherman	James	Vertical Flight Society
Shi	Ken	National Research Council Canada

Last Name	First Name	Organization
Shi	Wenjuan	University of Delaware
Shibata	Masao	Toyota Central R&D Labs., Inc.
Shieh	Tom	Toyota Motor North America, Research and Development
Shifa	Sayeeda	AVL Fuel Cell Canada
Shimizu	Takahiro	Japan Automobile Research Institute
Shimotori	Soichiro	Toshiba Energy Systems & Solutions Corporation
Shimpalee	Sirivatch	University of South Carolina
Shin	Sung-Hee	Hyundai Motor Group
Shindler	Brian	
Shinohara	Akihiro	Toyota Central R&D Labs., Inc.
Shinozaki	Kazuma	Toyota Central R&D Labs., Inc.
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Shreffler	Eric	Michigan Economic Development Corporation
Shrestha	Rakish	Sandia National Laboratories
Shrivastava	Udit	Cummins Inc.
Shulda	Sarah	National Renewable Energy Laboratory
Shurland	Melissa	U.S. Department of Transportation, Federal Railroad Administration
Shutlz	Avi	U.S. Department of Energy
Siegel	Jason	University of Michigan
Silver	Jonathan	Plug Power Inc.
Sim	Jeff	Ionomr Innovations Inc.
Simmons	Kevin	Pacific Northwest National Laboratory
Simon	Nevin	Plug Power Inc.
Sinanan	Anson	Cummins Inc.
Singh	Prabhakar	University of Connecticut
Singh	Raj	Oklahoma State University
Singhal	Subhash	Independent Consultant
Siriwardane	Ranjani	U.S. Department of Energy/National Energy Technology Laboratory
Siroky	Mark	California Air Resources Board

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Skriba	Louis	Gigajoule Jug Consultants
Slack	Helen	PCC
Slack	John	Nikola Motor Company
Small	Terrence	General Electric Company
Smith	Owen	National Renewable Energy Laboratory
Smith	Stacy	Oak Ridge Associated Universities
Snurr	Randall	Northwestern University
Snyder	Joshua	Drexel University
Snyder	Seth	Idaho National Laboratory
Soderholm	Lynda	Argonne National Laboratory
Sofronis	Petros	University of Illinois at Urbana–Champaign
Sokolowski	Joshua	University at Buffalo
Soloveichik	Grigorii	U.S. Department of Energy, Advanced Research Projects Agency–Energy (ARPA-E)
Soltis	Patrick	University of California, Berkeley
Somerday	Brian	Somerday Consulting, LLC
Song	Xueyan	West Virginia University
Song	Zhaoning	The University of Toledo
Space	Brian	North Carolina State University
Spatz	John	Private investor
Spaulding	Alex	Commonwealth Scientific and Industrial Research Organization (CSIRO) US
Speakes-Backman	Kelly	U.S. Department of Energy
Specchia	Stefania	Politecnico di Torino
Spence	Kieran	De Nora S.p.A.
Spendelow	Jacob	Los Alamos National Laboratory
Spitsen	Paul	U.S. Department of Energy
Sprik	Sam	National Renewable Energy Laboratory
Sridhar Gupta	Prasanth Gupta	GNS Science (New Zealand)
Stafshede	Patric	Celcibus AB
Stanford	Joseph	U.S. Department of Transportation, Volpe Center

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Star	Andrew	Argonne National Laboratory
Stavila	Vitalie	Sandia National Laboratories
Stechel	Ellen	Arizona State University
Steele	Lindsay	Pacific Northwest National Laboratory
Stege	Alex	CF Industries Holdings, Inc.
Steier	Katharina	Manchester Metropolitan University
Steinbach	Andrew	3M Company
Steinlechner	Johann	Heppolt Hydrogen
Steinwasser	Gerald	Mühlbauer Group
Stekli	Joseph	Electric Power Research Institute
Stern	Lesley	California Air Resources Board
Stetson	Ned	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Stevens	Jeff	U.S. Environmental Protection Agency
Stevens	Robert	U.S. Department of Energy/National Energy Technology Laboratory
Stevenson	Jeff	Pacific Northwest National Laboratory
Stewart	Sarah	Robert Bosch LLC
Stinson	Monique	Argonne National Laboratory
Stinson	William	Columbia University
Stöcker	Carsten	CATALER Europe Czech s.r.o.
Stoeckli	Albert	Niala Systems
Storck	Sebastian	BASF SE
Stork	Kevin	U.S. Department of Energy, Vehicle Technologies Office
Stottler	Gary	Stottler Development LLC
St-Pierre	Jean	Hawaii Natural Energy Institute
Straley	William	Fujiseiki USA Inc.
Strange	Nicholas	SLAC National Accelerator Laboratory/National Renewable Energy Laboratory
Strasser	Derek	Giner, Inc.
Strasser	Molly	Xcel Energy

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Stringer	Steve	Los Alamos National Laboratory
Stubbins	James	University of Illinois
Stuckey	Philip	FC Renew LLC
Sudik	Andrea	Loop Energy
Sugarman	Jim	High-Impact Events
Sui	Lang	U.S. Environmental Protection Agency
Sulic	Martin	Oak Ridge Institute for Science and Education (ORISE)
Sun	Fuxia	3M Company
Sun	Pingping	Argonne National Laboratory
Sun	Qiang	Northeastern University
Sun	Shuhui	Institut National de la Recherche Scientifique (INRS)
Sun	Zhe	University of Houston
Sun	Zhen	Weichai America Corp.
Sundarraman	Meenakshi	IndianOil R&D Centre
Sunderrajan	Suresh	Argonne National Laboratory
Sutherland	Ian	Jacobs Engineering
Sutton	Katrina	CALSTART
Sverdrup	George	GMS Consulting
Swain	Brett Franklin	Civilian Aeronautic Space Agency
Swamy	Priya	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Swartz	Scott	Nexceris, LLC
Swider-Lyons	Karen	Plug Power, Inc.
Szczepanski	Ed	DENSO International America, Inc.
Szymanski	Stephen	Nel Hydrogen
Taddese	Binyam	DTE Energy
Taie	Zac	U.S. Department of Energy
Takaishi	Hideyuki	Takaishi Industry Co., Ltd.
Takashi	Konishi	Toray Industries, Inc.
Talati	Shuchi	U.S. Department of Energy, Office of Fossil Energy and Carbon Management

