U.S. Department of Energy
Hydrogen Program

2023 Annual Merit Review and Peer Evaluation Report

June 5–8, 2023
Arlington, Virginia

U.S. DEPARTMENT OF
ENERGY

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U.S. Department of Energy Hydrogen Program

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and
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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) 2023 U.S. Department of Energy (DOE) Hydrogen Program Annual Merit Review and Peer Evaluation Meeting (AMR), held virtually and in person June 5–8, 2023. 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 on U.S. hydrogen priorities from Deputy Secretary of Energy David Turk, followed by remarks on accelerating innovation from science through deployment by Dr. Geraldine Richmond, under secretary for science and innovation, and David Crane, director of the Office of Clean Energy Demonstrations. The opening plenary session included three panel discussions. The first panel included leaders from the U.S. Departments of Commerce, Transportation, and Labor, and the discussion focused on the national hydrogen strategy and interagency collaboration. I then provided an overview of the DOE Hydrogen Program. This was followed by a second panel, which highlighted the Program's approach to agency-wide collaboration and coordination, with perspectives from nine representatives of DOE offices involved in the Program. After the second panel, Sheri Bone, principal deputy director of the Office of Economic Impact and Diversity (since renamed the Office of Energy Justice and Equity), rounded out the plenary session with perspectives on energy and environmental justice. The final panel provided perspectives from Hydrogen and Fuel Cell Technologies Office (HFTO) program managers, complementing the Program overview I delivered.

The AMR technical session included tracks on each of HFTO's subprograms: Hydrogen Production Technologies; Hydrogen Infrastructure Technologies; Fuel Cell Technologies; Systems Development and Integration; and Analysis, Codes and Standards. It also included a dedicated two-and-a-half-day track on DOE intra-agency activities, including project updates from the Office of Fossil Energy and Carbon Management, the Office of Nuclear Energy, and the Advanced Research Projects Agency–Energy (ARPA-E), as well as several other offices within the Office of Energy Efficiency and Renewable Energy, including Solar Energy Technologies, Water Power Technologies, Wind Energy Technologies, and Industrial Efficiency and Decarbonization. A one-day session on interagency activities included presentations on hydrogen activities supported by other federal agencies, including the Environmental Protection Agency, the National Oceanic and Atmospheric Administration, NASA, and the Departments of Defense, Transportation, and Agriculture.

The AMR was attended by more than 2,500 people, including more than 130 reviewers who reviewed more than 100 projects funded by HFTO and more than 20 reviewers who provided feedback on the overall Program and its subprograms. DOE values the transparent public process of soliciting technical input on its projects and programs from relevant experts with deep 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 on the following pages 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 for each project present the reviewer comments to be considered during the upcoming fiscal year (October 1, 2023–September 30, 2024). The projects have been grouped according to subprogram and reviewed according to the appropriate evaluation criteria. The scores and comments are provided to each project's principal investigators (PIs) so that they receive direct feedback (although the authors of the individual comments remain anonymous). DOE instructs the PIs to consider these summary evaluations fully—along with any comments from DOE managers—in their FY 2024 plans.

On behalf of the DOE Hydrogen Program, I would like to express my sincere appreciation to all the 2023 AMR participants—especially the reviewers, researchers, and presenters—for your strong commitment, expertise, and dedication to advancing hydrogen and fuel cell technologies and addressing our nation's critical energy and environmental needs. 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 2024 AMR, which is scheduled for the week of May 6, 2024.

Sincerely,

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

Hydrogen Production Technologies

Hydrogen Production

Project Number	Project Title *Principal Investigator Name and 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*	3.4	X		
P-170	Benchmarking Advanced Water-Splitting Technologies: Best Practices in Materials Characterization *Olga Marina, Pacific Northwest National Laboratory*	3.7	X		
P-179	BioHydrogen (BioH2) Consortium to Advance Fermentative Hydrogen Production *Katherine Chou, National Renewable Energy Laboratory*	3.2	X		
P-184	Scalable and Highly Efficient Microbial Electrochemical Reactor for Hydrogen Generation from Lignocellulosic Biomass and Waste *Hong Liu, Oregon State University*	3.0	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		
P-197	Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzers *Andrew Steinbach, 3M Company*	3.4	X		
P-198	Enabling Low-Cost Proton Exchange Membrane Electrolysis at Scale Through Optimization of Transport Components and Electrode Interfaces *Chris Capuano, Nel Hydrogen*	3.2	X		
P-199	Integrated Membrane Anode Assembly and Scale-up *Adam Paxson, Plug Power Inc.*	3.2	X		
P-200	Low-Cost Manufacturing of High-Temperature Electrolysis Stacks *Scott Swartz, Nextech Materials, Ltd.*	3.3	X		
P-201	Automation of Solid Oxide Electrolyzer Cell and Stack Assembly *Todd Striker, Cummins Inc.*	3.0	X		
P-202	Novel Microbial Electrolysis Cell Design for Efficient Hydrogen Generation from Wastewaters *Bruce Logan, The Pennsylvania State University*	3.0	X		
P-203	Novel Microbial Electrolysis System for Conversion of Biowastes into Low-Cost Renewable Hydrogen *Noah Meeks, Southern Company Services, Inc.*	3.1	X		
P-204	Hydrogen Production Cost and Performance Analysis *Brian James, Strategic Analysis, Inc.*	3.3	X		

Hydrogen Production: HydroGEN Seedling[1]

Project Number	Project Title *Principal Investigator Name and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
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*	3.0	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*	3.0	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*	2.9			X

Hydrogen Infrastructure Technologies

Hydrogen Infrastructure

Project Number	Project Title *Principal Investigator Name and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
H2-041	H2@Scale Cooperative Research and Development Agreement: California Research Consortium (Reference Station, Fueling Performance Test Device, Station Cap Model) *Sam Sprik, National Renewable Energy Laboratory*	3.0	X		
IN-001a	Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Metals *Chris San Marchi, Sandia National Laboratories*	3.6	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 and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
IN-001b	Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Polymers *Kevin Simmons, Pacific Northwest National Laboratory*	3.5	X		
IN-015	Optimizing the Heisenberg Vortex Tube for Hydrogen Cooling *Jacob Leachman, Washington State University*	3.3	X		
IN-016	Free-Piston Expander for Hydrogen Cooling *Devin Halliday, Gas Technology Institute*	3.3	X		
IN-019	Ultra-Cryopump for High-Demand Transportation Fueling *Kyle Gross, RotoFlow*	2.1		X	
IN-020	Self-Healable Copolymer Composites for Extended-Service Hydrogen Dispensing Hoses *Marek Urban, Clemson University*	2.6	X		
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*	2.5	X		
IN-025	Hydrogen Delivery Technologies Analysis *Amgad Elgowainy, Argonne National Laboratory*	3.4	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*	3.5	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*	3.1	X		
IN-030	Micro-Mechanically Guided High-Throughput Alloy Design Exploration toward Metastability-Induced Hydrogen Embrittlement Resistance *C. Cem Tasan, Massachusetts Institute of Technology*	3.0	X		
IN-034	HyBlend: Pipeline Cooperative Research and Development Agreement (CRADA) Cost and Emissions Analysis *Mark Chung, National Renewable Energy Laboratory*	3.5	X		
IN-035	HyBlend: Pipeline Cooperative Research and Development Agreement (CRADA) Materials Research and Development *Chris San Marchi, Sandia National Laboratories*	3.7	X		
IN-036	Cost-Effective Pre-Cooling for High-Flow Hydrogen Fueling *Devin Halliday, GTI Energy*	3.1	X		
IN-037	Autonomous Fueling System for Heavy-Duty Fuel Cell Electric Trucks *Renju Zacharia, Nikola Motor Company*	2.4		X	

Project Number	Project Title *Principal Investigator Name and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
IN-039	Analytic Framework for Optimal Sizing of Hydrogen Fueling Stations for Heavy-Duty Vehicles at Ports *Todd Wall, Pacific Northwest National Laboratory*	3.2	X		
IN-040	The HyRIGHT Project: 700 bar Hydrogen Refueling Interface for Gaseous Heavy-Duty Trucks *Will James, Savannah River National Laboratory*	3.2	X		
TA-049	High-Pressure, High-Flow-Rate Dispenser and Nozzle Assembly for Heavy-Duty Vehicles *Spencer Quong, Electricore Inc.*	3.6	X		

Hydrogen Storage

Project Number	Project Title *Principal Investigator Name and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
ST-127	Hydrogen Materials Advanced Research Consortium (HyMARC) Overview *Mark Allendorf, Sandia National Laboratories*	3.0	X		
ST-236	Low-Cost, High-Performance Carbon Fiber for Compressed Natural Gas Storage Tanks *Xiaodong Li, University of Virginia*	3.3	X		
ST-237	Carbon Composite Optimization Reducing Tank Cost *Duane Byerly, Hexagon R&D*	3.2	X		
ST-238	Low-Cost, High-Strength Hollow Carbon Fiber for Compressed Gas Storage Tanks *Matthew Weisenberger, University of Kentucky*	3.2	X		
ST-240	Cost-Optimized Structural Carbon Fiber for Hydrogen Storage Tanks *Amit Naskar, Oak Ridge National Laboratory*	2.9	X		
ST-241	First Demonstration of a Commercial-Scale Liquid Hydrogen Storage Tank Design for International Trade Applications *Ed Holgate, Shell*	2.9	X		

Fuel Cell Technologies

Project Number	Project Title *Principal Investigator Name and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
FC-160	ElectroCat 2.0 (Electrocatalysis Consortium) *Deborah Myers, Argonne National Laboratory, and Piotr Zelenay, Los Alamos National Laboratory*	3.3	X		
FC-317	Stationary Direct Methanol Fuel Cells Using Pure Methanol *Xianglin Li, University of Kansas*	2.8			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-326	Durable Membrane Electrode Assemblies for Heavy-Duty Fuel Cell Electric Trucks *John Slack, Nikola Motor Company*	2.6		X	
FC-327	Durable High-Power-Density Fuel Cell Cathodes for Heavy-Duty Vehicles *Shawn Litster, Carnegie Mellon University*	3.4	X		
FC-330	High-Efficiency Reversible Solid Oxide System *Hossein Ghezel-Ayagh, FuelCell Energy, Inc.*	3.3	X		
FC-331	A Novel Stack Approach to Enable High Round-Trip Efficiencies in Unitized Proton Exchange Membrane Regenerative Fuel Cells *Katherine Ayers, Nel Hydrogen*	3.0	X		
FC-333	Advanced Membranes for Heavy-Duty Fuel Cell Trucks *Andrew Baker, Nikola Motor Company*	3.4		X	
FC-336	A Systematic Approach to Developing Durable, Conductive Membranes for Operation at 120°C *Tom Zawodzinski, University of Tennessee, Knoxville*	2.8		X	
FC-337	Cummins Proton Exchange Membrane Fuel Cell System for Heavy-Duty Applications *Jean St-Pierre, Cummins Inc.*	2.5		X	
FC-338	Domestically Manufactured Fuel Cells for Heavy-Duty Applications *Karen Swider-Lyons, Plug Power Inc.*	2.5		X	
FC-339	M2FCT: Million Mile Fuel Cell Truck Consortium *Rod Borup, Los Alamos National Laboratory, and Adam Weber, Lawrence Berkeley National Laboratory*	3.4	X		
FC-344	Low-Cost Corrosion-Resistant Coated Aluminum Bipolar Plates by Elevated Temperature Formation and Diffusion Bonding *Tianli Zhu, Raytheon Technologies Research Center*	3.1	X		

Project Number	Project Title *Principal Investigator Name and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
FC-345	Development and Manufacturing for Precious-Metal-Free Metal Bipolar Plate Coatings for Proton Exchange Membrane Fuel Cells *CH Wang, Treadstone Technologies, Inc.*	2.9		X	
FC-346	Fully Unitized Fuel Cell Manufactured by a Continuous Process *Jon Owejan, Plug Power Inc.*	3.2	X		
FC-347	Development of Low-Cost, Thin Flexible Graphite Bipolar Plates for Heavy-Duty Fuel Cell Applications *David Chadderdon, NeoGraf Solutions, LLC*	3.2	X		
FC-348	Fuel Cell Bipolar Plate Technology Development for Heavy-Duty Applications *Siguang Xu, General Motors LLC*	2.8		X	
FC-349	Foil-Bearing-Supported Compressor–Expander *Giri Agrawal, R&D Dynamics Corporation*	3.1	X		
FC-350	High-Efficiency and Transient Air Systems for Affordable Load-Following Heavy-Duty Truck Fuel Cells *Doug Hughes, Eaton Corporation*	3.0	X		
FC-351	Durable and Efficient Centrifugal Compressor-Based Filtered Air Management System and Optimized Balance of Plant *Mike Bunce, MAHLE Powertrain, LLC*	3.1	X		
FC-352	Leveraging Internal Combustion Engine Air System Technology for Fuel Cell System Cost Reduction *Paul Wang, Caterpillar Inc.*	3.3	X		
FC-353	Fuel Cell Cost and Performance Analysis *Brian James, Strategic Analysis, Inc.*	3.2	X		
FC-363	Advanced Fuel Cell Vehicle DC-DC Converter Development *Vivek Sujan, Oak Ridge National Laboratory*	3.0	X		

Systems Development and Integration

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SDI-001	Integrated Modeling, Techno-Economic Analysis, and Reference Design for Renewable Hydrogen to Green Steel and Ammonia *Steve Hammond, National Renewable Energy Laboratory*	3.1	X		

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SDI-002	Hydrogen Energy Storage System at Borrego Springs Toward a Hydrogen-Enabled 100% Renewable Microgrid *Kumaraguru Prabakar, National Renewable Energy Laboratory*	3.1	X		
SDI-004	Hydrogen Coach Bus Fueling Demonstration *Richard Boardman, Idaho National Laboratory*	3.7	X		
TA-001	Membrane Electrode Assembly Manufacturing Research and Development *Peter Rupnowski, National Renewable Energy Laboratory*	3.0	X		
TA-016	Fuel Cell Hybrid Electric Delivery Van *Jason Hanlin, Center for Transportation and the Environment*	3.6	X		
TA-017	Innovative Advanced Hydrogen Mobile Fueler *Sara Odom, Electricore Inc.*	2.9			X
TA-018	High-Temperature Electrolysis, Stack, and Systems Testing *Micah Casteel, Idaho National Laboratory*	3.4	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*	3.4	X		
TA-035	Power Electronics for Electrolyzer Applications to Enable Grid Services *Robert Hovsapian, National Renewable Energy Laboratory*	3.4			X
TA-037	Demonstration and Framework for H2@Scale in Texas and Beyond *Rich Myhre, Frontier Energy, Inc.*	3.4	X		
TA-039	Solid Oxide Electrolysis System Demonstration *Hossein Ghezel-Ayagh, FuelCell Energy, Inc.*	3.4	X		
TA-042	Next-Generation Hydrogen Station Analysis *Genevieve Saur, National Renewable Energy Laboratory*	3.3	X		
TA-043	Solid Oxide Electrolysis Cell Stack Development and Manufacturing *Olga Marina, Pacific Northwest National Laboratory*	3.1	X		
TA-044	System Demonstration for Supplying Clean, Reliable, and Affordable Electric Power to Data Centers Using Hydrogen Fuel *Paul Wang, Caterpillar Inc.*	3.0	X		
TA-045	Waterfront Maritime Hydrogen Demonstration Project *Narendra Pal, Hornblower Group*	3.1	X		
TA-048	Advanced Research on Integrated Energy Systems (ARIES)/Flatirons Facility – Hydrogen System Capability Buildout *Daniel Leighton, National Renewable Energy Laboratory*	3.5			X
TA-052	Solid Oxide Electrolysis Cells Integrated with Direct Reduced Iron Plants for Producing Green Steel *Jack Brouwer, University of California, Irvine*	3.1	X		

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
TA-053	Grid-Interactive Steelmaking with Hydrogen (GISH) *Ronald O'Malley, Missouri University of Science and Technology*	3.4	X		
TA-056	Ultra-Efficient Long-Haul Hydrogen Fuel Cell Tractor *Darek Villeneuve, Daimler Trucks North America*	3.5	X		
TA-057	High-Efficiency Fuel Cell Application for Medium-Duty Truck Vocations *Stan Bower, Ford Motor Company*	3.5	X		
TA-058	Freight Emissions Reduction via Medium-Duty Battery Electric and Hydrogen Fuel Cell Trucks with Green Hydrogen Production via a New Electrolyzer Design and Electrical Utility Grid Coupling *Jacob Lozier, General Motors LLC*	3.6	X		
TA-059	Medium-Duty Vehicle Total Cost of Ownership and Target Development *Ram Vijayagopal, Argonne National Laboratory*	3.4	X		
TA-060	Offshore Wind to Hydrogen – Modeling, Analysis, Testing, and International Collaboration Work *Genevieve Saur, National Renewable Energy Laboratory*	3.3	X		
TA-062	Validation of Interconnection and Interoperability of Grid-Forming Inverters Sourced by Hydrogen Technologies in View of 100% Renewable Microgrids *Kumaraguru Prabakar, National Renewable Energy Laboratory*	3.4	X		
TA-065	Total Cost of Ownership Analysis of Hydrogen Fuel Cells in Off-Road Heavy-Duty Applications – Preliminary Results *Rajesh Ahluwalia, Argonne National Laboratory*	3.4	X		

Analysis, Codes and Standards

Systems Analysis

Project Number	Project Title *Principal Investigator Name and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SA-174	Life Cycle Analysis of Hydrogen Pathways *Amgad Elgowainy, Argonne National Laboratory*	3.4	X		
SA-178	Cradle-to-Grave Transportation Analysis *Amgad Elgowainy, Argonne National Laboratory*	3.7	X		

Project Number	Project Title *Principal Investigator Name and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SA-181	Global Change Analysis Model Expansion – Hydrogen Pathways *Page Kyle, Pacific Northwest National Laboratory*	3.5	X		
SA-186	Updates to National Energy Modeling Systems To Include Hydrogen Module *Michael Schaal, OnLocation, Inc.*	3.4	X		

Safety, Codes and Standards

Project Number	Project Title *Principal Investigator Name and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SCS-001	Component Failure Research and Development *Kevin Hartmann, National Renewable Energy Laboratory*	3.2	X		
SCS-005	Research and Development for Safety, Codes and Standards: Material and Component Compatibility *Joe Ronevich, Sandia National Laboratories*	3.7	X		
SCS-010	Research and Development for Safety, Codes and Standards: Hydrogen Behavior *Ethan Hecht, Sandia National Laboratories*	3.2	X		
SCS-011	Hydrogen Quantitative Risk Assessment *Ben Schroeder, Sandia National Laboratories*	3.6	X		
SCS-019	Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources *Nick Barilo, Pacific Northwest National Laboratory*	3.7	X		
SCS-021	National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory *William Buttner, National Renewable Energy Laboratory*	3.6	X		
SCS-022	Fuel Cell and Hydrogen Energy Association Codes and Standards Support *Karen Quackenbush, Fuel Cell and Hydrogen Energy Association*	3.2	X		
SCS-028	Hydrogen Education for a Decarbonized Global Economy (H2EDGE) *Eladio Knipping, Electric Power Research Institute*	3.2	X		
SCS-030	MC Formula Protocol for H35HF Fueling *Taichi Kuroki, National Renewable Energy Laboratory*	3.4	X		

Project Number	Project Title *Principal Investigator Name and Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SCS-031	Assessment of Heavy-Duty Fueling Methods and Components *Shaun Onorato, National Renewable Energy Laboratory*	3.5	X		
SCS-033	Risk Assessments of Design and Refueling for Hydrogen Locomotive and Tender *Brian Ehrhart, Sandia National Laboratories*	3.1	X		
SCS-H2042	Hydrogen Contaminant Detector *Matthew Post, National Renewable Energy Laboratory*	3.2	X		

Table of Contents

Introduction

The U.S. Department of Energy (DOE) Hydrogen Program Annual Merit Review and Peer Evaluation Meeting (AMR) consists of a detailed merit review and technical expert peer evaluation of the DOE Hydrogen and Fuel Cell Technologies Office (HFTO). The AMR also provides an overview of the entire DOE Hydrogen Program (the 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), the Loan Programs Office (LPO), the Office of Clean Energy Demonstrations (OCED), and the Advanced Research Projects Agency–Energy (ARPA-E). In addition, the AMR highlights relevant activities across other federal and state agencies involved in the field of hydrogen and fuel cells.

The Fiscal Year (FY) 2023 AMR was held as a hybrid meeting June 5–8, 2023. Detailed evaluations of 107 HFTO-funded projects were completed by 132 peer reviewers, and 23 Program reviewers provided both a high-level evaluation of the hydrogen activities conducted by multiple DOE offices and an evaluation of inter-office collaboration on hydrogen and fuel cells. Appendix A contains Hydrogen Program review results that consist of comments and scores on progress toward Program goals. A representative selection of hydrogen and fuel cell programs and projects funded by other DOE offices in the Program were also presented, though not reviewed, at the AMR. All AMR presentations are available online to the public in the 2023 AMR Proceedings.[i]

DOE uses the results of this merit review and peer evaluation to help shape priorities and plans for upcoming fiscal years and to guide ongoing improvements to the overall Program strategy.

The goals of the AMR include the following:

- Review and evaluate FY 2023 accomplishments and outyear plans for HFTO subprograms, and rigorously and systematically track progress against targets and metrics.
- Provide an opportunity for input from stakeholders[1] to help shape the Program so that it addresses the highest-priority barriers, facilitates technology transfer and market impact, continually improves its effectiveness in making progress toward national goals, and ensures benefits are maximized and harms are minimized for all communities affected by hydrogen and fuel cell research, development, demonstration, and deployment (RDD&D) activities (especially communities that have been disproportionately burdened by the energy practices of the past).
- Foster interactions among national laboratories, industry, and universities conducting RDD&D activities to enhance collaboration and coordination and leverage resources and talents.
- Provide opportunities for early career development in science, technology, engineering, and mathematics (STEM) fields through exposure to cutting-edge DOE-funded research.
- Provide an open venue for stakeholder engagement with DOE programs, with a particular focus on strengthening diversity, equity, inclusion, and accessibility (DEIA) and engagement within the energy and environmental justice community.
- Provide transparency regarding the use and impact of taxpayer funding, including on specific outcomes from that funding, such as innovations; patents; commercialized or near-commercial technologies; and progress in manufacturing, safety, codes and standards, workforce development, and other key enabling activities.

Organization of the Report

This report introduction provides a brief overview of the Program, including highlighted 2023 accomplishments and high-level activities and accomplishments within each Program office. This section also includes a discussion of the peer review process and analysis methodology.

[1] The Program considers "stakeholders" here in the broadest sense, including component and system developers and manufacturers, integrators, end users, and all other communities and groups that may be affected by hydrogen and fuel cell projects and installations.

Following the introduction are the detailed peer review results. The HFTO project peer review results are grouped into five subprograms, as follows:

- **Hydrogen Production Technologies**
  - Production Technologies
  - Production–HydroGEN Seedling Projects
- **Hydrogen Infrastructure Technologies**
  - Hydrogen Infrastructure
  - Hydrogen Storage
- **Fuel Cell Technologies**
- **Systems Development and Integration**
- **Analysis, Codes and Standards**
  - Systems Analysis
  - Safety, Codes and Standards.

Each of these sections begins with a brief subprogram overview, including summaries of key activities and accomplishments in 2023, goals, milestones, and budget. The subprogram overviews are followed by individual reports for projects presented orally during the 2023 AMR. These reports include brief summaries and review results, including the scores and qualitative comments for each project.

The main body of the report is supplemented by five appendices:

- **Appendix A:** AMR Program reviewers' comments and scores on the overall DOE Hydrogen Program
- **Appendix B**: List of the meeting participants
- **Appendix C:** Evaluation criteria used for the Program and project reviews
- **Appendix D**: List of projects that were presented at the AMR but not reviewed, including those funded by other DOE offices or external stakeholders.
- **Appendix E:** List of the Program's funding opportunity announcements (FOAs) and project selections since the 2022 AMR.

Overview of the Hydrogen Program

The Program provides funding and strategic direction for RDD&D activities to advance the production, transport, storage, and use of clean hydrogen across numerous applications and multiple sectors of the economy. These activities are authorized by Title VIII of the Energy Policy Act of 2005[ii] and the Energy Act of 2020.[iii] As the Program's lead office, HFTO coordinates hydrogen activities across EERE, FECM, NE, OE, SC, OCED, LPO, and ARPA-E. The Program's participating offices pursue a broad range of hydrogen-related activities, guided by input from several rigorous processes, including technical, economic, and environmental analyses; stakeholder workshops; requests for information; and others. Most of the Program's individual projects are selected through competitive, merit-based funding opportunities. In addition, a growing network of stakeholders informs the Program's strategy and direction, including industry representatives across applications and sectors, state and regional organizations, other federal agencies, and the Program's international counterparts.

Program activities are aligned with the Biden Administration's goals, including achieving a 50%–52% reduction in economy-wide greenhouse gas emissions by 2030, 100% carbon-emissions-free electricity by 2035, and net-zero greenhouse gas emissions by 2050 across the entire economy.[iv] The Program's efforts—which span the full range of RDD&D—are consistent with these goals and include activities to reduce the cost and improve the performance and durability of hydrogen technologies, while also enabling scale-up of clean hydrogen production. Progress in these areas is key to jump-starting markets for clean hydrogen, including heavy-duty transportation applications, decarbonized industrial and chemical processes, and long-duration energy storage.

In FY 2023, Congress appropriated a total of $417.5 million for DOE hydrogen and fuel cell activities (see Table 1 below, which shows the funding published in the congressional budget request[v]). This funding includes $216.2 million for EERE activities and $128 million for FECM activities. Funding for hydrogen and fuel cell activities in

NE and SC amounted to $23 million and $50.4 million, respectively, with additional hydrogen-related funding within ARPA-E yet to be determined.

On November 15, 2021, President Biden signed into law the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law, or BIL), which includes $9.5 billion over five years for clean hydrogen.[vi] Of this funding, $8 billion will be for regional clean hydrogen hubs; $1 billion for electrolysis research, development, and demonstration (RD&D); and $500 million for clean hydrogen technology manufacturing and recycling RD&D.

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

DOE Office / Program	FY 2022 (enacted)	FY 2023 (enacted)	FY 2024 (requested)
Energy Efficiency and Renewable Energy	**$163.4**	**$216.2**	**$206.6**
Hydrogen and Fuel Cell Technologies Office	$157.5	$170.0	$163.1
Advanced Manufacturing Office	$0.0	$25.0	$0.0
Industrial Efficiency and Decarbonization Office	-		$30.0
Solar Energy Technologies Office	$5.1	$7.5	$3.5
Vehicle Technologies Office	-	$10.0	-
Water Power Technologies Office	$0.8	$2.6	-
Wind Energy Technologies Office	-	$1.1	$10.0
Fossil Energy and Carbon Management	**$113.0**	**$128.0**	**$112.0**
Carbon Management Technologies	$88.0	$101.0	$91.0
Resource Sustainability	$20.0	$26.0	$20.0
Energy Asset Transformation	$5.0	$1.0	$1.0
Nuclear Energy	**$23.0**	**$23.0**	**$13.5**
Crosscutting Technology Development	$10.0	$12.0	$9.5
Light Water Reactor Sustainability	$13.0	$11.0	$4.0
Office of Technology Transitions	**-**	**-**	**$0.1**
Science	**$17.4**	**$50.3**	**$49.5**
Advanced Research Program Agency–Energy	**$2.0**	**TBD[a]**	**TBD[a]**
TOTAL	**$318.8**	**$417.5**	**$381.7**

[a] ARPA-E funding is determined annually based on programs developed through office and stakeholder priorities. Therefore, funding for FY 2023 and 2024 is not available at this time.

Background: National Clean Hydrogen Strategy and H2@Scale

One of the key accomplishments in 2023 was publication of the ***U.S. National Clean Hydrogen Strategy and Roadmap***,[vii] a comprehensive national framework for accelerating large-scale production, processing, delivery, storage, and use of clean hydrogen to help meet bold decarbonization goals across virtually all sectors of the economy. Released June 5, 2023, following public review of a draft version, the *Strategy and Roadmap* was informed by extensive stakeholder feedback, and the document will be updated at least every three years, as required by the BIL. The *Strategy and Roadmap* provides a snapshot of hydrogen production, transport, storage, and use in the United States today and examines future demand scenarios—with strategic opportunities to expand domestic production of clean hydrogen to 10 million metric tonnes (MMT) annually by 2030, 20 MMT annually by 2040, and 50 MMT annually by 2050. The *Strategy and Roadmap* prioritizes three key strategies to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool—see Figure 1.

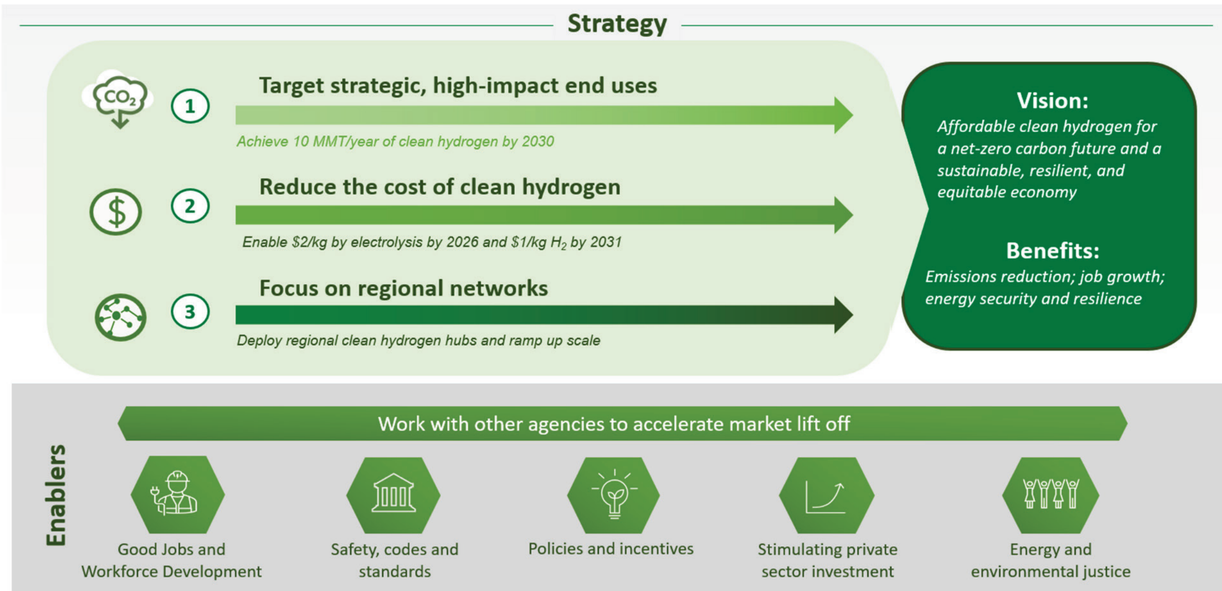

Figure 1. Strategies and key enablers for realizing the clean hydrogen vision

Federal agencies—in partnership with state, local, and tribal governments and other stakeholders—will take action to develop and deploy technologies to ensure a sustainable, resilient, and equitable clean hydrogen economy, utilizing the guiding principles shown in Figure 2 (below).