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Tang	Zhihong	Praxair Surface Technologies, Inc.
Tanman	Arman	U.S. Environmental Protection Agency
Tao	Greg	Chemtronergy, LLC
Tasan	Cem	Massachusetts Institute of Technology
Tavakoli Mehrabadi	Bahareh Alsadat	Nikola Motor Company
Taylor	Donald	Taylor Energy
Tchouvelev	Andrei	A. V. Tchouvelev & Associates Inc.
Tedeschi	Rick	Tedeschi Consulting Solutions
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Tellez	Raul M	Spectrum Tecnología de Empaque, SRL
Terada	Ichiro	AGC Inc.
Terlip	Danny	Zero Emission Industries
Tessier	Pascal	Hockessin Innovation
Thakare	Jivan	University of North Dakota, Energy & Environmental Research Center
Thiel	Mark	Covestro (retired)
Thieu	Anh Thao	Air Liquide
Thoma	Grant	3M Company
Thomas	Chris	3M Company
Thomas	Eleanor	Center for Transportation and the Environment (CTE)
Thomas	Julien	GenH2
Thomas	Owen	AVL Fuel Cell Canada
Thomas	Sandy	Clean Car Options
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Tong	Jianhua "Joshua"	Clemson University
Toqan	Majed	Creative Power Solutions
Toughiry	Mark	U.S. Department of Transportation
Toussi	Omid	Ionomr Innovations Inc.
Townsend	Justin	Oak Ridge Associated Universities
Tran	Ba	Pacific Northwest National Laboratory
Trewyn	Brian	Colorado School of Mines
Truitt	Jordan	Air Liquide
Tsai	Andy	T3 Scientific LLC
Tsang	Julie	CB Insights
Tsuchiya	Hiroshi	New Energy and Industrial Technology Development Organization, Japan
Tsuji	Yoichiro	FC-Cubic TRA
Tsunoda	Takahiro	Japan Atomic Power Company
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Turner	Tylyn	Sandia National Laboratories
Turner	Vance	ProVance Holdings Inc.
Turon	Genis	Toyota Motor North America
Tzitzis	Justin	ExoCell Power
Ulissi	Zachary	Carnegie Mellon University
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Unione	Alfred	Leidos
Upadhyaya	Raghvendra	U.S.–India Business Council
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vanHoudt	Johannes	U.S. Department of Transportation, Federal Aviation Administration
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Vásquez Franco	Mariana	cellcentric/Technical University of Darmstadt
Vasudevan	Anand	Spotimyze Energy
Veenstra	Mike	Ford Motor Company
Ventola	David	Dürr Megtec
Verma	Sumit	Shell Oil Company
Vetrano	John	U.S. Department of Energy, Office of Science
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Wagner	Hugo	Airbus S.A.S.
Wahlert	Kayt	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
Wakabayashi	Max	Nissan Chemical Corporation
Walchuk	George	Exxon Mobil Corporation
Wan	Liwen	Lawrence Livermore National Laboratory
Wang	Bin	The University of Oklahoma
Wang	Boning	University of Colorado Boulder
Wang	Chenyu	Los Alamos National Laboratory
Wang	Conghua "CH"	TreadStone Technologies, Inc.
Wang	Fangfang	University of Illinois at Urbana–Champaign
Wang	Frank	Green Technology Ltd Co.
Wang	Guofeng	University of Pittsburgh
Wang	Jianhui	Southern Methodist University
Wang	Junhua	W7energy LLC
Wang	Keping	Ballard Power Systems
Wang	Lan	Versogen
Wang	Liang	Toyota Research Institute, North America
Wang	Lucun	Idaho National Laboratory
Wang	Min	Idaho National Laboratory
Wang	Paul	Caterpillar Inc.
Wang	Qianpu	National Research Council Canada
Wang	Rongyue	Argonne National Laboratory
Wang	Teng	University of Delaware
Wang	Timothy	NuMat Technologies
Wang	Weitian	University of Tennessee Space Institute
Wang	Xiaohua	Argonne National Laboratory
Wang	Xiaojing	Los Alamos National Laboratory

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Wang	Yanli	Oak Ridge National Laboratory
Wang	Zhang	Plug Power Inc.
Wanninayake	Namal	De Nora S.p.A.
Wardius	Don	Covestro
Warren	Kent	University of Colorado Boulder
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Wasiloff	Eric	U.S. Army Ground Vehicle System Center
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Watson	Tom	Tenneco
Weaver	Robert	
Weber	Adam	Lawrence Berkeley National Laboratory
Weeda	Marcel	Netherlands Organisation for Applied Scientific Research
Weeks	Brian	Gas Technology Institute
Wei	Haibing	Hefei University of Technology
Wei	Max	Lawrence Berkeley National Laboratory
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Weinheimer	Grady	Plug Power Inc.
Weisenberger	Matthew	University of Kentucky
Wendt	Daniel	Idaho National Laboratory
Weng	Dacong	Honeywell Aerospace
Westhoff	Casey	Umicore
Westlake	Brittany	Electric Power Research Institute
Westover	Tyler	Idaho National Laboratory
Wheeler	Douglas	DJW Technology, LLC
White	Douglas	ElectriCar Consulting LLC.
White	Zakar	Carnegie Mellon University
Widmer	John	Caterpillar Inc.
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Wilcox	Jennifer	U.S. Department of Energy
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Willey	Jason	Plug Power Inc.
Williams	Mark	National Energy Technology Laboratory
Williams	Robin	Hawaii Solar & Wind, LLC
Williams	Travis	University of Southern California
Williamson	John	Komatsu Ltd.
Williford	Melissa	Oak Ridge Associated Universities
Wipke	Keith	National Renewable Energy Laboratory
Wishart	Anna	
Witman	Matthew	Sandia National Laboratories
Wolf	Stanley	Federal Energy Regulatory Commission
Wolffe	Vaughn	
Wong	Michael	Rice University
Wong	Ronny	Sarawak Energy
Wood	Brandon	Lawrence Livermore National Laboratory
Woods	Stephen	NASA, White Sands Test Facility
Wright	Benjamin	The Chemours Company
Wrubel	Jacob	National Renewable Energy Laboratory
Wu	Gang	University at Buffalo
Wu	Siyuan	University of California, Davis
Wu	Wei	Idaho National Laboratory
Wu	XiaoYu	University of Waterloo
Wunder	Nicholas	National Renewable Energy Laboratory
Wyatt	Keenan	National Renewable Energy Laboratory
Wycisk	Ryszard	Vanderbilt University
Wyman	Christine	Bracewell LLP
Xia	Gordon	University of Louisiana at Lafayette

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Xie	Xiaohong	Pacific Northwest National Laboratory
Xie	Zhiqiang (Andrew)	University of Tennessee Space Institute
Xie	Zhong	National Research Council Canada
Xing	Yangchuan	University of Missouri
Xu	Hui	Giner, Inc.
Xu	Pan	Ballard Power Systems
Xue	Junpeng	Pukyong National University
Yamada	Teruyuki	Federation of Electric Power Companies of Japan
Yamaguchi	Makoto	FC-Cubic TRA
Yamanis	John Jean	ElectroChem Ventures LLC
Yan	Changfeng	Chinese Academy of Sciences, Guangzhou Institute of Energy Conversion
Yan	Gao	Los Alamos National Laboratory
Yan	Litao	Pacific Northwest National Laboratory
Yan	Yanfa	The University of Toledo
Yan	Yushan	Versogen
Yandrasits	Michael	3M Company
Yang	Amy	Unilia (Canada) Fuel Cells, Inc.
Yang	Bo	California Air Resources Board
Yang	Fan	Plug Power Inc.
Yang	Hong	University of Illinois at Urbana–Champaign
Yang	Lijun	Ballard Power Systems
Yang	Lisa	Toyota North America
Yang	Xiaohua	Institut National de la Recherche Scientifique (INRS)
Yang	Yong	Austin Power Engineering LLC
Yao	Fei	University at Buffalo
Yaremchuk	Kevin	GlobalBridge Solutions, LLC
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Yilmaz	Abdurrahman	University of Connecticut
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Yoon	Heayoung	The University of Utah
Yoon	Songhak	Fraunhofer IWKS
Yoshida	Toshihiko	
Youn	Edward	National Institute of Clean and Low-Carbon Energy (NICE) America Research Inc.
Young	Daniel	Vitesco Technologies
Young	James	National Renewable Energy Laboratory
Yu	Choongho	Texas A&M University
Yu	Haoran	Oak Ridge National Laboratory
Yu	Shule	University of Tennessee Space Institute
Yu	Siying	University of Illinois at Urbana–Champaign
Yu	Yehong	Zhejiang University
Yuan	Xiao-Zi	National Research Council Canada
Yuasa	Minoru	New Energy and Industrial Technology Development Organization, Japan
Yuh	Chao-Yi	FuelCell Energy, Inc.
Yurchick	Christopher	Ramaco Carbon
Yuska	Daniel	U.S. Department of Transportation, Maritime Administration
Zaccarine	Sarah	Colorado School of Mines
Zachman	Michael	Oak Ridge National Laboratory
Zambotti	Jason	W. L. Gore and Associates, Inc.
Zang	Guiyan	Argonne National Laboratory
Zawodzinski	Tom	University of Tennessee
Zelenay	Piotr	Los Alamos National Laboratory
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Zerby	Jacob	The Chemours Company
Zhai	Jimmy	CSEI
Zhai	Shang	Stanford University
Zhang	Ao	University of California, Los Angeles

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Zhang	Hao	Ballard Power Systems
Zhang	Hongtu	University of California, Los Angeles
Zhang	Jie	The University of Texas at Dallas
Zhang	Kun	Shell
Zhang	Ying	Tennessee Technological University
Zhao	Feng	Storagenergy Technologies, Inc.
Zhao	Nana	National Research Council Canada
Zhao	Xueru	Brookhaven National Laboratory
Zheng	Jackie	Oak Ridge National Laboratory
Zheng	Kathleen	Strategic Analysis, Inc.
Zheng	Yanjie	Vanderbilt University
Zhou	Li	Toyota Research Institute, North America
Zhou	Michelle	Hyundai Center for Robotic-Augmented Design in Living Experiences (CRADLE)
Zhou	Xiao-Dong	University of Louisiana at Lafayette
Zhou	Yucun	Georgia Institute of Technology
Zhu	Gaohua	Toyota
Zhu	Jiahong	Tennessee Technological University
Zhu	Tianli	Raytheon Technologies
Zierau	Matthew	DTE Energy
Ziminsky	Willy	General Electric Company
Zimmer	Stephen	United States Council for Automotive Research
Zimmermann	Curtis	BASF
Zokoe	James	Cummins Inc.
Zulevi	Barr	Pajarito Powder, LLC
Zutter	Brian	Sandia National Laboratories

Appendix C: Project Evaluation Forms

General Project Evaluation Form

This evaluation form is for use with the following Hydrogen Program review panels/projects: Hydrogen Technologies (Hydrogen Production,[1] Delivery/Infrastructure, and Storage); Fuel Cell Technologies; Technology Acceleration; Safety, Codes and Standards; and Systems Analysis.[2]

Evaluation Criteria: U.S. Department of Energy (DOE)
2021 Hydrogen Program Annual Merit Review

Please provide specific, concise comments to support your evaluation. It is important that you write in full sentences and clearly convey your meaning to prevent incorrect interpretation.

1. Approach to Performing the Work

The degree to which project objectives and critical barriers have been clearly identified and are being addressed, and the extent to which the project is well-designed, feasible, and integrated with other relevant efforts. **(Weight = 20%)**

4.0 – Outstanding. Sharply focused on overcoming critical barriers; difficult to improve significantly.

3.5 – Excellent. Effective; contributes to overcoming most barriers.

3.0 – Good. Generally effective but could be improved; contributes to overcoming some barriers.

2.5 – Satisfactory. Has some weaknesses; contributes to overcoming some barriers.

2.0 – Fair. Has significant weaknesses; may have some impact on overcoming barriers.

1.5 – Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.

1.0 – Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Approach to Performing the Work:

[1] HydroGEN seedling projects use Form B.

[2] Newly awarded projects will be evaluated using the same criteria as this General Project form, but with a lower scoring weight on Accomplishments (5%) and a higher weight on Approach (40%) and Proposed Future Work (25%).

2. Accomplishments and Progress Toward Overall Project and DOE Goals

The degree to which progress toward project objectives has been made and measured against well-defined performance indicators, and the degree to which the project has demonstrated progress toward addressing critical barriers to achieving DOE goals. **(Weight = 35%)**

4.0 – Outstanding. Outstanding progress toward project objectives is demonstrated through clear and measurable performance indicators; results have directly led to overcoming one or more critical barriers.

3.5 – Excellent. Excellent progress toward project objectives is demonstrated through clear and measurable performance indicators; results suggest that one or more critical barriers will be overcome.

3.0 – Good. Significant progress has been made, but there are weaknesses that need to be addressed to improve the rate of progress or improve the clarity of the project's objectives and performance indicators; contributes to overcoming some barriers.

2.5 – Satisfactory. Moderate progress has been made, but there are weaknesses that need to be addressed to improve the rate of progress or improve the clarity of the project's objectives and performance indicators; contributes to overcoming some barriers.

2.0 – Fair. Modest progress—rate of progress has been slow; may have some impact on overcoming barriers.

1.5 – Poor. Minimal progress toward project objectives and poorly defined performance indicators; unlikely to contribute to overcoming the barriers.

1.0 – Unsatisfactory. Little to no demonstrated progress toward project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Accomplishments and Progress Toward Overall Project and DOE Goals:

3. Collaboration and Coordination with Other Institutions

The degree to which the project effectively engages and coordinates project partners and interacts with other entities and projects to accelerate project progress and improve the likelihood of the project's success and impact.
(Weight = 10%)

4.0 – Outstanding. Close, appropriate collaboration with other institutions; partners are full participants and well-coordinated.

3.5 – Excellent. Good collaboration; partners participate and are well-coordinated.

3.0 – Good. Collaboration exists; partners are fairly well-coordinated.

2.5 – Satisfactory. Some collaboration exists; coordination between partners could be significantly improved.

2.0 – Fair. A little collaboration exists; coordination between partners could be significantly improved.
1.5 – Poor. Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners.

1.0 – Unsatisfactory. No apparent coordination with partners.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Collaboration and Coordination with Other Institutions:

4. Relevance/Potential Impact

The degree to which the project supports and advances progress toward the Hydrogen Program goals and objectives, as delineated in the Hydrogen and Fuel Cell Technologies Office Multi-Year RD&D plan and/or the Program and subprogram overview presentations given during the plenary session of the AMR. **(Weight = 20%)**

4.0 – Outstanding. Project is critical to the Hydrogen Program and has potential to significantly advance progress toward DOE RD&D goals and objectives.

3.5 – Excellent. The project aligns well with the Hydrogen Program and DOE RD&D objectives and has the potential to advance progress toward DOE RD&D goals and objectives.

3.0 – Good. Most project aspects align with the Hydrogen Program and DOE RD&D objectives.
2.5 – Satisfactory. Project aspects align with some of the Hydrogen Program and DOE RD&D objectives.

2.0 – Fair. Project partially supports the Hydrogen Program and DOE RD&D objectives.

1.5 – Poor. Project has little potential impact on advancing progress toward the Hydrogen Program and DOE RD&D goals and objectives.

1.0 – Unsatisfactory. Project has little to no potential impact on advancing progress toward the Hydrogen Program and DOE RD&D goals and objectives.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Relevance/Potential Impact:

5. Proposed Future Work

The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points, considering barriers to its goals and, when sensible, mitigating risk by providing alternate pathways. **Note: if a project has ended, please leave blank. (Weight = 15%)**

4.0 – Outstanding. Plans clearly build on past progress and are sharply focused on critical barriers to project goals; difficult to improve significantly.

3.5 – Excellent. Effective; contributes to overcoming most barriers.

3.0 – Good. Plans generally build on past progress and should contribute to overcoming some barriers.

2.5 – Satisfactory. Has some weaknesses; contributes to overcoming some barriers.

2.0 – Fair. Plans may lead to improvements, but need better focus on addressing project weaknesses; may have some impact on overcoming barriers.

1.5 – Poor. Minimally responsive to project objectives; unlikely to resolve project weaknesses and contribute to overcoming barriers.