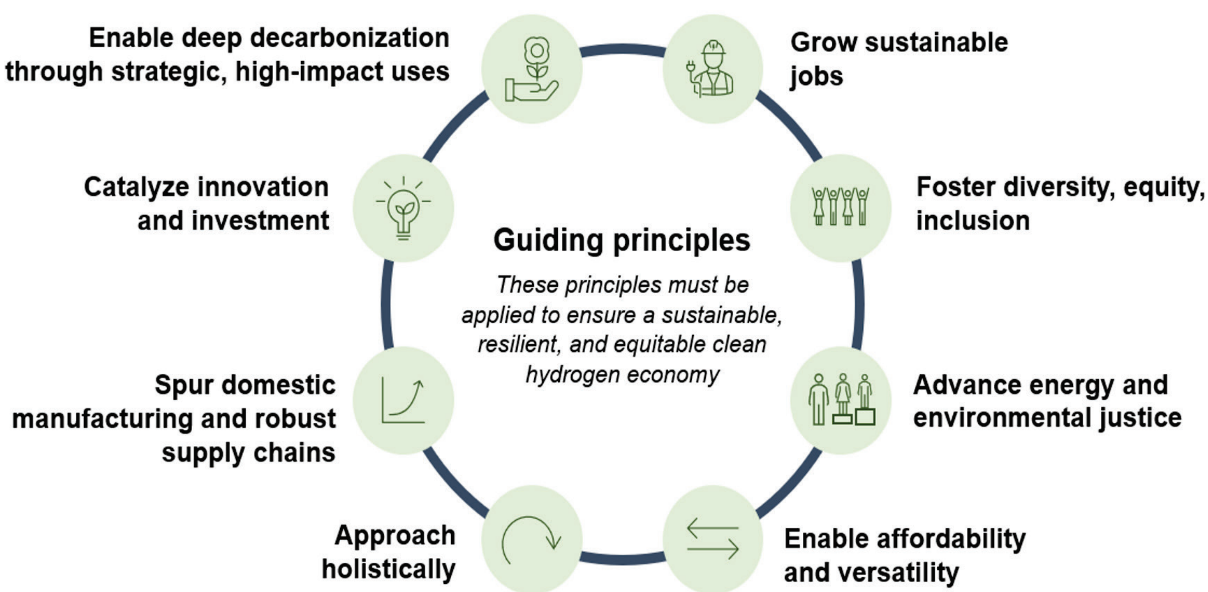

Figure 2. Eight guiding principles for the development of clean hydrogen production, transport, delivery, storage, and use

The national strategy described above builds upon DOE's **H2@Scale** initiative, established several years ago, which provided an overarching vision for how hydrogen can enable clean energy pathways across applications and sectors in an increasingly interconnected energy system, as shown in Figure 3 below. More details are provided on the H2@Scale webpage.[viii]

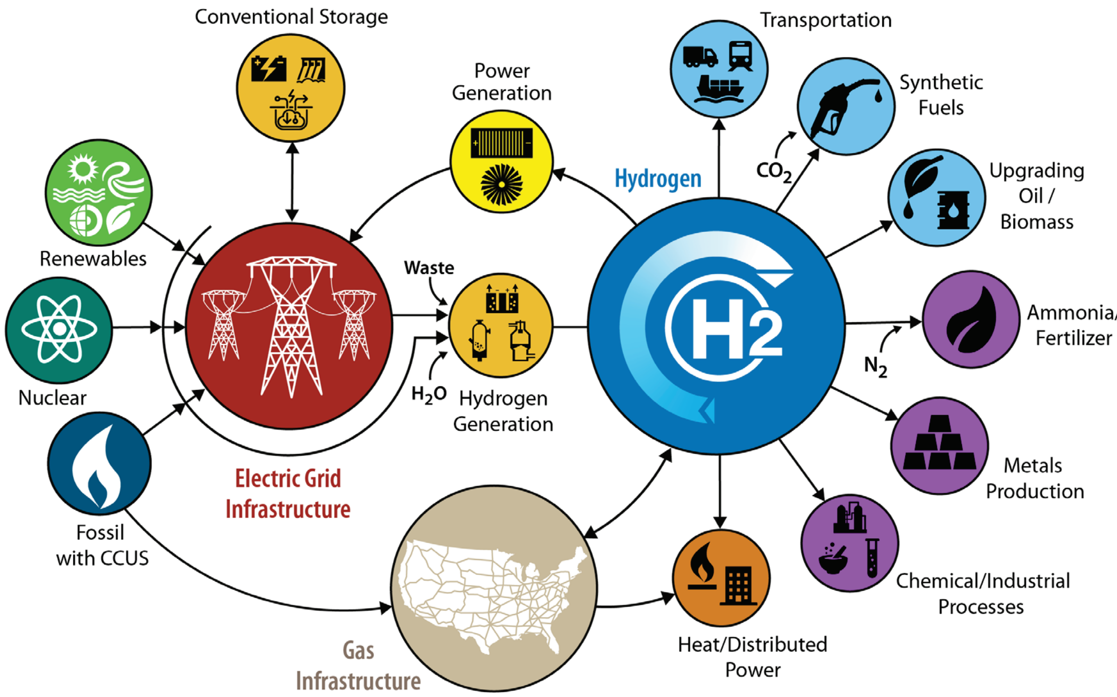

Figure 3. Schematic of H2@Scale

Program Highlights

Over the last year, the Program accelerated its efforts in all areas, as demonstrated by key highlights and accomplishments below.

Actions in Response to the Bipartisan Infrastructure Law

In addition to providing $9.5 billion in funding for regional clean hydrogen hubs, electrolysis RD&D, and clean hydrogen manufacturing and recycling RD&D, the BIL requires DOE to develop a national strategy and roadmap for clean hydrogen and an initial clean hydrogen production standard. Below are relevant Program actions in 2023.

- ***U.S. National Clean Hydrogen Strategy and Roadmap*:** The *U.S. National Hydrogen Strategy and Roadmap* was released in June 2023. Please refer to the "Background" section in this document for more information.
- **Regional Clean Hydrogen Hubs:** In October 2023, President Biden and DOE announced the selection of seven regional clean hydrogen hubs (H2Hubs), which will receive $7 billion in funding authorized by the BIL.[ix] The selected H2Hubs span the nation and will accelerate the commercial-scale deployment of low-cost clean hydrogen technologies. Managed by OCED, the H2Hubs are a key pillar of the national clean hydrogen strategy. Funding for the seven selected H2Hubs is subject to award negotiations, which are currently underway.
- **Electrolysis RD&D and Clean Hydrogen Manufacturing and Recycling RD&D:** In March 2023, DOE announced the availability of the first phase of funding—$750 million—of the $1.5 billion authorized in the BIL for RD&D to reduce the cost of clean hydrogen via electrolysis and RD&D of clean hydrogen systems and materials manufacturing and recycling.[x] Project selections for the $750 million FOA issued by HFTO are expected in the first quarter of 2024.
- **Clean Hydrogen Production Standard:** In June 2023, DOE released an updated guidance document containing the DOE proposal for a Clean Hydrogen Production Standard (CHPS).[xi] This updated guidance takes into account feedback received during the public comment period in response to the draft guidance document issued in September 2022. It establishes a target of 4.0 kg CO_2e/kg H_2 for life cycle (i.e., well-to-gate) greenhouse gas emissions associated with hydrogen production.

Hydrogen Shot and Related Developments

Since the launch of the Hydrogen Shot in June 2021, the Program has ramped up efforts to meet the aggressive goal of $1 per kilogram of clean hydrogen in one decade. The Program has implemented a number of actions and initiatives focused on the Hydrogen Shot in the last year.

- In September 2023, DOE announced the selection of 16 projects to receive nearly **$48 million to improve the performance of hydrogen infrastructure and fuel cell technologies**.[xii] These RD&D projects will receive funding for work focused on lowering costs for clean hydrogen technologies, enhancing hydrogen infrastructure, and improving the performance of hydrogen fuel cells in support of the Hydrogen Shot.
- In December, DOE released ***Hydrogen Shot Technology Assessment: Thermal Conversion Approaches***,[xiii] a report on various thermal conversion pathways for clean hydrogen production, including technology status and envisioned approaches for achieving the Hydrogen Shot goals through research, development, and deployment advances. This report was issued by the National Energy Technology Laboratory, with funding from FECM. The next two reports in this series will provide similar assessments of hydrogen production from electrolysis pathways and from advanced pathways, such as photoelectrochemical, solar-thermochemical, and biological hydrogen production.
- The **Hydrogen Shot Incubator Prize**[xiv] is a $2.6 million competition to foster innovative concepts for producing clean hydrogen. In October 2022, DOE announced nine Phase 1 winners of the Hydrogen Shot Incubator Prize competition. In this phase (*Propose!*), the winning teams received $60,000 for their early-stage concepts for novel hydrogen production technologies—$10,000 in cash and $50,000 in vouchers to spend at national laboratories to further develop their concepts. Winners of the next phase (*Prove!*) will receive $300,000 in national laboratory vouchers and $100,000 in cash to support their demonstration efforts in preparation for a "Pitch Day" with potential investors and commercial partners.[xv]

- The **Hydrogen Shot Fellowship**[xvi] recruits diverse talent to make the Hydrogen Shot a reality. Funded through HFTO, Hydrogen Shot fellows engage in related work from one or more HFTO technical programs—including Hydrogen Production Technologies, Hydrogen Infrastructure Technologies, Fuel Cell Technologies, Systems Development and Integration, and Analysis, Codes and Standards—as well as other functional areas including communications, workforce development, and stakeholder engagement and inclusion. The application period is currently open until all positions are filled.

Inflation Reduction Act

President Joseph R. Biden signed the Inflation Reduction Act[xvii] (IRA) into law in August 2022. The IRA includes several incentives for hydrogen and fuel cell technologies, including the Clean Hydrogen Production Tax Credit, which will provide credits of up to $3/kg of clean hydrogen based on the carbon intensity of production. The U.S. Department of the Treasury has been coordinating with DOE and the U.S. Environmental Protection Agency (EPA) on the tax credit and issued a notice of proposed rulemaking in December 2023.[xviii] The comment period deadline is February 26, 2024. DOE provided resources[xix] on the Clean Hydrogen Production Credit, including a white paper and a new version of the Greenhouse gases, Regulated Emissions, and Energy use in Technologies model, 45VH2-GREET, which has been adopted by the Department of the Treasury to determine emissions rates for purposes of the Tax Credit.

Funding for Hydrogen and Fuel Cell RD&D

The Program employs a comprehensive portfolio of tools to spur innovation across all aspects of the hydrogen value chain and through the entire life cycle of emerging technologies. **S**ince the publication of the *2022 AMR Report*, DOE has announced more than $1.3 billion in funding opportunities and lab calls and more than $150 million in project selections (in addition to the $7 billion announced by OCED for the H2Hubs) for hydrogen-related RDD&D. This funding has come from offices across DOE: HFTO, ARPA-E, FECM, NE, OCED, SC, and the offices of Advanced Manufacturing & Materials Technologies, Industrial Efficiency & Decarbonization, Manufacturing and Energy Supply Chains, Technology Transitions, Solar Energy Technologies, and Vehicle Technologies. Appendix E provides more details on FOAs and project selections.

Hydrogen Project Recognitions

In September 2022, two innovative technologies with ties to the HydroGEN Advanced Water Splitting Materials Consortium were honored with R&D 100 Awards. One of these innovations, a platinum group metal (PGM)–free catalyst for use in proton exchange membrane (PEM) electrolyzers, was developed by Argonne National Laboratory in a project funded by HFTO. The other innovation is SolarCatMesh, a photoelectrochemical device developed by Lawrence Berkeley National Laboratory that uses sunlight to convert water directly into hydrogen and oxygen. While SolarCatMesh's development was not funded directly by HFTO, the inventors include current and former HydroGEN experts.[xx]

Reports, Program Records, and Tools

- **Reports and Publications:** In addition to the *U.S. National Clean Hydrogen Strategy and Roadmap* and the *Hydrogen Shot Technology Assessment: Thermal Conversion Approaches* mentioned above, the following reports and publications were also released or updated in 2023:
    - *Pathways to Commercial Liftoff: Clean Hydrogen*[xxi]—released in March 2023 by the Office of Technology Transitions, in coordination with OCED, HFTO, OP, LPO, and other offices—examines the clean hydrogen market's potential to reach full-scale commercialization in light of transformational policies and programs.
    - The *Industrial Decarbonization Roadmap*[xxii]—released by the DOE Advanced Manufacturing Office in September 2022, with input from HFTO and relevant offices—features a discussion of potential roles for hydrogen in decarbonizing industrial applications.
    - The *U.S. National Blueprint for Transportation Decarbonization*[xxiii]—released in January 2023 by the U.S. Departments of Energy, Transportation, and Housing and Urban Development and the EPA—includes an examination of the role of clean hydrogen in decarbonizing transportation, particularly in heavy-duty sectors such as long-haul trucking, rail, and maritime.

- HFTO's "Progress in Hydrogen and Fuel Cells" fact sheet[xxiv] was updated to include the latest information on accomplishments achieved through HFTO efforts, including reducing cost and improving durability of fuel cells; advancing technologies for producing, delivering, and storing hydrogen; spurring deployments; and catalyzing innovation.

- **Program Records:** To document the source of key numbers and facts, the Program develops and publishes records that explain inherent assumptions, source data, and calculation methodologies. Four new Program records have been published since the 2022 AMR: *Heavy-Duty Fuel Cell System Cost–2022*, *Electrolyzer Installations in the United States*, *Historical Cost Reduction of PEM Electrolyzers,* and *PEM Electrolyzer Capacity Installations in the United States*. The full library of Program records (published since 2005) is available on the Program website.[xxv]

Workshops

The research community, government, and the private sector continue to convene in various workshops to identify gaps in RDD&D, determine next steps to enable large-scale hydrogen use, and inform the planning and design of Program responses to BIL provisions. A complete list of all workshops held by HFTO, including links to the proceedings of each workshop, can be found on the HFTO website.[2]

Interagency Collaboration

In August 2023, the **Hydrogen Interagency Task Force** (HIT)[xxvi] was launched to help execute on the national clean hydrogen strategy and to further advance a whole-of-government approach to clean hydrogen. The U.S. government can serve a key role in supporting the development of a robust market for clean hydrogen, with strong domestic supply chains and sustainable jobs, through effective policies and RDD&D activities that address barriers from supply through end use. The purpose of the HIT is to accelerate progress in clean hydrogen technology RDD&D, address regulatory challenges, promote environmental justice, and address key issues such as permitting and safety, codes and standards.

The HIT builds on prior efforts of the Hydrogen and Fuel Cells Interagency Working Group (IWG), which was coordinated by HFTO and enabled strong collaboration across agencies for nearly two decades at the technical programmatic level. The IWG convened federal agencies to share information on hydrogen-related RDD&D programs, perform gap analyses, and collaborate on joint projects. The HIT coordinates efforts from 11 agencies, many of whom participated in the IWG, including the U.S. Departments of Energy, Agriculture, Commerce, Defense, Transportation, the Interior, Labor, and State; the EPA; NASA; the Office of Science and Technology; the Small Business Administration; and the White House Climate Policy Office. Additional agencies are expected to join as activities progress. The Deputy Secretary of Energy and the Deputy National Climate Advisor to the President jointly serve as the HIT co-chairs, and HFTO serves as the HIT secretariat, building upon over 15 years of serving as lead for the IWG, authorized in the Energy Policy Act of 2005.

International Collaboration

HFTO leads the Program in engaging with hydrogen and fuel cell efforts around the world through a range of multilateral and bilateral partnerships. A key priority is to sustain a coordinated framework for international engagement that will accelerate technical and market progress by leveraging complementary activities to focus on gaps and avoid duplication of efforts. The Program has taken a leadership role in this area by co-leading the **Hydrogen Breakthrough** (along with counterparts from the United Kingdom and India). The Hydrogen Breakthrough, one of the initiatives of the Breakthrough Agenda,[3] aims to strengthen international collaboration in specific areas to accelerate progress toward the goal of enabling "affordable renewable and low-carbon hydrogen globally available by 2030."

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

[3] The Breakthrough Agenda (https://climatechampions.unfccc.int/breakthrough-agenda/) is a commitment made by countries to make clean technology solutions the most affordable, accessible, and attractive option in each emitting sector, by the end of this decade.