1.0 – Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming barriers.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Proposed Future Work:

Project Strengths:

Project Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

HydroGEN Seedling Project Evaluation Form

This evaluation form is for use with HydroGEN seedling projects.

Evaluation Criteria: U.S. Department of Energy (DOE)
2021 Hydrogen Program Annual Merit Review

Please provide specific, concise comments to support your evaluation. It is important that you write in full sentences and clearly convey your meaning to prevent incorrect interpretation.

1. Approach to Performing the Work

The degree to which barriers have been clearly identified, and are being addressed through project innovation; and the extent to which the project is well-designed, feasible, and integrated with the HydroGEN Consortium network. A strong emphasis should be placed on the appropriateness of the scope of work toward validation of the project's technology innovation. **(Weight = 20%)**

4.0 – Outstanding. Sharply focused on critical barriers and validating technology innovation; difficult to improve significantly.

3.5 – Excellent. Effective; contributes to overcoming most barriers and validating technology innovation.

3.0 – Good. Generally effective but could be improved; contributes to overcoming some barriers and validating technology innovation.

2.5 – Satisfactory. Has some weaknesses; contributes to overcoming some barriers and validating technology innovation.

2.0 – Fair. Has significant weaknesses; may have some impact on overcoming barriers and/or validating technology innovation.

1.5 – Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers or validating technology innovation.

1.0 – Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers or validating technology innovation.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Approach to Performing the Work:

2. Accomplishments and Progress Toward Overall Project and DOE Goals

The degree to which progress has been made and measured against performance indicators, and the degree to which the project has demonstrated progress toward DOE goals as well as the HydroGEN Consortium mission. A particular emphasis should be placed on the strength of the data presented by the accomplishments (including data from the HydroGEN nodes leveraged by the project) in terms of supporting accomplishments. An additional emphasis should be placed on the strength of the project's current budget period's Go/No-Go Criteria if applicable and on project progress toward meeting these criteria. **(Weight = 30%)**

4.0 – Outstanding. Sharply focused on critical barriers with significant and convincing data to support the accomplishments toward ambitious Go/No-Go Criteria; difficult to improve significantly.

3.5 – Excellent. Effective; contributes to overcoming most barriers and provides data that considerably supports the accomplishments toward impactful Go/No-Go Criteria.

3.0 – Good. Generally effective but could be improved; contributes to overcoming some barriers and provides adequate data to support accomplishments toward meaningful Go/No-Go Criteria.

2.5 – Satisfactory. Has some weaknesses; contributes to overcoming some barriers and provides some data to support accomplishments toward adequate Go/No-Go Criteria.

2.0 – Fair. Has significant weaknesses; may have some impact on overcoming barriers and has limited data and accomplishments to support the Go/No-Go Criteria; Go/No-Go Criteria may be weak.

1.5 – Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers and meet the Go/No-Go Criteria; Go/No-Go criteria are not adequate or missing.

1.0 – Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers and meet the Go/No-Go Criteria; Go/No-Go criteria are not adequate or missing.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Accomplishments and Progress Toward Overall Project and DOE Goals:

3. Collaboration Effectiveness with HydroGEN and, if Applicable, Other Research Entities

The degree to which the project has engaged with the HydroGEN EMN and has effectively used nodes to accelerate materials development and improve the likelihood of the project's success and impact. This also includes the effectiveness of project engagement with the broader materials research community, including work with HydroGEN's cross-cutting benchmarking/protocols (2b) project team, the HydroGEN Data Team, pathway-specific Working Groups, and others. An additional factor is the broader value and impact of the project's data sharing through the HydroGEN Data Hub. **(Weight = 25%)**

4.0 – Outstanding. Close, appropriate collaboration with other institutions, specifically the HydroGEN Consortium with appropriate use of nodes, contributions to the benchmarking/protocols (2b) project and the HydroGEN Data Hub; partners are full participants and well-coordinated.

3.5 – Excellent. Good collaboration, specifically the HydroGEN Consortium with appropriate use of nodes, contributions to the benchmarking/protocols (2b) project and the HydroGEN Data Hub; partners participate and are well-coordinated.

3.0 – Good. Collaboration exists with the HydroGEN Consortium and includes node utilization and engagement with the benchmarking/protocols (2b) project and the HydroGEN Data Hub; partners are fairly well-coordinated.

2.5 – Satisfactory. Some collaboration exists; coordination between partners could be significantly improved, specifically with respect to the HydroGEN Consortium node utilization activities, and engagement with the benchmarking/protocols (2b) project and the HydroGEN Data Hub.

2.0 – Fair. A little collaboration exists; coordination between partners could be significantly improved, specifically with respect to the HydroGEN Consortium node utilization activities, and engagement with the benchmarking/protocols (2b) project and the HydroGEN Data Hub.

1.5 – Poor. Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners and HydroGEN Consortium.

1.0 – Unsatisfactory. No apparent coordination with partners and HydroGEN Consortium.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Effectiveness with HydroGEN and, if Applicable, Other Research Entities:

4. Relevance/Potential Impact

The degree to which the project supports and advances progress toward the DOE Hydrogen Program goals and objectives, and also supports the HydroGEN Consortium mission. A strong emphasis should be placed on the project's potential to advance the discovery and development of novel, advanced water splitting materials systems which will enable meeting the DOE ultimate hydrogen production goal of $2/kg H_2. An additional factor to consider is how well the project fits into, leverages, and potentially enhances the framework and resources of the HydroGEN Consortium. **(Weight = 15%)**

4.0 – Outstanding. Project is critical to the Hydrogen Program and has potential to significantly advance progress toward DOE RD&D goals and objectives and is significantly leveraging and contributing to the resources and framework of the HydroGEN consortium.

3.5 – Excellent. The project aligns well with the Hydrogen Program and DOE RD&D objectives and has the potential to advance progress toward DOE RD&D goals and objectives and is aptly leveraging and contributing to the resources and framework of the HydroGEN consortium.

3.0 – Good. Most project aspects align with the Hydrogen Program and DOE RD&D objectives and the project is adequately leveraging and contributing to the resources and framework of the HydroGEN consortium.

2.5 – Satisfactory. Project aspects align with some of the Hydrogen Program and DOE RD&D objectives and the project is leveraging and contributing to the resources and framework of the HydroGEN consortium to some extent.

2.0 – Fair. Project partially supports the Hydrogen Program and DOE RD&D objectives and the project is not adequately leveraging and contributing to the resources and framework of the HydroGEN consortium.

1.5 – Poor. Project has little potential impact on advancing progress toward the Hydrogen Program and DOE RD&D goals and objectives and the project has minimal interaction with HydroGEN to leverage and contribute to the resources and framework of the HydroGEN consortium.

1.0 – Unsatisfactory. Project has little to no potential impact on advancing progress toward the Hydrogen Program and DOE RD&D goals and objectives and the project is not leveraging and contributing to the resources and framework of the HydroGEN consortium.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Relevance/Potential Impact:

5. Proposed Future Work

The degree to which the project has effectively planned its potential future work in a logical manner and leverages progress made in previous budget periods toward meeting end-of-project goals and advancing the materials research mission of the HydroGEN Consortium. **(Weight = 10%)**

4.0 - Outstanding. Sharply focused on critical barriers, meeting end-of-project goals and advancing the materials research mission of the HydroGEN Consortium; difficult to improve significantly.

3.5 - Excellent. Effective; contributes to overcoming most barriers, meeting most end-of-project goals and advancing the materials research mission of the HydroGEN Consortium.

3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers, meeting some end-of-project goals and has potential to advance the materials research mission of the HydroGEN Consortium.

2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers, meeting some end-of-project goals and may contribute to advancing the materials research mission of the HydroGEN Consortium.