The Hydrogen Breakthrough currently focuses on five priority-action areas: ***Standards and Certification ("H.1")***, which aims to accelerate a program to develop international renewable and low-carbon hydrogen standards and to facilitate associated certification schemes; ***Demand Creation and Management ("H.2")***, which aims to strengthen demand for renewable and low-carbon hydrogen by coordinating the agreement and announcement of packages of public and private commitments for use of renewable and low-carbon hydrogen; ***Research and Innovation ("H.3")***, which aims to increase the number and geographical distribution of new, innovative hydrogen research and demonstration projects; ***Finance and Investment ("H.4")***, which aims to enhance the overall public offer of international assistance for clean hydrogen projects, with the goal of mobilizing private investment at scale in emerging and developing economies; and ***Landscape Coordination ("H5")***, which aims to enhance the coordination and transparency of international collaboration on clean hydrogen.

The Program continues to engage with a number of multilateral organizations and initiatives, including the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE); the Clean Energy Ministerial Hydrogen Initiative (CEM H2I); Mission Innovation's Clean Hydrogen Mission; the International Renewable Energy Agency's Collaborative Framework on Green Hydrogen; the International Energy Agency's Hydrogen Technology Collaboration Program (TCP) and Advanced Fuel Cells TCP; and the Center for Hydrogen Safety.

Recent international activities include the following:

- **International Hydrogen Partnership Launches Groundbreaking H2-DEIA Platform:** In celebration of its 20th anniversary and in partnership with the Hydrogen Council, IPHE announced in early October 2023 the launch of the H2-DEIA platform at the Hydrogen Americas Summit in Washington, DC. Committed to increasing diverse representation and building a culture of inclusion and equity, H2-DEIA (pronounced like *dia* [day] in Spanish) serves a global purpose: uniting governments, industry, academia, non-profit organizations, research institutes, capital investors, and the broader stakeholder community to help shape a skilled, diverse workforce for the clean hydrogen industry. Recognizing the importance of assessing workforce needs—particularly technical knowledge and capabilities unique to the field of clean hydrogen—H2-DEIA supports various initiatives to identify skill gaps; addresses challenges faced by underrepresented groups; and strengthens the recruitment, retention, and advancement of clean hydrogen professionals.
- **H2 Twin Cities:** H2 Twin Cities is an initiative of CEM H2I, which fosters the formation of self-assembled international community partnerships to exchange information; share best practices; and strengthen commitment to environmental justice, social equity, and clean energy jobs, particularly at the city and municipality levels. Secretary of Energy Granholm announced the 2022 winners[xxvii] as part of COP27 activities in Sharm el-Sheikh, Egypt. The 2023 winners are expected to be announced in the first half of 2024.
- **Hydrogen Americas Summit:** The Program collaborated with the DOE Office of International Affairs to assist with co-hosting the Hydrogen Americas 2023 Summit, which was jointly hosted by DOE and the Sustainable Energy Council.[xxviii] The Summit convened over 3,400 representatives from government, industry, and a wide range of stakeholder groups from across the Americas to identify opportunities to advance the growth of clean hydrogen markets and industry in the Americas.
- **Tribal Clean Energy Summit:** In October 2022, tribal leaders joined the DOE Office of Indian Energy at the 2022 Tribal Clean Energy Summit[xxix] for a nation-to-nation discussion to explore how tribes can harness clean energy to enhance energy sovereignty, address climate resilience, and build stronger economies. The Summit focused on federal energy programs and opportunities; increased access to energy project financing and capital; energy access, security, reliability, and transition issues; workforce development and transition; and consultation and meaningful tribal leader participation in national energy infrastructure decision-making.
- **Mission Innovation:** DOE has engaged in several activities under Mission Innovation, such as organizing technical webinars, including the Membrane Innovation Webinar.[xxx] In March 2023, Lawrence Berkeley National Laboratory, in collaboration with HFTO and Mission Innovation, hosted a webinar that focused on the use of—and potential environmentally friendly alternatives to—perfluorosulfonic acid (PFSA) ionomers in commercial PEM technology for fuel cells and electrolyzers.
- **FIRST Global Hydrogen Horizons:** DOE sponsored Dean Kamen's *FIRST* Global Hydrogen Horizons competition to promote STEM, convening students across 190 countries. Running October 7–10, 2023, in Singapore, the Hydrogen Horizons Challenge featured student teams focused specifically on the important role of hydrogen in our global renewable energy and net-zero-carbon future. They used their creativity and problem-

solving skills to design and build a skilled robot and navigate it in a simulation to produce hydrogen and use it to store, transport, and convert energy.

In addition, DOE partners at the national laboratories continue to add value to their work through international engagement. For example, in January 2024, the U.S. Agency for International Development and the Clean Energy Ministerial's Clean Energy Solutions Center committed funding to the National Renewable Energy Laboratory (NREL) for a series of hydrogen training workshops. The seven-part workshop series seeks to engage with a broad international audience across Asia, Africa, Latin America, and the Caribbean. The workshops are intended to help key stakeholders in developing or emerging economies assess the potential benefits, enabling conditions, and tradeoffs associated with the development of a hydrogen market, and understand factors to consider when making strategy, policy, and investment decisions about the future of hydrogen.

Workforce Development; Diversity, Equity, Inclusion, and Accessibility; and Environmental Justice

The Program continued its efforts to improve DEIA and environmental justice through various outreach efforts, initiatives, and funding opportunities. In addition to ongoing workforce development programs and deployment programs that benefit disadvantaged communities, the Program's efforts since the 2022 AMR include the following:

- **Funding for Minority-Serving Institutions:** In November 2022, HFTO awarded $1.5 million to five projects at three minority-serving institutions (MSIs) to train the next-generation hydrogen workforce. These projects will advance key clean hydrogen technologies while growing the skills and knowledge of science and engineering students. A key goal of these projects is to give participating students direct exposure to cutting-edge research, which includes engaging with DOE national laboratory researchers, who will support the selected projects.[xxxi]
- **STEMtember: Career Development Opportunities for Minority Students:** DOE celebrated STEMtember this year with a spotlight on opportunities available to minority students nationwide, including the Graduate Education for Minority (GEM) Students Fellowship, which provides qualified students with access to a network of leading research organizations, and the Minority Educational Institution Student Partnership Program (MEISPP), which provides paid internships with DOE and the national laboratories to students at accredited MSIs.[xxxii]
- **HFTO Postdoctoral Recognition Award:** This award recognizes outstanding postdoctoral fellows working to advance hydrogen and fuel cell technologies at DOE national laboratories. DOE announced the winner of this award during the 2023 AMR.[xxxiii] The current round of this award is in progress and will be announced at the 2024 AMR.
- **High School Demonstration:** HFTO hosted a high school robotics team at the 2023 AMR. The team demonstrated its robot during the poster session, giving students the opportunity to interact with hydrogen and fuel cell researchers and other stakeholders.
- **Deployments and Infrastructure Planning in Environmental Justice Communities:** In 2023, through an HFTO-funded demonstration and deployment project with the Center for Transportation and the Environment, the United Parcel Service (UPS) began using fuel cell hybrid electric vans to deliver packages. This project will replace 15 diesel-powered UPS vans in Ontario, California, with zero-emissions fuel cell hybrid electric vans, resulting in significant reductions in local air pollutants in disadvantaged communities. In addition, DOE awarded $7.4 million in February 2023 to seven projects to develop medium- and heavy-duty electric vehicle and hydrogen corridor infrastructure plans.[xxxiv] These projects will be coordinated between the Vehicle Technologies Office and HFTO and will support efforts to improve air quality in underserved areas of major U.S. cities.
- **Webinars:** HFTO conducts a monthly webinar series, covering a variety of hydrogen-related topics.[xxxv] Since the 2022 AMR, the following webinars were specifically focused on DEIA, environmental justice, or workforce development topics: "H2IQ Hour: Workforce Development in Hydrogen and Fuel Cells" and "Early Career Network: H2 Career Insights."

Office Overviews and Updates

Hydrogen and Fuel Cell Technologies Office in Collaboration with Relevant Offices in the Office of Energy Efficiency and Renewable Energy

HFTO pursues a broad portfolio of activities to overcome the technological, economic, and institutional barriers to the widespread adoption of hydrogen and fuel cell technologies. These activities address all aspects of the hydrogen value chain and span all stages of current and emerging technologies. They leverage other activities across relevant EERE offices including the Industrial Efficiency and Decarbonization, Vehicle Technologies, Wind Energy Technologies, Solar Energy Technologies, Water Power Technologies, and Advanced Materials and Manufacturing Technologies Offices.

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

- Conduct RD&D to advance clean hydrogen and fuel cell technologies.
- Develop and integrate complete operational hydrogen and fuel cell systems.
- Demonstrate and validate hydrogen and fuel cell systems in real-world conditions and conduct commercial readiness assessments to inform and guide RD&D efforts.
- Support the development of manufacturing technologies and processes, supply chains, and the workforce to enable industry to achieve scale and associated cost reductions.
- Address safety issues and facilitate development of codes and standards.
- Conduct crosscutting analyses of hydrogen and fuel cell technologies and markets to help guide RD&D and deployment priorities.

In addition to working closely with the Program's participating office, HFTO actively coordinates with other DOE offices such as the Offices of Technology Transitions, Policy, Energy Justice and Equity, and International Affairs, Arctic Energy, and others. For example, HFTO chairs the DOE-wide Hydrogen Joint Strategy Team (JST), with OCED serving as vice chair, to ensure strong coordination across the spectrum of activities from basic research through deployment.

Highlights of key HFTO RDD&D accomplishments and progress are shown in Table 3. A brief overview of each subprogram is provided in its respective chapter.

Table 2. Selected Examples of HFTO Progress and Accomplishments – 2023

Hydrogen Production Technologies

- ✓ Developed and published technical target tables for PEM, liquid alkaline, and oxygen-ion-conducting solid oxide electrolyzers at the stack and system levels.
- ✓ Launched 10-MW low-temperature electrolyzer testing and validation facility at NREL; this test bed will provide industry the ability to pilot-test commercial-scale electrolyzer stacks and systems with full balance of plant.
- ✓ Held workshops to determine key challenges and cost drivers associated with large-scale electrolyzer installations to help guide HFTO on how to reduce the cost and complexity of large-scale electrolyzer installations.
- ✓ Established performance baseline PEM electrolyzer test procedures of 1.9 V at 3 A/cm^2, validated to within <5 mV of variation at three national labs; completed durability test of a low-Ir-loading anode (0.4 mg Ir/cm^2) for 4,000 h to establish a benchmark degradation rate of 28 mV/kh. (H2NEW)
- ✓ Determined a standard set of materials, conditioning, and test procedures for zero-gap liquid alkaline electrolyzers and began benchmarking experiments; established standardized testing protocols and operating procedures for solid oxide electrolysis cells and completed round-robin testing at three national labs with conformity of results. (H2NEW)
- ✓ Demonstrated high-performance proton-conducting solid oxide electrolysis cells with improved durability via a simple, low-cost, and scalable acid etch process to enhance the electrode-electrolyte interface, yielding record-setting current densities (>2.8 A/cm^2 at 1.3 V at 600°C), reduced degradation, and increased Faradaic efficiencies. (HydroGEN)
- ✓ Demonstrated a completely integrated GaInP/GaAs III-V tandem photoelectrochemical system that achieved targeted durability at >5% solar-to-hydrogen efficiency. The system employs a catalyst-coated membrane leveraged from PEM electrolyzers and is able to operate at neutral pH conditions. (HydroGEN)
- ✓ Created a thermodynamic analysis tool that interfaces with the advanced computation data and bypasses time-consuming supercell defect calculations; from this data, synthesized >10 identified compounds of interest, resulting in ≥2 new validated water-splitting materials, with screening ongoing on others. (HydroGEN)
- ✓ Demonstrated successful small-scale hybrid microbial electrolysis cells using waste streams, with the potential to meet or exceed the target of 20 $L_{H2}/L_{reactor}$/day.

Hydrogen Infrastructure Technologies

Hydrogen Storage

- ✓ Enabled a 20% reduction (from the 2019 record value) in the projected cost of 700 bar composite overwrapped pressure vessel tanks by improving carbon fiber properties and conversion.
- ✓ Developed and refined a method for process design, operation simulation, and cost analysis for hydrogen storage using adsorbents for stationary/backup power applications and identified two materials that can outperform compressed hydrogen systems. (HyMARC)
- ✓ Completed and published studies on liquid hydrogen (LH2) storage systems for heavy trucks:
  - Configuration, performance, cost, and safety studies show system cost of \$174–\$183/kg usable H_2 and >40 g H_2/L reduce impact on truck capital cost and minimize impact on cargo volume.
  - Capacity, dormancy, refueling, and discharge studies show that cryogenic H_2 has advantages over compressed gas for heavy trucks, with LH2 offering >600 miles on 82 kg of useable H_2, and that LH2 storage systems meet volumetric (35 g/L) and gravimetric (15%) storage targets.

Hydrogen Infrastructure

- ✓ Completed a series of fast-fill fueling tests into an array of vehicular storage tanks, representative of heavy-duty vehicle storage capacity (>80 kg), at the NREL Energy Systems Integration Facility. The tests achieved an 82-kg fill in about 6.5 minutes, with average and peak hydrogen flow rates of 12.6 kg/min and 23 kg/min.
- ✓ Developed HELPR (Hydrogen Extremely Low Probability of Rupture), a probabilistic fracture mechanics structural integrity assessment tool, for public release. HELPR evaluates the probability of pipeline rupture and can be used to determine opportunities for system and operational improvements and inform regulatory structural integrity assessment.
- ✓ Released Hydrogen Delivery Scenario Analysis Model (HDSAM) 4.0, with updates for heavy-duty fueling infrastructure with tube trailer and LH2 tanker truck delivery, unique cost-estimating equations for six geographic pipeline regions, updated bulk hydrogen storage to align with other recent DOE-funded work, and an improved model interface.

Fuel Cell Technologies

- ✓ Reduced the projected heavy-duty vehicle fuel cell system durability-adjusted cost to \$179/kW at 50,000 systems/year in 2022, based on lab-demonstrated technology, surpassing the FY 2022 target of \$185/kW and FY 2021 baseline of \$196/kW.
- ✓ Developed intermetallic PtCo catalysts that improved heavy-duty membrane electrode assembly performance (after a 90,000-cycle accelerated stress test) by over 45% compared with the commercial baseline. (Million Mile Fuel Cell Truck [M2FCT])
- ✓ Developed electrode structures with a grooved electrode design enabling up to 50% higher power density than flat electrodes with the same materials, especially under the dry conditions needed for heavy-duty vehicles. (M2FCT)
- ✓ Improved a PGM-free cathode's initial fuel cell performance by ~60% in H_2-air compared with the FY 2021 baseline. (ElectroCat)
- ✓ Established a near-term (2027) manufacturing capacity target for heavy-duty fuel cells of 20,000 stacks per year in a single production line, while still aiming toward the 2030 DOE targets for cost, durability, and efficiency.
- ✓ Transitioned fuel cell technology from Los Alamos National Laboratory (LANL) and Brookhaven National Laboratory to the private sector through the L'Innovator™ Program, with \$2 million in DOE funding, helping Advent Technologies secure ~\$160 million of private investment and enabling a fuel cell manufacturing and R&D facility in Boston, Massachusetts.

Table 3. Selected Examples of HFTO Progress and Accomplishments – 2023 (cont.)

- ✓ Promoted DEIA by partnering with LANL and MSIs to support hydrogen and fuel cell workforce development, providing opportunities to over 100 MSI students to pursue advanced degrees and enter the hydrogen and fuel cell workforce.

Systems Development and Integration

- ✓ Launched a 10-MW high-temperature electrolyte testing and validation facility at Idaho National Laboratory (INL). This test bed will provide industry with the ability to pilot-test commercial-scale electrolyzers with full balance of plant.
- ✓ Demonstrated the nation's first integrated, behind-the-meter electrolyzer installation at a nuclear power plant, at the Nine Mile Point nuclear power plant in Oswego, New York. (Constellation Energy Generation, funded by HFTO and in collaboration with NE)
- ✓ Completed installation and initiated commissioning of the integrated 1.25-MW electrolyzer and 1-MW fuel cell systems at the NREL Flatirons Campus to support Advanced Research on Integrated Energy Systems. (NREL-ARIES)
- ✓ In collaboration with NE, initiated front-end engineering design studies of full thermal integration of high-temperature electrolyzers at multiple light water reactor nuclear plants. (Westinghouse)
- ✓ Demonstrated 15 fuel cell hybrid electric medium-duty UPS delivery trucks operating in disadvantaged communities in Ontario, California. (Center for Transportation and the Environment)
- ✓ Completed design, fabrication, commissioning, and testing of the "H2Rescue" Class 7 disaster relief truck, which can provide power (72 hours of export power up to 25 kW), water, and a communications base during natural disasters. (U.S. Departments of Defense and Homeland Security, Cummins)
- ✓ Initiated an I-10 (Los Angeles to Houston) heavy-duty hydrogen fueling corridor study in collaboration with the EERE Vehicle Technologies Office. (GTI Energy)
- ✓ Designed and built an advanced hydrogen mobile fueler and demonstrated the refueling of hydrogen buses at the Foothills Transit facility in Pomona, California. The fueler has the capacity to support small fleets of medium- and heavy-duty vehicles. (Electricore and Air Liquide)
- ✓ Developed a reference design and techno-economic analysis for direct-coupled wind/solar to hydrogen to industrial end use, such as steel and ammonia. (NREL)
- ✓ Demonstrated 1 tonne/week direct reduction of iron with hydrogen, enabling >90% emissions reduction compared with traditional processes. (Missouri University of Science and Technology)

Analysis, Codes and Standards

Systems Analysis

- ✓ Launched H2A Lite, a user-friendly tool to characterize the cost of eight different methods of hydrogen production, given user-defined assumptions.
- ✓ Published a third white paper from the IPHE Hydrogen Production Analysis Task Force, describing best practices to characterize emissions associated with hydrogen delivery.
- ✓ Contributed to the Annual Technology Baseline for Transportation, which now includes medium- and heavy-duty vehicles and contains information on the cost and emissions associated with dozens of different powertrain and fuel pathways.
- ✓ Launched an interagency agreement with the National Oceanic and Atmospheric Administration to conduct R&D and modeling to improve estimates of the indirect global warming potential of hydrogen.

Safety, Codes and Standards

- ✓ Developed a technical basis for fatigue design curves for pipeline steels, providing simple relationships that reduce the testing burden for hydrogen pipelines.
- ✓ Provided the technical justification for revised LH2 storage setback distances in NFPA 2 (National Fire Protection Association Hydrogen Technologies Code).
- ✓ Recognized 20 years of the Hydrogen Safety Panel's contribution to the safe deployment of hydrogen technologies, including over 600 safety reviews of over 400 projects.
- ✓ Met DOE and industry target metrics for high-flow heavy-duty fueling (<10-minute fill time).

Workforce Development and Diversity, Equity, Inclusion, and Accessibility

- ✓ Supported Dean Kamen's FIRST Global Hydrogen Horizons competition, to promote STEM convening students across 190 countries.
- ✓ Developed documents addressing common concerns and frequently asked questions about hydrogen.
- ✓ Required the submission of DEIA or community benefits plans in FOA applications and developed training resources for special purposes reviewers for the FOA merit review process.
- ✓ Held several H2IQ Hour Webinars focused on environmental and community-related issues, including workforce development and careers in hydrogen; various emissions and how to address them; and projects in disadvantaged communities.
- ✓ Reviewed the hydrogen component in the Energy Industry Foundation's online training course by Julius Education and the Center for Energy Workforce Development.
- ✓ Continued outreach and engagement with Tribes, including attending the Reservation Economic Summit; discussing workforce development across various technology areas with the Alliance for Tribal Clean Energy; and attending the DOE Office of Indian Energy's program review in November 2022.

Office of Clean Energy Demonstrations

The Office of Clean Energy Demonstrations (OCED) has committed $8 billion toward hydrogen activities, within the Office's $25 billion portfolio of clean energy programs. Up to $7 billion of those funds are allocated to the H2Hubs, which were selected on October 13, 2023. The selections included seven hubs, spanning much of the country: Appalachia (Ohio, Pennsylvania, and West Virginia), California, Gulf Coast (Texas), Heartland (North Dakota, South Dakota, and Minnesota), Mid-Atlantic (Delaware, New Jersey, and Pennsylvania), Midwest (Illinois, Indiana, and Michigan), and Pacific Northwest (Montana, Oregon, and Washington). The H2Hubs will form the foundation of a national clean hydrogen network that contributes to decarbonizing multiple sectors of the economy, including heavy industry, chemicals, and heavy-duty vehicles.

OCED also allocated $1 billion to kick-start a demand-side initiative to accelerate commercial liftoff of the clean hydrogen economy. In June 2023, DOE solicited a request for proposals to identify an independent entity to administer the initiative. This entity will work directly with the H2Hubs awardees and incorporate their input to structure the program and ensure regional differences and needs are considered. The purpose of the program is to ensure H2Hubs have the market certainty they need during the early years of production to unlock private investment and realize the full potential of clean hydrogen.

Office of Fossil Energy and Carbon Management

In FY 2023, funding for hydrogen in FECM's **Office of Resource Sustainability** was $26 million. The Office's hydrogen focus areas were:

- Developing and exploring new catalysts and processes that can enable transformational concepts for clean hydrogen production.
- Working to ensure the suitability of existing natural gas pipelines and infrastructure for the safe, resilient, and efficient transportation of hydrogen at scale.
- Exploring low-cost, reliable, and safe options for bulk underground hydrogen storage.

In FY 2023, hydrogen-focused funding in FECM's **Office of Carbon Management** was $113 million. The Office's hydrogen efforts focused on low-cost, carbon-neutral hydrogen production and utilization technologies, including:

- Turbines
- Various production pathways, including gasification, reforming/pyrolysis, and reversible solid oxide fuel cells
- Point-source carbon capture
- Carbon transport and storage.

Table 4 shows selected examples of FECM's 2023 RDD&D progress and accomplishments.

Table 4. Selected Examples of FECM 2023 Progress and Accomplishments

Office of Resource Sustainability

- ✓ Assessed the compatibility of natural gas pipeline materials with hydrogen and other gases.
- ✓ Determined the hydrogen storage potential in existing domestic underground natural gas storage facilities.
- ✓ Conducted market assessments for liquid organic hydrogen carriers.
- ✓ Investigated the underground storage of hydrogen and natural gas mixtures by evaluating reservoir dynamics, engineering choices, and infrastructure challenges.
- ✓ Executed a funding opportunity—"Clean Hydrogen Production, Storage, Transport and Utilization to Enable a Net-Zero Carbon Economy"—and selected twelve projects across three areas of interest.

Office of Carbon Management

- ✓ Applied hydrogen combustion fundamentals, pilot testing, and analysis tools to enable low-NO_x hydrogen combustor designs and zero-carbon, dispatchable power generation.
- ✓ Investigated ammonia combustion fundamentals and analysis tools to enable low-NO_x ammonia combustor designs.
- ✓ Developed ceramic matrix composite materials and manufacturing methods to increase the temperature capability of gas turbine hot-gas-path components for use in hydrogen turbines and to improve turbine efficiency.
- ✓ Completed a front-end engineering design study for a clean hydrogen production facility, which will gasify waste coal, biomass, and plastic feedstocks.
- ✓ Continued development of several pre-combustion CO_2/H_2 separation technologies at small pilot scale.
- ✓ Completed a front-end engineering design study of a pre-combustion carbon capture system on an autothermal reforming plant.
- ✓ Continued development of reversible solid oxide fuel cell technologies to produce either hydrogen or electricity, depending on grid demand.
- ✓ Released a report, "Hydrogen Shot Technology Assessment: Thermal Conversion Approaches," which presents a snapshot of various thermal conversion pathways for clean hydrogen production, including technology status and approaches for achieving the Hydrogen Shot goal through RD&D advances.
- ✓ Issued a funding opportunity: Clean Hydrogen Production, Storage, Transport and Utilization to Enable a Net-Zero Carbon Economy.

Office of Nuclear Energy

In 2023, the Office of Nuclear Energy (NE) continued to focus on R&D activities to support the demonstration of hydrogen production applications for the existing nuclear fleet and advanced reactors. These activities are conducted under the NE Light Water Reactor Sustainability Program and the NE Integrated Energy Systems Program. Table 5 shows selected examples of NE's 2023 progress and accomplishments.

Table 5. Selected Examples of NE 2023 Progress and Accomplishments

Projects in Collaboration with HFTO

- ✓ Demonstrated the first direct nuclear-to-hydrogen production in the United States, using a commercially provided low-temperature electrolysis module to at the Nine Mile Point Nuclear Power Plant in upstate New York.
- ✓ Completed site preparations and installation of a new power supply transformer, switch gear, and power relays to tie the Davis–Besse Nuclear Power Plant switchyard to electrolysis units placed near the power plant.
- ✓ Completed the engineering work necessary to operate a high-temperature electrolysis (HTE) module at the Prairie Island Nuclear Power Plant to draw extraction steam from the turbine deck to indirectly generate pure steam for a commercial MWe-scale HTE module.
- ✓ Conducted over 5,000 hours of testing operations with Bloom Energy's first modular prototype HTE systems; testing included a sequence of power management demonstrations—including rapid ramping of a test module—on systems that support reserve power supply to the grid from a nuclear power plant.
- ✓ Designed and built a 300 kWe HTE module to undergo long-duration performance and durability testing at INL.
- ✓ Filled an important gap in proving HTE technology readiness by testing the electrical, thermal, water, and hydrogen connections to multiple HTE modules that are manifolded to produce 4–20 kg-H2/hour for use in the fleet of hydrogen fuel cell coaches in service at INL.
- ✓ Awarded a project to GE to test a co-electrolysis stack at the INL Energy Systems Laboratory for potential use of the syngas mixture of H2 and CO (produced by co-electrolysis) to produce fuels and chemicals.
- ✓ Awarded a project to Westinghouse Electric Company and INL to complete hydrogen production studies at nuclear power plants, including integrated cost estimates and techno-economic analyses, licensing impact assessments, grid interaction studies, and testing using commercial nuclear plant simulators.

Light Water Reactor Sustainability Program

- ✓ Conducted preliminary design and cost analysis of power and heat connections between existing nuclear power plants and large central hydrogen production plants.
- ✓ Tested human interfaces for integrated nuclear power plant and hydrogen plant operation using real operators in a control room environment.
- ✓ Continued the Hydrogen Regulatory Research and Review Group (H3RG) and safety analysis of hydrogen production close to nuclear power plant.
- ✓ Conducted cost analysis of integrating a nuclear plant with HTE, in support of efforts to reduce the cost of hydrogen production.
- ✓ Conducted technical analysis of an energy arbitrage option by comparing the costs and benefits of battery storage and thermal energy storage systems with hydrogen production, storage, and power generation in gas turbines or utility-scale fuel cells.
- ✓ Evaluated the business case for synthesizing transportation fuels using clean hydrogen produced at nuclear power plants.

Office of Science, Basic Energy Sciences

Since the 2022 AMR, Office of Science's hydrogen activities have continued to focus on fundamental chemical and materials science research to advance understanding of the underlying science and to identify and advance potentially transformative approaches for hydrogen production and use. These efforts include new projects that aim to make fundamental scientific advances that will help achieve the Hydrogen Shot. Recent accomplishments include the following:

- Achieved new insights into nickel–hydride photochemistry that enabled photoelectrocatalytic hydrogen evolution at 0 V overpotential. Demonstrating hydrogen evolution from a first-row photoelectrocatalyst opens new opportunities in solar fuel applications.
- Improved understanding of the oxygen reduction reaction (ORR) in iron- and nitrogen-doped graphitic (Fe-N-C) electrocatalysts by elucidating the role of water molecules in the process.
- Demonstrated how controlled manipulation of structures can be used to dramatically increase (by orders of magnitude) the efficiency of hydrogenation reactions. This was accomplished using a combination of simulations and precision synthesis of a palladium-containing intermetallic catalyst.
- Announced $264 million in funding for 29 projects to develop solutions for the scientific challenges underlying the Energy Earthshot Initiative. This funding will support 11 new Energy Earthshot Research Centers led by DOE national laboratories and 18 university research teams addressing one or more of the Energy Earthshots, including the Hydrogen Shot.

In August 2021, the Office of Science led the **Roundtable on Foundational Science for Carbon-Neutral Hydrogen Technologies**, in coordination with EERE, FECM, and NE.[xxxvi] The roundtable identified four high-priority basic science research opportunities that could enable a carbon-neutral, hydrogen-based energy and chemical infrastructure and provide the focus for the scientific efforts in Basic Energy Sciences.

Advanced Research Projects Agency–Energy

In FY 2023, ARPA-E funding for hydrogen-related activities was more than $5 million across all programs. 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. ARPA-E programs with projects relevant to hydrogen or related technologies include:

- Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH)[xxxvii]
- Duration Addition to electricitY Storage (DAYS)[xxxviii]
- Methane Pyrolysis Cohort
- Innovative Natural-gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-generation (INTEGRATE)[xxxix]
- Integration and Optimization of Novel Ion-Conducting Solids (IONICS)[xl]
- Renewable Energy to Fuels through Utilization of Energy-dense Liquids (REFUEL)[xli]
- Seeding Critical Advances for Leading Energy Technologies with Untapped Potential 2021 (SCALEUP 2021)[xlii]
- OPEN 2021.[xliii]

Introduction to the AMR Peer Review Process and Methodology

The AMR peer review process follows the guidelines in the *Peer Review Guide* developed by EERE. Project reviewers provide comments about selected HFTO-funded projects presented during the event. (Note that not all ongoing HFTO-funded projects were reviewed; Appendix D provides a list of projects that were presented but not reviewed.) Panel members include experts from a variety of backgrounds related to hydrogen and fuel cells. As shown in Table 6, this year, 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 selection of 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 6. Peer Review Panel: Represented Organizations

3M Company	Northeastern University
Advent Technologies, Inc.	Nuvera Fuel Cells, LLC
Air Liquide	Oak Ridge National Laboratory
Air Products and Chemicals, Inc.	Origis Energy
Argonne National Laboratory	Orlando Utilities Commission
Arizona Public Service	OxEon Energy, LLC
AVL Fuel Cell Canada	Pacific Northwest National Laboratory
Ballard Power Systems	Patturns

Battelle Memorial Institute	The Pennsylvania State University
Booz Allen Hamilton	pH Matter LLC
Bosch Research and Technology Center	Plug Power Inc.
Boston Government Services, LLC	Rutgers University
California Air Resources Board	Savannah River National Laboratory
California Hydrogen Business Council	Schaeffler Group USA Inc.
Columbia University	Secat, Inc.
Cryo H2 LLC	Shell Global
CSA Group	Southern Company
Cummins Inc.	Stottler Development LLC
Drexel University	Strategic Analysis, Inc.
Ed Green Engineering	T2M Global
Envision Energy USA	Tedeschi Consulting Solutions, LLC
Exxon Mobil Corporation	Toyota Motor North America
Ford Motor Company	UL Solutions
Forvia Faurecia Hydrogen Solutions	University of Arizona
Fuel Cell and Hydrogen Energy Association	University of California, Berkeley
General Motors Company	University of California, Irvine
Georgia Institute of Technology	University of California, San Diego
GTI Energy	University of Colorado Boulder
Hydrogen Safety Panel	University of Dayton Research Institute
HynErgy GmbH	University of Hawaii
Hyrax Intercontinental LLC	University of Illinois Urbana-Champaign
Hyzon Motors	University of Maryland
International Partnership for Hydrogen and Fuel Cells in the Economy	University of Michigan
Ion Power	University of New Mexico
Johns Hopkins University	University of Pittsburgh
Johnson Matthey plc	University of South Carolina
Kansas State University	University of Virginia
Largo Clean Energy	U.S. Army Corps of Engineers
Lawrence Berkeley National Laboratory	U.S. Army Ground Vehicle Systems Center
Lawrence Livermore National Laboratory	U.S. Department of Energy
Linde plc	U.S. Department of Transportation
Los Alamos National Laboratory	U.S. Naval Research Laboratory
NASA White Sands Test Facility	Versogen
National Renewable Energy Laboratory	Victoria University of Wellington
Natural Resources Defense Council	Washington State University
Nel Hydrogen	West Virginia University
Nexceris, LLC	Zero Carbon Energy Solutions, Inc.
Nikola Corporation	

Analysis Methodology

At this year's AMR, 107 HFTO-funded projects were reviewed. A total of 132 review panel members participated in the AMR process, providing 491 project evaluations.