2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers, makes minimal progress toward end-of project goals and insignificantly contributes to advancing the materials research mission of the HydroGEN Consortium.

1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers or meet end-of-project goals and will most likely not contribute to advancing the materials research mission of the HydroGEN Consortium.

1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers or meet end-of-project goals and is unlikely to contribute to advancing the materials research mission of the HydroGEN Consortium.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Proposed Future Work:

Project Strengths:

Project Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

New Project Evaluation Form

This evaluation form is for use with **newly awarded** R&D projects presented at the 2021 AMR.

Evaluation Criteria: U.S. Department of Energy (DOE)
2021 Hydrogen Program Annual Merit Review

Please provide specific, concise comments to support your evaluation. It is important that you write in full sentences and clearly convey your meaning to prevent incorrect interpretation.

1. Approach to Performing the Work

The degree to which project objectives and critical barriers have been clearly identified and are being addressed, and the extent to which the project is well-designed, feasible, and integrated with other relevant efforts. **(Weight = 40%)**

4.0 – Outstanding. Sharply focused on overcoming critical barriers; difficult to improve significantly.

3.5 – Excellent. Effective; contributes to overcoming most barriers.

3.0 – Good. Generally effective but could be improved; contributes to overcoming some barriers.

2.5 – Satisfactory. Has some weaknesses; contributes to overcoming some barriers.

2.0 – Fair. Has significant weaknesses; may have some impact on overcoming barriers.

1.5 – Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.

1.0 – Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Approach to Performing the Work:

2. Accomplishments and Progress Toward Overall Project and DOE Goals

The degree to which progress toward achieving project objectives has been made and measured against well-defined performance indicators, and the degree to which the project has demonstrated progress toward addressing critical barriers to achieving DOE goals. ***Note: Please evaluate accomplishments/progress made considering the amount of time the project has been underway; if a project has not been underway long enough to have made any progress, you may select "Not Applicable."*** **(Weight = 5%)**

4.0 – Outstanding. Outstanding progress towards project objectives is demonstrated through clear and measurable performance indicators; results have directly led to overcoming one or more critical barriers.

3.5 – Excellent. Excellent progress toward project objectives is demonstrated through clear and measurable performance indicators; results suggest that one or more critical barriers will be overcome.

3.0 – Good. Significant progress has been made, but there are weaknesses that need to be addressed to improve the rate of progress or improve the clarity of the project's objectives and performance indicators; contributes to overcoming some barriers.

2.5 – Satisfactory. Moderate progress has been made, but there are weaknesses that need to be addressed to improve the rate of progress or improve the clarity of the project's objectives and performance indicators; contributes to overcoming some barriers.

2.0 – Fair. Modest progress—rate of progress has been slow; may have some impact on overcoming barriers.

1.5 – Poor. Minimal progress towards project objectives and poorly defined performance indicators; unlikely to contribute to overcoming the barriers.

1.0 – Unsatisfactory. Little to no demonstrated progress toward project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Accomplishments and Progress Toward Overall Project and DOE Goals:

3. Collaboration and Coordination with Other Institutions

The degree to which the project effectively engages and coordinates project partners and interacts with other entities and projects to accelerate project progress and improve the likelihood of the project's success and impact.
(Weight = 10%)

4.0 – Outstanding. Close, appropriate collaboration with other institutions; partners are full participants and well-coordinated.

3.5 – Excellent. Good collaboration; partners participate and are well-coordinated.

3.0 – Good. Collaboration exists; partners are fairly well-coordinated.

2.5 – Satisfactory. Some collaboration exists; coordination between partners could be significantly improved.

2.0 – Fair. A little collaboration exists; coordination between partners could be significantly improved.
1.5 – Poor. Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners.

1.0 – Unsatisfactory. No apparent coordination with partners.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Collaboration and Coordination with Other Institutions:

4. Relevance/Potential Impact

The degree to which the project supports and advances progress toward the Hydrogen Program goals and objectives, as delineated in the Hydrogen and Fuel Cell Technologies Office Multi-Year RD&D plan and/or the Program and subprogram overview presentations given during the plenary session of the AMR. **(Weight = 20%)**

4.0 – Outstanding. Project is critical to the Hydrogen Program and has potential to significantly advance progress toward DOE RD&D goals and objectives.

3.5 – Excellent. The project aligns well with the Hydrogen Program and DOE RD&D objectives and has the potential to advance progress toward DOE RD&D goals and objectives.

3.0 – Good. Most project aspects align with the Hydrogen Program and DOE RD&D objectives.
2.5 – Satisfactory. Project aspects align with some of the Hydrogen Program and DOE RD&D objectives.

2.0 – Fair. Project partially supports the Hydrogen Program and DOE RD&D objectives.

1.5 – Poor. Project has little potential impact on advancing progress toward the Hydrogen Program and DOE RD&D goals and objectives.

1.0 – Unsatisfactory. Project has little to no potential impact on advancing progress toward the Hydrogen Program and DOE RD&D goals and objectives.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Relevance/Potential Impact:

5. Proposed Future Work

The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points, considering barriers to its goals and, when sensible, mitigating risk by providing alternate pathways. **(Weight = 25%)**

4.0 – Outstanding. Plans clearly build on past progress and are sharply focused on critical barriers to project goals; difficult to improve significantly.

3.5 – Excellent. Effective; contributes to overcoming most barriers.

3.0 – Good. Plans generally build on past progress and should contribute to overcoming some barriers.

2.5 – Satisfactory. Has some weaknesses; contributes to overcoming some barriers.

2.0 – Fair. Plans may lead to improvements, but need better focus on addressing project weaknesses; may have some impact on overcoming barriers.

1.5 – Poor. Minimally responsive to project objectives; unlikely to resolve project weaknesses and contribute to overcoming barriers.

1.0 – Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming barriers.

- ☐ 4.0 – Outstanding
- ☐ 3.5 – Excellent
- ☐ 3.0 – Good
- ☐ 2.5 – Satisfactory
- ☐ 2.0 – Fair
- ☐ 1.5 – Poor
- ☐ 1.0 – Unsatisfactory

Comments on Proposed Future Work:

Project Strengths:

Project Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

2021 AMR Hydrogen Program Review Questions

1. The Hydrogen Program has a mission and strategy that are clearly articulated and has appropriate goals and milestones as well as quantitative metrics that are SMART (Specific, Measurable, Actionable, Relevant, and Timely).

Please comment on the overall Hydrogen Program (including activities in the U.S. Department of Energy [DOE] Hydrogen and Fuel Cell Technologies Office, Office of Fossil Energy, Office of Science, Office of Nuclear Energy, and ARPA-E), as well as each subprogram/activity area, as appropriate. (Note: The Hydrogen Technologies subprogram comprises three categories: Hydrogen Production (with HydroGEN Seedling as a sub-category), Hydrogen Infrastructure, and Hydrogen Storage.)

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

	Strongly Disagree				Neutral				Strongly Agree		
	1	2	3	4	5	6	7	8	9	10	NA
Hydrogen Program Overall Rating	○	○	○	○	○	○	○	○	○	○	○
Hydrogen Technologies Subprogram Rating	○	○	○	○	○	○	○	○	○	○	○
Fuel Cell Technologies Subprogram Rating	○	○	○	○	○	○	○	○	○	○	○
Technology Acceleration Subprogram Rating	○	○	○	○	○	○	○	○	○	○	○
Safety, Codes and Standards Subprogram Rating	○	○	○	○	○	○	○	○	○	○	○
Systems Analysis Subprogram Rating	○	○	○	○	○	○	○	○	○	○	○

Comments:

2. The Hydrogen Program is well-focused and well-managed and is effectively fostering research, development, demonstration, and deployment (RDD&D) to enable innovation and advance the state of technology for hydrogen and fuel cell technologies to be competitive and achieve widespread commercialization and adoption by industry.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or NA if you have no opinion. Please add any additional comments.

Strongly Disagree				Neutral				Strongly Agree		
1	2	3	4	5	6	7	8	9	10	NA
○	○	○	○	○	○	○	○	○	○	○

Comments:

3. The Hydrogen Program's portfolio of projects is appropriately balanced across research areas to help achieve the Program's mission and goals.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or NA if you have no opinion. Please add any additional comments.

Strongly Disagree				Neutral				Strongly Agree		
1	2	3	4	5	6	7	8	9	10	NA
○	○	○	○	○	○	○	○	○	○	○

Comments:

4. The Hydrogen Program is collaborating with appropriate groups of stakeholders.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Strongly Disagree				Neutral				Strongly Agree		
1	2	3	4	5	6	7	8	9	10	NA
○	○	○	○	○	○	○	○	○	○	○

Comments:

5. The Hydrogen Program's RDD&D aligns well with industry and stakeholder needs and is appropriate given complementary private-sector, state, and other non-DOE investments.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Strongly Disagree				Neutral				Strongly Agree		
1	2	3	4	5	6	7	8	9	10	NA
○	○	○	○	○	○	○	○	○	○	○

Comments:

6. The Hydrogen Program is funding high-impact projects that have the potential to significantly advance the state of technology for the hydrogen and fuel cells industry.

	Strongly Disagree				Neutral				Strongly Agree		
	1	2	3	4	5	6	7	8	9	10	NA
Hydrogen Program Overall Rating	○	○	○	○	○	○	○	○	○	○	○
Hydrogen Technologies Subprogram Rating	○	○	○	○	○	○	○	○	○	○	○
Fuel Cell Technologies Subprogram Rating	○	○	○	○	○	○	○	○	○	○	○
Technology Acceleration Subprogram Rating	○	○	○	○	○	○	○	○	○	○	○
Safety, Codes and Standards Subprogram Rating	○	○	○	○	○	○	○	○	○	○	○
Systems Analysis Subprogram Rating	○	○	○	○	○	○	○	○	○	○	○

Comments:

7. Research Consortia Approach (including Energy Materials Network Consortia and others): Do you have any comments or recommendations on the Hydrogen Program's consortia approach for conducting laboratory-supported research (e.g., HydroGEN, H2NEW, HyMARC, ElectroCat, H-Mat, and M2FCT)? Please state what is working effectively and areas that may benefit from further improvement.

Comments:

8. H2@Scale: What are the strengths and weaknesses of the H2@Scale initiative? Do you have any recommendations for other H2@Scale analysis, research topics, or demonstrations to enable the scale-up and value proposition of hydrogen and fuel cell technologies (e.g., a region with low electricity prices, excess curtailment, and hydrogen supply opportunity along with a co-located demand for hydrogen, etc.)? Please provide any other recommendations on H2@Scale.

Comments:

9. International Collaboration: The Hydrogen Program collaborates through a number of international partnerships. For example, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is an international partnership to coordinate activities on hydrogen and fuel cells across 20 countries and the European Commission. Additional international collaboration initiatives with U.S. participation addressing hydrogen include the Clean Energy and Hydrogen Ministerials, Mission Innovation, the International Energy Agency, and others. Please comment on actions DOE can undertake in conjunction with these international activities that can effectively accelerate progress in hydrogen and fuel cell technologies.

Comments:

10. Prizes: Agencies have shown interest in implementing prizes and competitions as a mechanism to complement the conventional grant process. Examples include the H-Prize (H2Refuel) for a small-scale hydrogen fueling appliance that complements large retail stations. Please provide comments on the prize/competition approach and provide any suggestions for future prizes or competitions that would align with the goal of accelerating the widespread success of hydrogen and fuel cell technologies.

Comments:

11. Please comment on the overall strengths and weakness of the Hydrogen Program and its portfolio of projects. Please provide strengths and weaknesses for each subprogram as appropriate. On which technology areas should the Hydrogen Program put more or less focus for future activities?

Comments:

12. Do you have any other comments or suggestions to improve the overall effectiveness of the Hydrogen Program or any of its specific subprograms?

Comments:

Appendix D: List of Projects Presented but Not Reviewed

Project ID	Project Title	Principal Investigator Name	Organization
AMO-001	Flexible Natural Gas/Hydrogen Engine for CHP Applications	David Montgomery	Caterpillar, Inc.
ARPAE-001	ARPA-E Hydrogen and Fuel Cells Portfolio	Grigorii Soloveichik	U.S. Department of Energy
ARPAE-002	Development of PiperION Membranes and Ionomers	Yushan Yan	Versogen
ARPAE-003	Bipolar Membranes with an Electrospun 3D Junction	Peter Pintauro	Vanderbilt University
ARPAE-004	Cost-Effective, Intermediate-Temperature Fuel Cells for Carbon-Free Power Generation	Greg Tao	Chemtronergy
ARPAE-005	Adaptive Solid Oxide Fuel Cells for Ultra-High-Efficiency Systems	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.
ARPAE-006	Progress on Solid Oxide Fuel Cell/Turbine Hybrid Power System Design and Development	Scott Swartz	Nexceris, LLC
ARPAE-007	Channeling Engineering of Hydroxide Ion Exchange Polymers and Reinforced Membranes	Chulsung Bae	Rensselaer Polytechnic Institute
ARPAE-008	Modular Ultra-Stable Alkaline Exchange Ionomers to Enable High-Performance Fuel Cells and Electrolyzer Systems	Kristina Hugar	Ecoltectro, Inc.
ARPAE-009	Stable Diacid Coordinated Quaternary Ammonium Polymers for 80ºC–230ºC Fuel Cells	Yu Seung Kim	Los Alamos National Laboratory
ARPAE-010	Metal-Supported Solid Oxide Fuel Cells for Ethanol-Fueled Vehicles	Michael Tucker	Lawrence Berkeley National Laboratory
ARPAE-011	Low-Cost Intermediate-Temperature, Fuel-Flexible Protonic Ceramic Fuel Cell Stack	Ryan O'Hayre	Colorado School of Mines
BES-001	U.S. Department of Energy Fuels from Sunlight Hub: The Joint Center for Artificial Photosynthesis	Harry Atwater	California Institute of Technology
BES-002	Combining Non-Coupled Potentials and Charge Conservation to Access Electrochemical Barriers	Frank Abild-Pedersen	Stanford Linear Accelerator Center (SLAC) National Accelerator Laboratory, SUNCAT Center for Interface Science and Catalysis