The projects were evaluated using pre-established criteria. Reviewers were asked to provide numeric scores for five aspects of the work presented (scores were on a scale of 1–4, including half-point intervals, with 4 being the highest). For all projects, reviewers were also asked to provide qualitative comments regarding the five criteria, including 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 most 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 those 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: Potential impact on Hydrogen Program goals and 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 criteria. 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 with 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 – 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 (30%)
- Score 3: Collaboration effectiveness with HydroGEN and, if applicable, other research entities (25%)
- Score 4: Potential impact – the degree to which the project supports and advances progress toward the DOE Hydrogen Program goals and objectives, and also supports and advances the HydroGEN Consortium mission (15%)
- Score 5: Proposed future work (10%)

The 2023 AMR also included one recently awarded project that was placed in a separate scoring panel with modified scoring criteria and weights. The scores for this new project 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 project, reviewers were given the option not to evaluate Score 2 (Accomplishments). In cases where a reviewer exercised this option, the other criteria were re-weighted to total 100%.

Each individual project report includes a comparison of how that project aligns with all the other projects in its subprogram or activity area. Projects are compared based on the consistent set of criteria described above. To enable these comparisons, average scores were calculated across all the projects in each of the following panels: Hydrogen Delivery and Infrastructure, Hydrogen Storage, Production Technologies, Production–HydroGEN Seedling, Fuel Cell Technologies, and Systems Development and Integration. Scores for the two Analysis, Codes and Standards panels—Systems Analysis and Safety, Codes and Standards—were combined.

Each project report includes a chart showing these comparisons. The chart includes bars representing that project's average scores for each of the five relevant criteria. The gray vertical hash marks that overlay the blue bars represent the corresponding maximum, average, and minimum scores for all the projects in the same subprogram or category. A sample graph is provided in Figure 4.

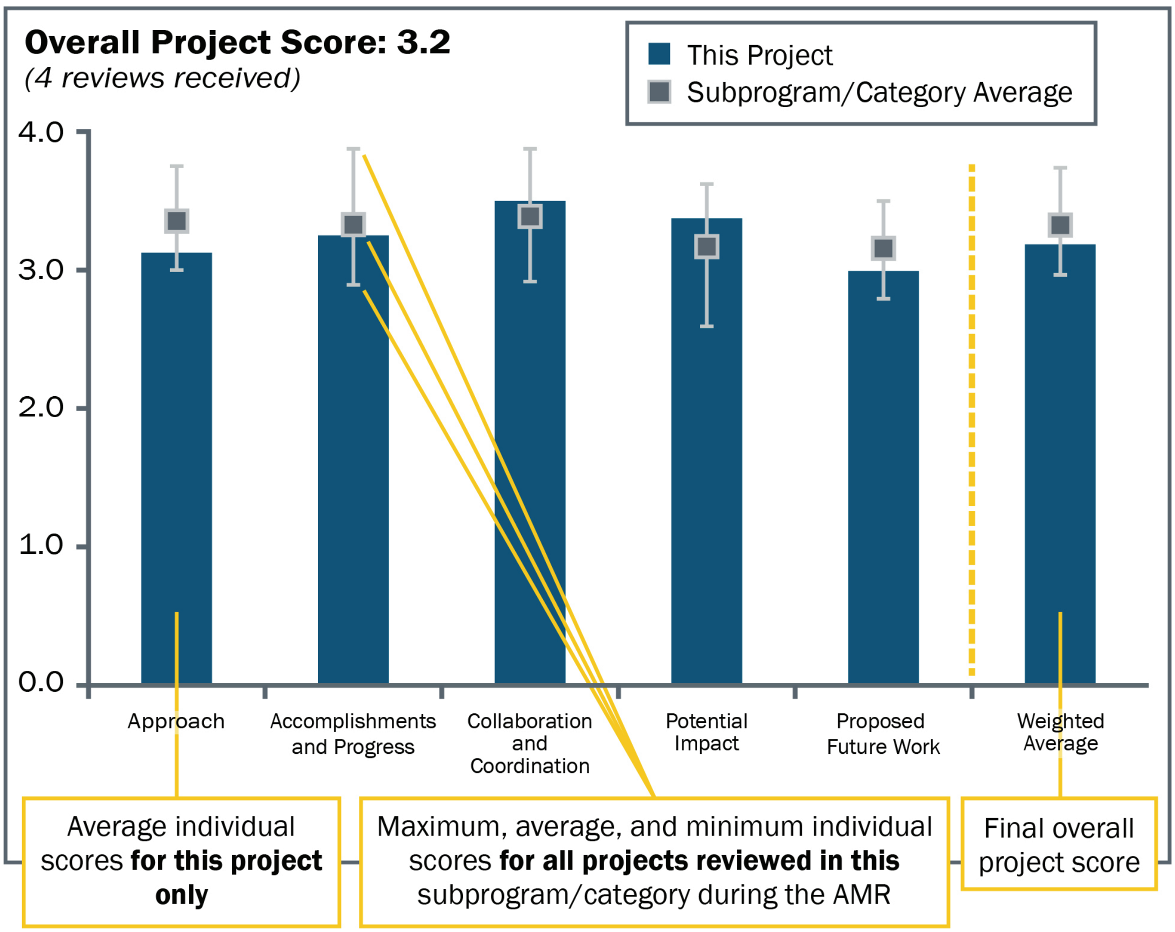

Figure 4. Sample project score graph with explanation

For clarification, Table 7 illustrates a hypothetical review in which five projects in a subprogram were presented and reviewed. Table 7 displays the average scores for each of these hypothetical projects, according to the five criteria.

Table 7. Sample Project Scores

	Approach (20%)	Accomplishments (35%)	Collaboration and Coordination (10%)	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 7. 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 7) 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

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Hydrogen Production Technologies – 2023

Hydrogen Production Technologies Subprogram Overview

Introduction

The Hydrogen Production Technologies subprogram funds research, development, and demonstration (RD&D) to reduce the cost and improve the efficiency and reliability of technologies used to produce hydrogen from diverse renewable domestic feedstocks and energy resources. Activities of this subprogram support the Hydrogen Energy Earthshot (Hydrogen Shot) goal of $1 for one kilogram of clean hydrogen in one decade and align with the *U.S. National Clean Hydrogen Strategy and Roadmap*. The subprogram also incentivizes the development of innovative off-roadmap technologies with potential to meet the Hydrogen Shot goal through the American-Made H-Prize: Hydrogen Shot Incubator, also known as the Hydrogen Shot Incubator Prize.

One RD&D focus of the Hydrogen Production Technologies subprogram is water splitting through low- and high-temperature electrolysis using renewable energy resources. The Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law [BIL]) includes a provision for clean, low-carbon hydrogen production from water electrolysis. Since the enactment of the BIL, all electrolysis activities have been funded through procurements authorized under the BIL, including both the Sect. 816 Clean Hydrogen Electrolysis Program and Sect. 815 Clean Hydrogen Manufacturing and Recycling Program. Electrolysis RD&D has been coordinated primarily through activities with the Hydrogen from Next-generation Electrolyzers of Water (H2NEW), HydroGEN Advanced Water Splitting Materials (HydroGEN), and Electrocatalysis (ElectroCat) consortia.

In support of the H2@Scale initiative, the Hydrogen Production Technologies subprogram also continues to fund non-electrolysis technologies at lower technology readiness levels (TRLs) through the subprogram's annual appropriations. These advanced hydrogen production pathways include direct solar water-splitting processes, such as photoelectrochemical (PEC) and solar thermochemical (STCH), as well as biological processes that can convert biomass or waste streams into hydrogen.

Goals

The Hydrogen Production Technologies subprogram aims to develop clean, low-carbon hydrogen production technologies. Specific subprogram objectives include the following:

- Develop and validate low-cost, sustainable, and low-carbon hydrogen production technologies with the potential to meet an intermediate hydrogen production cost target of \$2/kg H_2 by 2026 and the Hydrogen Shot target of \$1/kg H_2 by 2031.
- Develop new, low-cost materials and components to improve performance and durability of hydrogen production technologies, including high- and low- temperature electrolysis and lower-TRL approaches such as PEC and STCH hydrogen production.

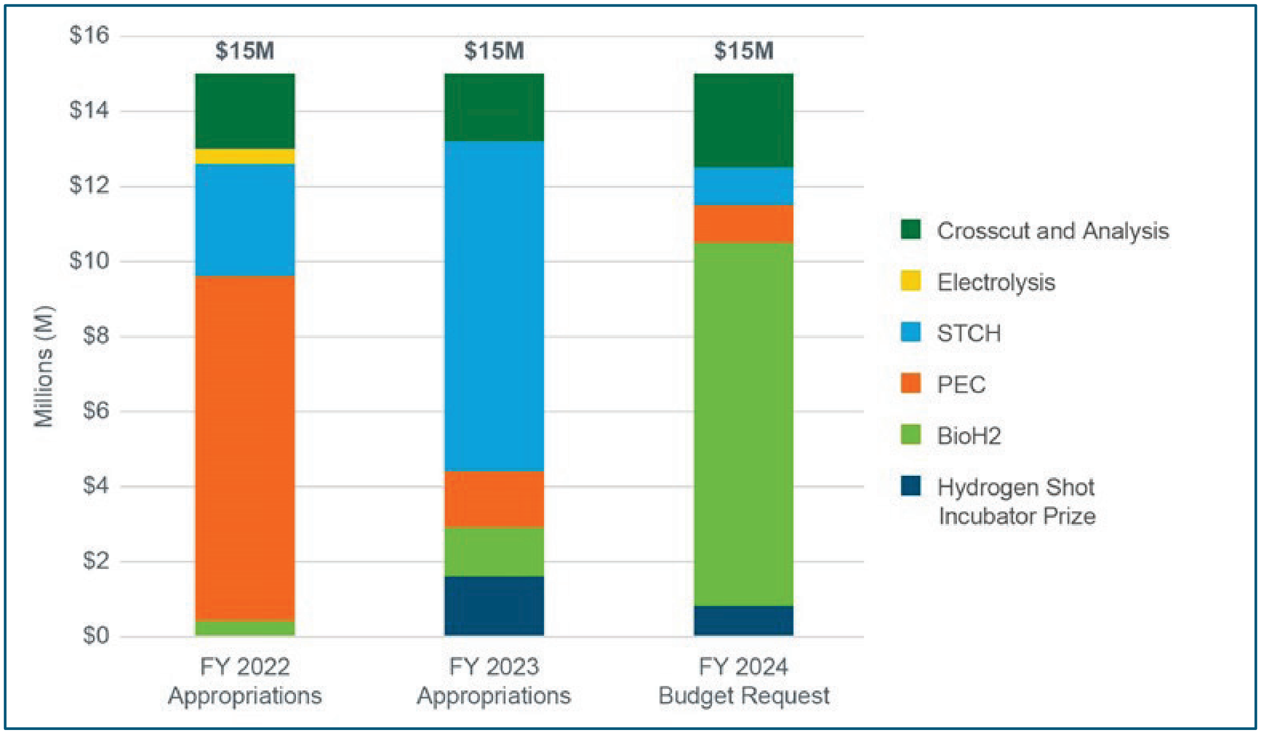
Key Milestones

The Hydrogen Production Technologies subprogram has established the following key milestones:

- Develop clean hydrogen production technologies able to meet cost targets of \$2/kg H_2 by 2026 and \$1/kg H_2 by 2031.
- Develop proton exchange membrane electrolyzer technologies able to meet stack targets of \$100/kW at 3 A/cm^2 and 1.8 V with an 80,000-hour lifetime by 2026.
- Develop high-temperature electrolyzer technologies able to meet stack targets of \$125/kW at 1.2 A/cm^2 and 1.28 V with a 40,000-hour lifetime by 2026.

Budget

The Fiscal Year (FY) 2023 appropriation for the Hydrogen Production Technologies subprogram was $15 million, which covers all non-electrolysis work, with an emphasis on advanced pathways. All electrolysis work is supported under the BIL Sect. 816 Clean Hydrogen Electrolysis Program and Sect. 815 Clean Hydrogen Manufacturing and Recycling Program, which, in total, provide more than $200 million/year.



The $15 million received for each FY 2022 and FY 2023 supported direct solar water-splitting research, including work toward advancing PEC and STCH durability and efficiency; biological hydrogen production using microbial processes (BioH2); and hydrogen production cost analysis. Funding also supported the Hydrogen Shot Incubator Prize to incentivize development of innovative off-roadmap technologies with the potential to produce clean hydrogen at $1/kg in one decade. The FY 2024 request is $15 million to continue research and development (R&D) in advanced pathways for hydrogen production.

In FY 2024, the BIL (Sect. 816, in particular, and provisions in Sect. 815) will fund a range of electrolysis activities to improve efficiency, increase durability, and reduce the cost of producing clean hydrogen using electrolyzers to less than $2/kg by 2026. Emphasis will be on efforts to improve and develop new materials and components, as well as to advance manufacturing technologies to get to economies of scale for electrolyzer manufacturing. BIL Sect. 816 funding will continue to support national-lab-led consortia (H2NEW, HydroGEN, and ElectroCat) focused on electrolysis R&D, as well as efforts to develop megawatt-scale electrolyzer test and validation facilities. BIL Sect. 815 funding will support—for both electrolyzers and fuel cells—establishing a recovery and recycling consortium and a national-lab-led consortium focused on roll-to-roll manufacturing.

Annual Merit Review Results

During the 2023 Annual Merit Review, 43 projects funded by the Hydrogen Production Technologies subprogram were presented, and 17 were reviewed, including 4 HydroGEN Seedling projects (a breakdown by budget category is shown on the right). The 4 HydroGEN Seedling projects received scores ranging from 2.9 to 3.2, with an average score of 3.0. The other 13 reviewed projects received scores ranging from 3.0 to 3.7, with an average score of 3.2. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Number of Projects Reviewed by Budget Category	
BioH2	4
PEC	3
STCH	1
Electrolysis	5
Crosscut and Analysis	4

Following are reports for the 17 reviewed projects. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

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

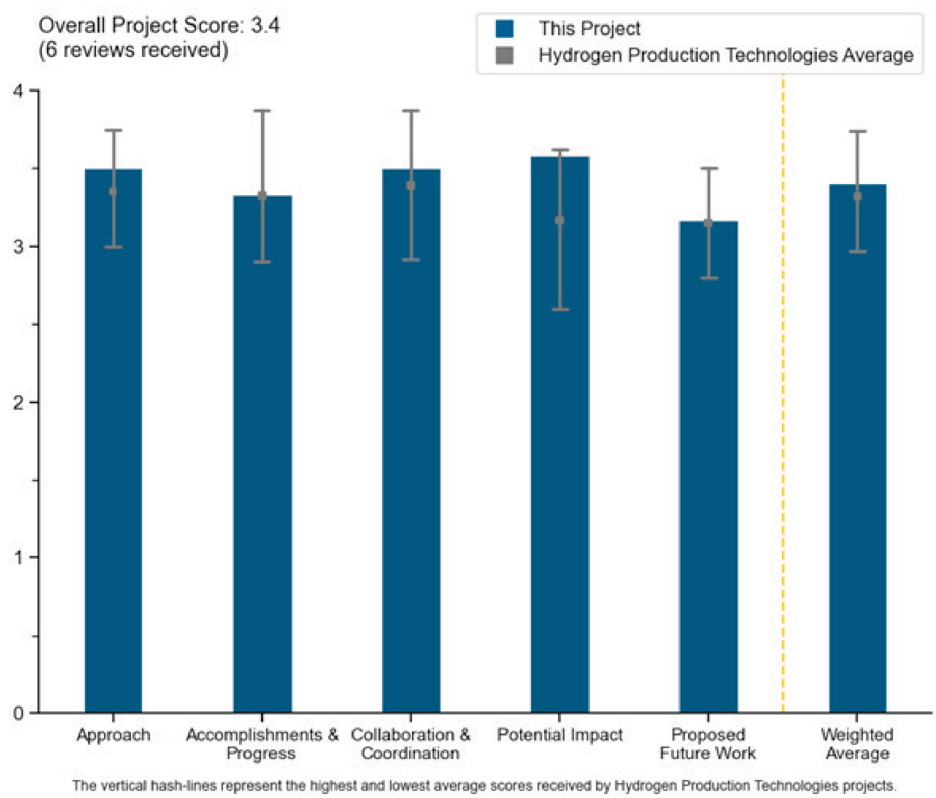
Huyen Dinh, National Renewable Energy Laboratory

DOE Contract #	WBS 2.7.0.518 (HydroGEN 2.0) and 2.7.0.513 (Node Support)
Start and End Dates	6/1/2016
Partners/Collaborators	Lawrence Berkeley National Laboratory, Sandia National Laboratories, Idaho National Laboratory, Lawrence Livermore National Laboratory
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 technology pathways supported by HydroGEN include photoelectrochemical (PEC), solar thermochemical (STCH), low-temperature electrolysis (LTE), and 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 technologies.