Project ID	Project Title	Principal Investigator Name	Organization
BES-003	Fundamental Research Underpinning Hydrogen and Fuel Cells	Raul Miranda	U.S. Department of Energy
FC-145	Corrosion-Resistant, Non-Carbon Electrocatalyst Supports for Polymer Electrolyte Fuel Cells	Vijay Ramani	Washington University
FC-156	Durable High-Power Membrane Electrode Assemblies with Low Platinum Loading	Swami Kumaraguru	General Motors
FC-157	High-Performance Polymer Electrolyte Fuel Cell Electrode Structures	Rob Darling	Raytheon Technologies
FC-171	ElectroCat: Advanced Platinum-Group-Metal-Free Cathode Engineering for High Power Density and Durability	Shawn Litster	Carnegie Mellon University
FC-304	ElectroCat: Fuel Cell Membrane Electrode Assemblies with Platinum-Group-Metal-Free Nanofiber Cathodes	Peter Pintauro	Vanderbilt University
FC-315	High-Efficiency Reversible Alkaline Membrane Fuel Cells	Hui Xu	Giner, Inc.
FC-318	ElectroCat: Accessible Platinum-Group-Metal-Free Catalysts and Electrodes	Jacob Spendelow	Los Alamos National Laboratory
FC-321	Lab Call Fiscal Year 2019: Solid Phase Processing for Reduced Cost and Improved Efficiency of Bipolar Plates	Ken Ross	Pacific Northwest National Laboratory
FC-332	Reversible Fuel Cell Cost Analysis	Max Wei	Lawrence Berkeley National Laboratory
FE-001	Performance Validation of a Thermally Integrated 50 kW High-Temperature Electrolyzer System	Tyler Westover	Idaho National Laboratory
FE-002	Integrated Water–Gas Shift Pre-Combustion Carbon Capture Process	Gokhan Alptekin	TDA Research, Inc.
FE-003	Ammonia Gas Turbine Combustor	Majed Toqan	Creative Power Solutions (USA), Inc.
FE-004	A Highly Efficient and Affordable Hybrid System for Hydrogen and Electricity Production	Ying Liu	Phillips 66 Company
FE-005	Low-Cost, Large-Area Solid Oxide Electrolyzer Cell Stack for Hydrogen and Chemicals	Olga Marina	Pacific Northwest National Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
FE-006	Microwave Catalysis for Process-Intensified Modular Production of Carbon Nanomaterials from Natural Gas	John Hu	West Virginia University Research Corporation
FE-007	Impacts of Hydrogen Blending in Natural Gas Networks	Bri-Mathias Hodge	National Renewable Energy Laboratory
FE-008	Modular Processing of Flare Gas for Carbon Nanoproducts	Alan Weimer	University of Colorado Boulder
H2-041	California Hydrogen Research Consortium	Sam Sprik	National Renewable Energy Laboratory
H2-042	Hydrogen Contaminant Detector	Bill Buttner	National Renewable Energy Laboratory
H2-053	Hydrogen Safety Panel Evaluation of Hydrogen Facilities	Nick Barilo	Pacific Northwest National Laboratory
H2-056	Hydrogen Safety Outreach to Expedite Hydrogen Fueling and Energy Project Deployment and Promote Public Acceptance for Zero-Emission Vehicles and Reliable Distributed Power Generation	Nick Barilo	Pacific Northwest National Laboratory
H2-057	Electrolyzer–Bioreactor Integration	Kevin Harrison	National Renewable Energy Laboratory
H2-059	Electrolytic Renewable Fuel Production Optimal Operation Investigation	Omar Guerra	National Renewable Energy Laboratory
H2-060	Hydrogen Blending into Natural Gas Pipelines	Chris San Marchi	Sandia National Laboratories
IA-001	U.S. Department of Energy Research and Development Overview	Sunita Satyapal	U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office
IA-002	U.S. Department of Transportation Maritime Administration Update	Michael Carter	U.S. Department of Transportation Maritime Administration
IA-003	California – New Awards and Funding	Andrew Martinez	California Air Resources Board
IA-004	The Michigan Hydrogen Economy	Joel Rinebold	Connecticut Center for Advanced Technology, Inc.
IA-005	Northeast Fuel Cell and Hydrogen: Heavy-Duty Demand Clustering	Charles Myers	Massachusetts Hydrogen Coalition

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IA-006	Regional Hydrogen – Midwest	Pat Valente	Ohio Fuel Cell Coalition
IA-007	California Hydrogen and Fuel Cell Vehicle Activities: Market Launch to Market Acceleration	Bill Elrick	California Fuel Cell Partnership
IA-008	H2@Rescue: Design and Deployment of Polymer Electrolyte Membrane Fuel Cell–Battery-Powered Hybrid Emergency Relief Truck	Nick Josefik	U.S. Army
IA-009	Energy Management Overview and Hydrogen Research Initiatives	David Cook	U.S. Navy
IA-010	Power Generation Needs of the Dismounted Soldier	Shailesh Shah	U.S. Army
IA-011	U.S. Army Combat Capabilities Development Command: Hydrogen Fuel Cell Project Overview and Update	Kevin Centeck	U.S. Army
IA-012	Federal Railroad Association Hydrogen and Fuel Cell Research Program	Melissa Shurland	U.S. Department of Transportation Federal Railroad Administration
IA-014	NASA Fuel Cell and Hydrogen Activities	Ian Jakupca	NASA
IA-015	Hydrogen Corridor Update	Diane Turchetta	U.S. Department of Transportation Federal Highway Administration
IA-016	Hydrogen Fuel Cells for Unmanned Systems	Ben Gould	U.S. Naval Research Laboratory
IA-017	Hydrogen Integration in Utility, Transportation, and Expeditionary Systems	Benjamin Wilcox	U.S. Navy
IN-001	Hydrogen Materials Consortium (H-Mat) Overview	Chris San Marchi	Sandia National Laboratories
IN-010	Cryogenically Flexible, Low-Permeability Hydrogen Hose (Small Business Innovation Research)	Jennifer Lalli	NanoSonic, Inc.
IN-014	Non-Destructive Examination Techniques for Pressure Vessels (Small Business Innovation Research): Detection of Micron-Scale Flaws through Nonlinear Wave Mixing	Matthew Webster	Luna Innovations Inc.
IN-018	Heavy-Duty Compressor Development	Josh Adams	Nel Hydrogen

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NE-001	Coupling a Light Water Reactor Nuclear Plant to High-Temperature Electrolysis	Tyler Westover	Idaho National Laboratory
NE-002	Technical and Economic Assessment of Hydrogen Production at Nuclear Plants	Paul Talbot	Idaho National Laboratory
NE-003	Safety Analysis of Closely Coupled Nuclear Power Plants and Hydrogen Production Plants	Richard Boardman	Idaho National Laboratory
P-102	Hydrogen Production and Delivery Analysis	Brian James	Strategic Analysis, Inc.
P-148A	HydroGEN: Low-Temperature Electrolysis	Shaun Alia	National Renewable Energy Laboratory
P-148B	HydroGEN: High-Temperature Electrolysis	Gary Groenewold	Idaho National Laboratory
P-148C	HydroGEN: Photoelectrochemical Water Splitting	Francesa Toma	Lawrence Berkeley National Laboratory
P-148D	HydroGEN: Solar Thermochemical Hydrogen Water Splitting	Anthony McDaniel	Sandia National Laboratories
P-148E	HydroGEN: Cross-Cut Modeling	Tadashi Ogitsu	Lawrence Livermore National Laboratory
P-152	Proton-Conducting Solid Oxide Electrolysis Cells for Large-Scale Hydrogen Production at Intermediate Temperatures	Prabhakar Singh	University of Connecticut
P-153	Degradation Characterization and Modeling of a New Solid Oxide Electrolysis Cell Utilizing Accelerated Life Testing	Scott Barnett	Northwestern University
P-154	Thin-Film, Metal-Supported High-Performance and Durable Proton-SOEC (Solid Oxide Electrolyzer Cell)	Tianli Zhu	Raytheon Technologies Research Center
P-161	Protective Catalyst Systems on III-V and Silicon-Based Semiconductors for Efficient, Durable Photoelectrochemical Water-Splitting Devices	Thomas Jaramillo	Stanford University
P-162	Novel Chalcopyrites for Advanced Photoelectrochemical Water Splitting	Nicolas Gaillard	University of Hawaii
P-165	Accelerated Discovery of Solar Thermochemical Hydrogen Production Materials via High-Throughput Computational and Experimental Methods	Ryan O'Hayre	Colorado School of Mines