Project Scoring



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 idea to have a foundational "home" for national laboratories to work on water-splitting technologies is excellent, with constancy of purpose and breadth of scope. This nurtures capabilities and relationships and provides stability for data-sharing (Data Hub). The focus on standards development and benchmarking is fantastic to see, and the team is encouraged to consider how to do more of this.
- The project has very good collaboration and inclusion of both national laboratories and industry shown in its approach. The approach shows clear separation of problems to address for each of the hydrogen technology areas.
- The overall design and approach to consortium operation is excellent, promoting information exchange, collaborative efforts with national laboratories and industry, and development and dissemination of best practices/protocols that help to elevate the entire R&D community.
- As a portfolio rather than a specific project, it is a little more difficult to assign specific performance metrics. Also, because of the maturity of the technologies (which by definition are low technology readiness levels [TRLs]), there is clearly a long way to go to achieve the $1/kg cost target. However, given that this is an aspirational target requiring unrealistically cheap electricity (~1.2 c/kWh) for the reference electrolysis pathway, there should be reluctance to require individual projects to show a path to $1/kg. However, it would make sense to determine what is realistically possible without the current pressure to meet an unrealistic target with what are likely unachievable cost estimates (e.g., $25/m^2 for PEC cells when the glass alone is probably this cost). Overarching barriers are well identified (cost, efficiency, and durability), but—without killing off potentially useful research avenues—some higher-level metrics could help focus on the barriers. The techno-economic analysis (TEA) seems to be used a little inconsistently in the seedlings (though only the PEC seedlings were reviewed). Slide 12 pulls together the challenges nicely—without, however, specifying actual performance metrics.
- The project combines four hydrogen production technologies—low-temperature water electrolysis (LTWE), high-temperature water electrolysis (HTWE), STCH, and PEC—that are very expensive. The Data Hub is beneficial for the green hydrogen production community. Roadmaps and deliverables for each technology need to be clearly defined. Some work, such as the Chemours project and HTWE, overlaps with the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) scope of work.
- It is unclear how the new STCH materials investigated perform compared to the state-of-the-art materials and what critical factors determined the hydrogen production rate. Proton-conducting solid oxide electrolysis cell (P-SOEC) Faraday efficiency should increase with current density (slide 29). Metal-supported SOEC should address Cr poisoning under high steam conditions, and the operating temperature of 700°C seems too high for metal support.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The consortium, including a couple of complementary programs and endeavors spanning many stakeholders and projects, has been successfully rolled out. The presentation highlighted key technical progress results from various projects across the four different low-TRL hydrogen production technologies directly supported through the consortium. Highlights of note include the following:
  - Regarding STCH, the project established high-throughput computational-driven discovery of the materials framework; this was used to synthesize >10 identified compounds of interest and validate two of these, setting the stage.
  - Regarding HTE, impressive performance and progress is reported for the H+ conducting intermediate-temperature electrolyzers.
  - Regarding PEC, the project has made significant progress in terms of demonstrating high solar-to-hydrogen (>17%), durability, as well as prototyping that represents a notable step forward in terms of TRL for this class of technology.
- Overall, most projects have made good progress. LTWE and HTWE projects have progressed very well. Idaho National Laboratory (INL) shows performance of 1.51 V at 6 A/cm^2 at 600°C (published in Nature), which is very impressive. Chemours thin proton exchange membranes (PEMs) with low hydrogen crossover is encouraging. The anion exchange membrane water electrolyzer (AEMWE) project achieved less than 2.0 V at 3 A/cm^2. STCH projects have made good progress on the new materials selection.

Durability for most projects was not sufficient. There was only about 200-hour durability for INL's project. For the AEMWE project, the durability data varied from 15 hours to 10 days. For STCH technology, a device assembly and testing data are recommended.

- A tremendous amount of technical progress has been made by the many projects. It is hard to absorb it all in a presentation this broad and dense, frankly. As for the HydroGEN effort itself, at the next Annual Merit Review (AMR), perhaps the team could break out metrics for the HydroGEN Consortium by year (for example, how many publications, workshops, non-disclosure agreements, etc. there were in the past year).
- The decent number of high-impact publications indicates some good science is being done. Not all projects have a clear path to DOE goals, but given the low TRL, it could be argued that if appropriate performance metrics supported by TEA are in place, then HydroGEN represents a valuable chance to build up human capacity through students and perhaps make an important or serendipitous discovery. That said, supported projects probably need to have a least some chance of making it to implementation, which is a struggle for PEC.
- Progress toward the $1/kg target for hydrogen has been demonstrated in all technology areas. The different technologies to produce hydrogen were presented in a way as to show the maturity of each. It might be useful to add a TRL number to each to track against future progress made.
- All subprograms are making good progress.

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.

- Benchmarking efforts, including establishing standard protocols accepted by the community, are invaluable across the various lower-TRL hydrogen-producing technologies. HydroGEN provides an effective framework for connecting university and industry researchers (at least those with funded projects) with national laboratory experts and resources. It appears that all or most projects involve close collaboration within the HydroGEN Energy Materials Network (EMN) framework, leveraging expertise and capabilities of national laboratory partners, as intended. It is great to see the demonstration of reproducible stability measurements for PEC devices across different laboratories.
- Most projects seem to be effectively leveraging the broad materials capabilities across the EMN network, which is a real strength of HydroGEN.
- It appears only one company (Chemours) is currently collaborating with HydroGEN. More industry engagement on the "HydroGEN 1.0" (i.e., EMN) side is encouraged. The project should be proactive and may need to show the industry how it can benefit. The Data Hub is a good vehicle for collaboration. It is nice that HydroGEN extended it to cover H2NEW. There is collaboration with similar European efforts, which is good.
- National laboratory and industry collaboration were presented as effective. The high volume of publications, workshops, and outreach for science, technology, engineering, and mathematics (STEM) were clearly shown as evidence of successful collaboration.
- There are strong collaborations between national laboratories and research institutions. More collaborations with industries are needed.
- Strong collaboration within laboratories and academia was observed.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- With the current potentially existential threat of per- and polyfluoroalkyl substance (PFAS) bans on current PEM technologies, there is a real need for alternatives. For STCH, it is becoming clear that finding stable yet active materials is very challenging, but there is still some life in perovskites, and the machine learning model developed is potentially significant for STCH and maybe other areas. For HTE, it is also useful to explore alternatives to current oxygen-conducting membranes to improve operating conditions and durability, given a lack of operational experience accumulated with SOECs. The LTE seedlings appear well directed. What is perhaps missing is fluorine-free ionomers. The PEC branch is the most challenging in terms of seeing a potential impact, as a realistic chance of success is hard to see.

- Critical work is being performed to address current technology limitations. The project has demonstrated progress made against these barriers and has evidence of progress made toward DOE hydrogen targets. The involvement of national laboratories and industry ensures areas of focus are valid and will serve to support broader penetration of these technologies into the commercial sector.
- Supporting knowledge-sharing, capability-building, and standards and protocols within the hydrogen production community across all low-TRL technologies can be expected to have a huge impact on accelerating the rate of development of these technologies. The Data Hub also has high potential for impact for the broader community, although it is unclear how big the impact is and can be. It is recommended that the project improve the ability to track data download and (if possible) information about who is downloading the data (industry vs. academic, U.S. vs. international, etc.) to better assess the success of this information-sharing vehicle.
- The national laboratories do great work on any problem they set their minds to, but the early-TRL nature of the projects in this portfolio creates the potential for misalignment with DOE objectives of accelerating deployment of low-cost, low-carbon hydrogen. Much project management is required, which seems to be there, but it is hard to know for sure. STEM workforce development is listed as an impact area; more needs to be said about this at the next AMR.
- The consortium fosters a strong collaboration to tackle the critical issues facing electrolysis for hydrogen technologies.
- The impact can be more significant if some breakthroughs can be made, which may lead to next-generation green hydrogen technology. Given that the consortium has existed since 2016, more progress is expected. There have been incremental improvements of the performance, but durability has not made a major breakthrough.

Question 5: Proposed future work

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

- Future work is structured to resolve open issues and continue progress toward technology challenges and barriers. Proposed future work aligns with technology needs for improvement.
- Each technology area outlined plans that seem reasonable, but the areas are too much and too detailed for the reviewer to provide a strong opinion.
- The proposed future work was not really articulated at the program level. Although individual areas talked about high-level goals (slides 22, 35, 45, 55), there was a distinct lack of numerical targets (admittedly, this is perhaps challenging across multiple seedling projects). A discussion of the overall strategy and what the coming research priorities look like would be preferred (more of a top-down view that considers whether the current project portfolio is adequate for what is really a rapidly developing industry).
- The future work is weak. It does not include clear technology development information. For example, the project should clarify the major technology focus and major technology barriers that need to be addressed.
- A focused research on degradation mechanisms is suggested.

Project strengths:

- The consortium successfully engages many stakeholders involved with advancing hydrogen production technologies across low- to medium-TRL scale. The consortium enhances interactions between national laboratory subject matter experts and university/industry researchers. The consortium has promoted best practices in benchmarking and testing protocols that greatly benefit the broader R&D community.
- This is a very strong team with expert experience in different hydrogen production technologies. The consortium is dedicated to developing next-generation hydrogen production technology. There has been good progress on HTWE and LTWE technologies. The Data Hub approach is beneficial to the researchers in this community.
- The project is a vehicle to unleash the tremendous capabilities of the national laboratories to significantly advance water-splitting science.

- A nice range of technologies is covered, with what appears to be effective collaboration, a feature of many projects. It is good to see that there is a decent allocation of funding to this strategic, forward-looking research.
- The project has a strong team and collaboration. Information and data collected are shared with the community to provide the current state of the technology available for other researchers.
- A consortium collaboration mechanism is a strength for the project.

Project weaknesses:

- It is hard to really get a feel for how HydroGEN, as a project, functions at the overall coordination level, as much of the discussion (with the exception of the cross-cutting work) was about the seedlings. It would be good to understand how TEA is informing the choice of performance metrics so that there is a clearer focus on the critical ones. The impression is that there is a certain inflexibility, or at least inertia, in the work program; so it would be interesting to better understand how agility could be brought to the portfolio and whether there should be an element of tactical, as opposed to strategic, work. The PFAS bans will need to be addressed, for instance, and the consortium could look for ways to support industry and/or use operational data to inform the work program.
- Some projects may be venturing into Basic Science land, which does not mean great work, but it probably should not be funded out of the Office of Energy Efficiency and Renewable Energy. Connecting projects to technical targets required for commercialization, or a technology roadmap, would dampen this impression. Otherwise, some discussion of how to think about science versus technology in this space would be useful.
- For the Data Hub, it is recommended that the project improve the ability to track data download and (if possible) information about who is downloading the data (industry versus academic, U.S. versus international, etc.) to better assess the success of this information-sharing vehicle.
- Most durability data was short, which limits the significance of project progress. The collaboration with the industries is not strong. There are no clear roadmaps and targets for each technology. Technology transfer needs to be well documented.
- Synergy across different subprograms such as HTE and STCH, which both involve high-temperature oxygen nonstoichiometric materials, may need encouragement.
- It was not clear how the data quality was being evaluated, prior to being uploaded to the Data Hub.

Recommendations for additions/deletions to project scope:

- Presumably, there was a TEA supporting the decisions made by HydroGEN around which technical areas to target and which projects to fund, but if not, there should be. The same can be said for technical targets. At the next AMR, it would be good to see more discussion of the “strategic planning” for HydroGEN and how it interacts with H2NEW. (The 2.0 seedling projects can present their own work.)
- The project should give greater emphasis on TEA/performance metrics, specifically avoiding the need to hit $1/kg, as this is a little unrealistic. A higher-level project portfolio analysis and awareness of looming issues or challenges are needed.
- It is recommended that the consortium strengthen its collaboration with industry to test the technologies under an industrial environment. Having a clear technology roadmap and targets in certain years is also recommended.
- In the future, the consortium can provide a year-to-year progress (since 2016) that would provide an overall outlook of the accomplishments. Focus should be given to long-durability testing.
- Degradation mechanisms studies should be planned.
- The project scope is appropriate.