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P-166	Computationally Accelerated Discovery and Experimental Demonstration of High-Performance Materials for Advanced Solar Thermochemical Hydrogen Production	Charles Musgrave	University of Colorado Boulder
P-167	Transformative Materials for High-Efficiency Thermochemical Production of Solar Fuels	Chris Wolverton	Northwestern University
P-168	Mixed Ionic Electronic Conducting Quaternary Perovskites: Materials by Design for Solar Thermochemical Hydrogen	Ellen Stechel	Arizona State University
P-175	Intermediate-Temperature Proton-Conducting Solid Oxide Electrolysis Cells with Improved Performance and Durability	Xingbo Liu	West Virginia University
P-176	Development of Durable Materials for Cost-Effective Advanced Water Splitting Utilizing All-Ceramic Solid Oxide Electrolyzer Stack Technology	John Pietras	Saint-Gobain
P-177	Proton-Conducting Ceramic Electrolyzers for High-Temperature Water Splitting	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.
P-196a	Hydrogen from the Next-generation of Electrolyzers of Water (H2NEW) Low-Temperature Electrolysis (LTE): Durability and Accelerated Stress Test Development	Deborah Myers	Argonne National Laboratory
P-196b	H2NEW LTE: Benchmarking and Performance	Nem Danilovic	Lawrence Berkeley National Laboratory
P-196c	H2NEW LTE: Manufacturing, Scale-Up, and Integration	Nem Danilovic	Lawrence Berkeley National Laboratory
P-196d	H2NEW LTE: System and Technoeconomic Analysis – Hydrogen from Next-Generation Electrolyzers	Bryan Pivovar	National Renewable Energy Laboratory
P-196e	H2NEW High-Temperature Electrolysis (THE): Durability and Accelerated Stress Test Development	Olga Marina	Pacific Northwest National Laboratory
P-196f	H2NEW HTE: Cell Characterization	David Ginley	National Renewable Energy Laboratory
P-196g	H2NEW HTE: Multiscale Degradation Modeling	Brandon Wood	Lawrence Livermore National Laboratory
P-197	Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzer Oxygen Evolution Reaction Catalysts and Electrodes	Andrew Steinbach	3M Company

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P-198	Enabling Low-Cost Polymer Electrolyte Membrane Electrolysis at Scale Through Optimization of Transport Components and Electrode Interfaces	Chris Capuano	Nel Hydrogen
P-199	Integrated Membrane Anode Assembly and Scale-up	Monjid Hamdan	Plug Power Inc.
PRA-001	2020 Hydrogen and Fuel Cell Technologies Office (HFTO) Postdoctoral Recognition Award – First Place: Development of Polymer Electrolytes for Electrochemical Devices	Eun Joo (Sarah) Park	Los Alamos National Laboratory
PRA-002	2020 HFTO Postdoctoral Recognition Award – Runner Up: Platinum-Group-Metal-Free Catalysts for Proton Exchange Membrane Fuel Cells – Electrode Diagnostics for Performance and Durability	Luigi Osmieri	Los Alamos National Laboratory
PRA-003	2020 HFTO Postdoctoral Recognition Award – Runner Up: Self-Improving GaN/Si Photocathode in Photoelectrochemical Water Splitting	Guosong Zeng	Lawrence Berkeley National Laboratory
SA-181	Global Change Analysis Model Expansion – Hydrogen Pathways	Page Kyle	Pacific Northwest National Laboratory
SCS-001	Component Failure Research and Development	Jacob Thorson	National Renewable Energy Laboratory
SCS-027	Guidance for Indoor Hydrogen Sensor Placement	Andrei Tchouvelev	A.V. Tchouvelev & Associates
SCS-028	Hydrogen Education for a Decarbonized Global Economy (H2EDGE)	Thomas Reddoch	Electric Power Research Institute
ST-008	Hydrogen Storage System Modeling: Public Access, Maintenance, and Enhancements	Matt Thornton	National Renewable Energy Laboratory
ST-143	Hydrogen Materials Advanced Research Consortium (HyMARC) Seedling: Atomic Layer Deposition Synthesis of Novel Nanostructured Metal Borohydrides	Steven Christensen	National Renewable Energy Laboratory
ST-144	HyMARC Seedling: Optimized Hydrogen Adsorbents via Machine Learning and Crystal Engineering	Don Siegel	University of Michigan
ST-148	Novel Plasticized Melt Spinning Process of Polyacrylonitrile (PAN) Fibers Based on Task-Specific Ionic Liquids	Sheng Dai	Oak Ridge National Laboratory
ST-202	HyMARC – National Renewable Energy Laboratory Activities	Tom Gennett	National Renewable Energy Laboratory

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ST-204	HyMARC – Pacific Northwest National Laboratory Activities	Tom Autrey	Pacific Northwest National Laboratory
ST-207	HyMARC – Lawrence Livermore National Laboratory Activities	Brandon Wood	Lawrence Livermore National Laboratory
ST-210	HyMARC Seedling: Metal–Organic Frameworks Containing Frustrated Lewis Pairs for Hydrogen Storage at Ambient Temperature	Shengqian Ma	University of South Florida
ST-213	HyMARC Seedling: Uniting Theory and Experiment to Deliver Flexible Metal–Organic Frameworks for Superior Methane (Natural Gas) Storage	Brian Space	University of South Florida
ST-222	HyMARC: Characterization of Hydrogen Storage Materials at Oak Ridge National Laboratory's Spallation Neutron Source	Anibal Ramirez-Cuesta	Oak Ridge National Laboratory
ST-224	HyMARC – Lawrence Berkeley National Laboratory Activities	Jeffrey Long	Lawrence Berkeley National Laboratory
ST-225	HyMARC – Lawrence Berkeley National Laboratory Advanced Light Source Activities	David Prendergast	Lawrence Berkeley National Laboratory
ST-231	Precursor Processing Development for Low-Cost, High-Strength Carbon Fiber for Composite Overwrapped Pressure Vessel Applications	Matthew Weisenberger	University of Kentucky
ST-233	HyMARC – Sandia National Laboratories Activities	Mark Allendorf	Sandia National Laboratories
ST-234	Development of Magnesium Borane Containing Solutions of Furans and Pyroles as Reversible Liquid Hydrogen Carriers	Craig Jensen	University of Hawaii
TA-008	Material–Process–Performance Relationships in Polymer Electrolyte Membrane Catalyst Inks and Coated Layers	Michael Ulsh	National Renewable Energy Laboratory
TA-013	Fuel Cell Bus Evaluations	Leslie Eudy	National Renewable Energy Laboratory
TA-029	Autonomous Hydrogen Fueling Station	Dustan Skidmore	Plug Power Inc.
TA-039	Solid Oxide Electrolysis System Demonstration	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.
TA-040	Hydrogen Storage Tank Packaging On Board Heavy-Duty Trucks	Shaun Onorato	National Renewable Energy Laboratory

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TA-044	System Demonstration for Supplying Clean, Reliable, and Affordable Electric Power to Data Centers using Hydrogen Fuel	Dave Montgomery	Caterpillar, Inc.
TA-045	Marine Hydrogen Demonstration	Narendra Pal	Hornblower
TA-051	Low Total Cost of Hydrogen by Exploiting Offshore Wind and Polymer Electrolyte Membrane Electrolysis Synergies	Hui Xu	Giner, Inc.
TA-052	Solid Oxide Electrolysis Cells Integrated with Direct Reduced Iron Plants for Producing Green Steel	Jack Brouwer	University of California, Irvine
TA-053	Grid-Interactive Steelmaking with Hydrogen	Ronald O'Malley	Missouri University of Science and Technology
WPTO-001	Marine Energy to Hydrogen Analysis Project	Jacob Thorson	National Renewable Energy Laboratory