Project #P-170: Benchmarking Advanced Water-Splitting Technologies: Best Practices in Materials Characterization

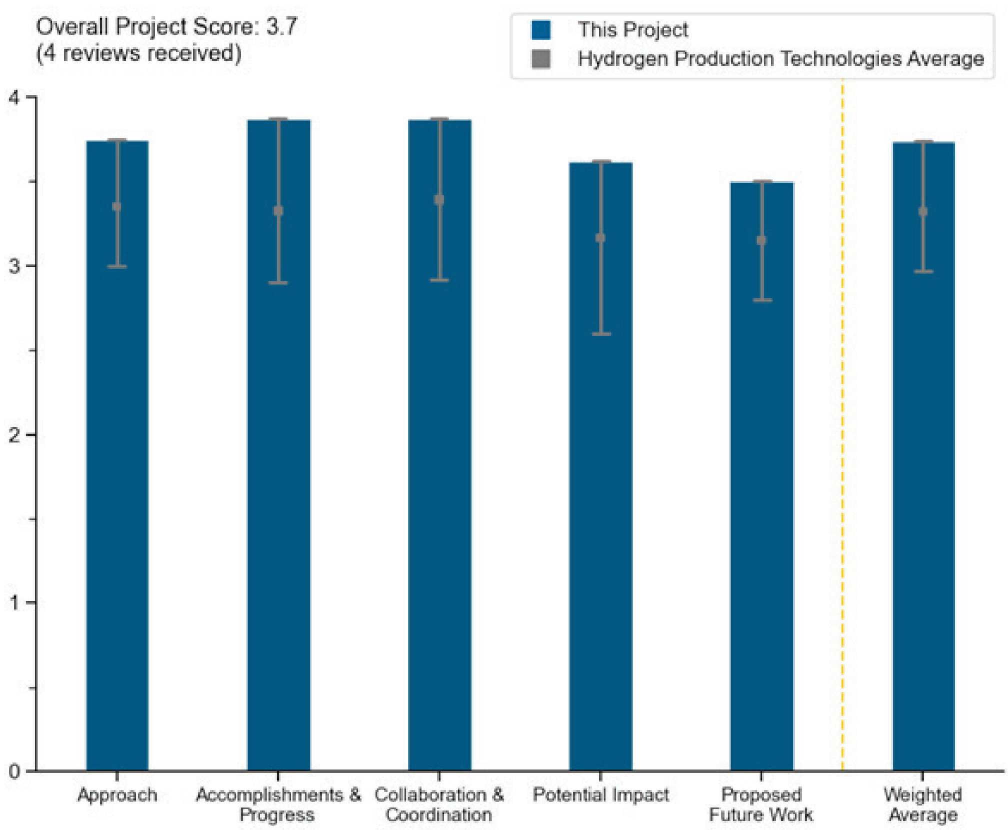
Olga Marina, Pacific Northwest National Laboratory

DOE Contract #	WBS 2.3.0.708
Start and End Dates	10/20/2021
Partners/Collaborators	Nel Hydrogen, Arizona State University, California Institute of Technology, H2 Technology Consulting LLC
Barriers Addressed	• Hydrogen generation by different technologies • Improve energy resilience and sustainability • Establish a universal system for benchmarking • Provide access to benchmarking results to community

Project Goal and Brief Summary

Making significant advances in advanced water-splitting technologies (AWST) requires the effective use of AWST research, development, and demonstration resources. To that end, this project will help establish a universal system for benchmarking. Researchers will develop and verify protocols for AWST validation testing and improvement within the categories of low-temperature electrolysis, high-temperature electrolysis, photoelectrochemical, and solar thermochemical hydrogen (STCH). This project will contribute to the strategic coordination of benchmarking in the water-splitting community and the advancement of test protocols.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production Technologies 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 to project objectives of developing benchmarks, developing protocols, and providing guidance to the various water-splitting communities has been exceptional. The workshops and other channels to engage the research community, DOE, and industry have been outstanding in their success in acquiring input from experts and practitioners. The general approach of developing well-defined benchmarks and protocols and how to deliver those to the community has been highly successful.
- The approach used to engage technical staff in developing standards is well-rounded. The project has scientists and engineers from several national laboratories and multiple universities and a few industrial participants.
- This is definitely a needed exercise to conduct. The approach of including multiple stakeholders is good.
- The project has an excellent approach to benchmarking. Slides 6, 7, and 8 give an excellent outline of the project approach and deliverables.

Question 2: Accomplishments and progress

This project was rated **3.9** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments and progress toward achieving the project goals have been outstanding. The team has made significant progress against all of the project milestones in a timely manner and contributed directly to achieving DOE goals to standardize the benchmarks and protocols for evaluating AWSTs. The development of so many protocols over so many different processes and water-splitting technologies is particularly impressive. The one area that seems to be slower than hoped, possibly because of specific challenges with defining good protocols and benchmarks, is the STCH AWST.
- Technical progress is represented by 55 Annual Merit Review (AMR) posters, 4 prior workshops, and 20 published protocols. There is strong engagement by the technical communities that receive funding from this project.
- Excellent progress has been made with this project. The project has completed 55 test protocols, with 35 identified for validation, and has published most of them in an open access journal.
- Progress is very good.

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 and coordination with other institutions, including international partners, has been outstanding. The team is broad and distributed over several institutions, which enables it to engage with a wide range of AWST stakeholders. The workshops bring together a large number of people from the AWST communities, which promotes collaboration, and also require close coordination and collaboration to organize them and make them successful. The published articles demonstrate significant collaboration across many institutions and researchers, including international partners. The establishment of protocols and benchmarks will also positively impact the ability of the AWST community to communicate and understand the accomplishments and challenges of each AWST research/development effort.
- Many academic and national laboratories have participated in the first four years, with some international participation with speakers from the German Democratic Republic, Switzerland, France, and Norway.
- The project has excellent coordination with DOE, national laboratories, academia, and industry. International coordination is unclear but appears to be happening also.
- The four partners have really identified an excellent list of collaborators to write the protocols on slide 14.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The potential impact of accomplishing the goals of this project is critical to the progress and development of AWSTs. Previous efforts have been hindered because of challenges with understanding the performance of different conditions, systems, materials, etc., but the results of this project have the ability to greatly reduce those barriers and improve progress in each AWST area.
- Once it concludes, the project will have huge implications in standardizing test protocols, especially as the industry is growing and welcoming newcomers. This will also allow existing participants in this field to have a fair way to compare performance and lifetime achievements.
- The project advances benchmarking and protocols, which is an important step in supporting the Hydrogen Program's goals and objectives.
- The project's technical impact aligns with DOE goals.

Question 5: Proposed future work

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

- The proposed future work is detailed and thoughtful and would add significantly to the success of this work. The one suggestion would be that the team should discuss how to increase the level of engagement with the community beyond what has previously been done or identify advanced testing protocols. For example, although the workshops have brought together various members of the AWST community, it could be expanded even further, for example, by creating sessions as relevant national meetings in which the community could provide results from their efforts framed by the protocols and benchmarks.
- The project has goals for future work similar to previous ones and is missing a vision for how this consortium will engage industry and government.
- The Fiscal Year 2023 Quarter 1 task is still listed as future work. It would be good to identify the sites to validate the protocols.
- Completion of the work with input from various organizations is planned.

Project strengths:

- The project is well organized, making excellent progress with outstanding results, and has exceptional collaboration/engagement with a high potential impact.
- The project's technical expertise is outstanding and well balanced across the major disciplines. AMR reporting and the annual workshops serve the role of external reporting.
- Prioritization and verification of protocols are the biggest strengths.
- The project has an excellent, dedicated team and is making very good progress.

Project weaknesses:

- This is more of a challenge than a weakness: there is a current lack of well-defined approaches to continually update protocols and benchmarks. The project mentions updating, but how updates will be made is not yet well defined.
- The project could clarify the frequency and mechanism for internal engagement among the consortium members (i.e., weekly, monthly, etc.). Perhaps the National Renewable Energy Laboratory Advanced Water Splitting Materials SharePoint is effective at this. It is cited in the AMR as the only other mechanism.
- While it is early, including new and emerging solid oxide electrolyzer technologies must be considered. The protocol should allow flexibility to expand the range of conditions to test that still give comparable data. This may emerge as the protocols are developed and validated for the current state-of-the-art technology.

- It will be hard to harmonize protocols across the world since each region will have its own sponsors and goals. Considering international input or validation would provide opportunities for harmonizing protocols.

Recommendations for additions/deletions to project scope

- It is unclear whether there is a mechanism for leadership turnover at the top level. This is essential to ensure technical innovation, engagement of external stakeholders (those not funded by this program), and fresh ideas from other informed stakeholders within DOE and academe. Engagement of industrial stakeholders is low or missing. It is unclear what outreach has taken place to bring in those stakeholders. It would be helpful to know whether there has been engagement from state governments, other than Colorado, and whether they see themselves as potential hosts for hydrogen technologies.
- More detail could be added about how to maintain a process for future protocol/benchmark updates. The team could describe how to continue to have community engage with the protocol and benchmark process, even after award end date, especially if this program no longer funds the workshops. This may already be implied in the proposed future work.
- Publications of protocols co-authored by international participants may make them stronger and acceptable worldwide.
- Progress is excellent. The team is encouraged to continue the good work.

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

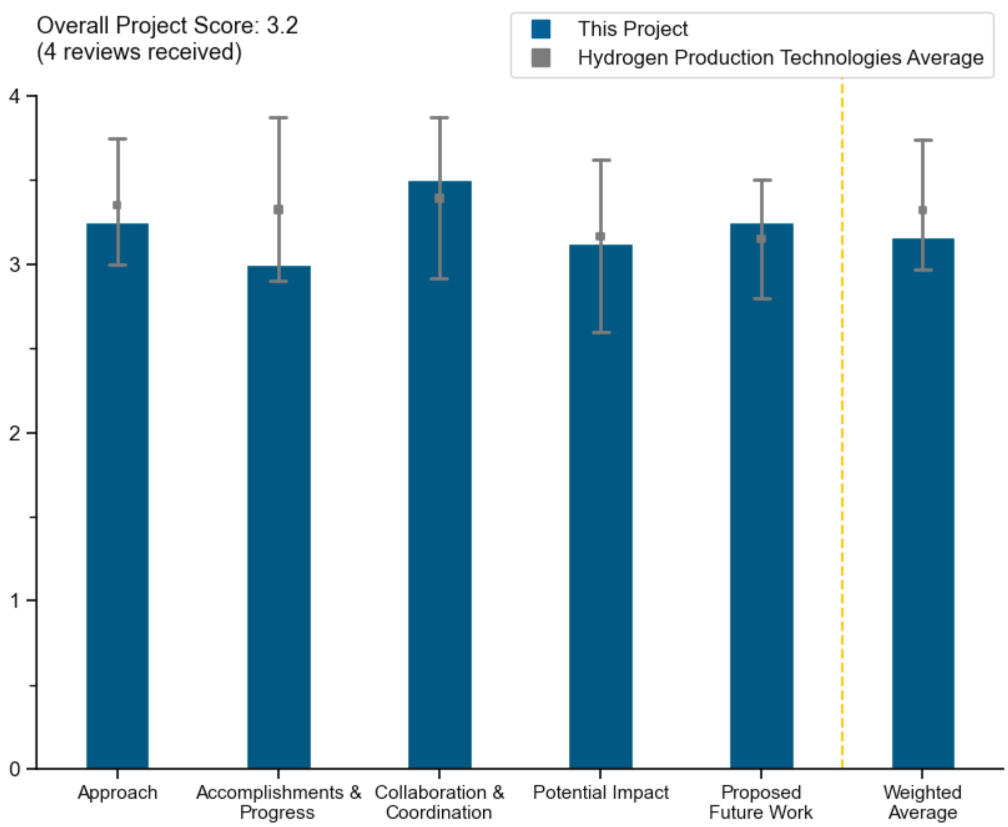
Katherine Chou, National Renewable Energy Laboratory

DOE Contract #	WBS 2.4.0.516
Start and End Dates	10/1/2018
Partners/Collaborators	Lawrence Berkeley National Laboratory, Argonne National Laboratory, Pacific Northwest National Laboratory
Barriers Addressed	• Capital cost • Feedstock cost • H_2 molar yield • System engineering

Project Goal and Brief Summary

The goal of the BioHydrogen Consortium is to develop a carbon-neutral microbial dark fermentation technology integrated with a microbial electrolysis cell (MEC) to convert waste lignocellulosic biomass into low-cost hydrogen. This collaborative team of national laboratory scientists aims (1) to 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) to optimize the bioreactor for high solids loading to reduce reactor cost, (3) to develop an integrated MEC system to improve hydrogen molar yield and reduce fermentation waste product, and (4) to conduct a technoeconomic analysis (TEA) and lifecycle analysis 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 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 has nice collaboration between multiple national laboratories in well-formulated tasks that cover the major technology areas for MEC-based conversion of lignocellulosic feeds (biology, reactor design, and electrochemistry). The sustained effort to address fundamental questions, with a track record of progress, is appreciated.
- The project comprises three parallel tasks for developing technologies for hydrogen production from waste lignocellulosic biomass and for conducting TEA for these technologies. The project stimulates collaboration between four national laboratories and groups developing different, but synergetic, technologies for hydrogen production. Task 1 improves biomass utilization to hydrogen production by employing enhanced pre-treatment and developing modified bacterial strains. Task 2 develops a bioreactor for a high yield of hydrogen under high-solids conditions. Task 3 develops an MEC for hydrogen production. The project needs to explain more clearly how the three technologies may be integrated or how each one is optimized for integration with the others, beyond just programmatic support. The issue of technology integration needs to be more clearly addressed in the next phases of the project.
- National Renewable Energy Laboratory (NREL) has developed a consortium with an effective approach to overcome the barriers of hydrogen production via a microbial pathway. The feedstock has been identified as costly. Perhaps more work can be completed to address feedstock, specifically approaches that eliminate the need to buffer feedstock.
- This is an interesting effort, with some significant progress toward scientific knowledge. Critical barriers have been identified and are addressed, but the progress toward the goal of hydrogen at a reasonable cost appears to have slowed. Based on the information presented, it is difficult to envision that the target of hydrogen cost on slide 14 by fermentation/MEC can be achieved, given the current status. This reviewer hopes to be proven wrong.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- Each task demonstrates significant accomplishments in the last year, showing significant improvement on the specific metric for each technology approach. TEA identified pathways for cost-reduction opportunities in the bio-hydrogen production route. Yet estimated cost of hydrogen production by these technologies remains significantly higher than even the older target of $2/kg, even after accounting for the projected improvements in the technology developments and for the hydrogen production tax credits. The project needs to analyze whether there are additional cost benefits, such as water removal, and particularly beneficial locations where the technology can be deployed that can help mitigate the higher cost of produced hydrogen.
- The NREL consortium is making good progress toward achieving the main objective of $2/kg. NREL could suggest the techno-economic framework for evaluating the levelized cost of hydrogen via the microbial process, as the levelized cost of hydrogen being calculated may not be consistent throughout all consortium members.
- The presentation, on slide 25, includes a table with quantitative metrics from 2021 Quarter 2 , not 2022, which is a problem. Some targets for 2022 and 2023 are mentioned throughout the presentation, but there is no summary table. From the material presented, additional progress has been achieved in 2022 (MEC current density and MEC total hydrogen production), but at least the former (40 A/m^2) is far from the numbers that are used in the TEA on slides 14 and 26. The TEA presented on slide 14 seems to show the current density and the electrode/material cost as the most significant components of the cost, while the impact of the work done in Tasks 1 and 2 is unclear. As a result, the fermentation process of milled corn stover (CS) versus unmilled CS versus deacetylated/mechanically refined (DMR) CS would affect the cost, or affect the productivity gains from the advanced engineered strains, and cannot be judged easily. Given the significant contribution of the MEC materials to the cost, more effort, such as another task, would be expected.
- The project continues to make advances in all four task areas.

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 provides for continuous ongoing close collaboration between teams in four national laboratories.
- NREL has great collaboration with all consortium members.
- Task leadership and required coordination among the tasks have been identified. However, the TEA work does not seem well connected with actual experimental information (see current activity assumed on slide 14). The TEA should reflect the current status based on the progress in the tasks and also guide the decisions on the path forward for the other tasks.
- The project has excellent collaboration at the national laboratory level, with what appears to be good leadership, but the project is limited by only national laboratory involvement.

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The developing technologies can provide a commercially viable pathway for production of low-cost hydrogen in decentralized, small-scale facilities in remote locations and in developing economies thorough monetizing non-food biomass and organic waste streams. These possible benefits need to be quantified in the TEA to help mitigate higher projected cost of hydrogen production.
- This project/consortium executes an interesting effort to utilize some biomass toward useful forms of energy, in this instance, by hydrogen obtained through the fermentation/MEC approach. The project could comment on how this pathway compares with alternative pathways that utilize biomass, such as gasification, pyrolysis, and even fermentation to ethanol. The TEA team has this information and could help provide the relative value of a successful project versus alternatives.
- Inherently, MEC will be a niche hydrogen production pathway, but this is the type of project DOE should fund if DOE wants to build the credibility and applicability of MEC routes to hydrogen.
- The NREL consortium has excellent alignment 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.

Question 5: Proposed future work

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

- The project team is aware of the challenges for each of the three experimental tasks on slide 17. The actions on slide 18 toward overcoming the barriers, though, are not always clear or consistent. For example, one can envision how the Task 1 team is planning to use strain engineering to maximize yield using identification of key remaining chemical bonds in biomass to break. In Task 2, though, it is not clear how the decline of conversion at higher solids will be addressed. The questions the project could answer involve the current solids/conversion, the target, the impact of the improvement on the cost, and how "optimization" of the reactor, other than impeller geometry, would help. Also, since nitrogen blanketing has been identified as an issue, the project could clarify how this will be addressed. Furthermore, mixing/solids loading will be affected by scale as it is known in processes with solids in liquids. The specific path/plan to study the impact is unclear. Similarly, clarification is needed on the ideas to be tested for Task 3 to improve conversion efficiencies and hydrogen molar yield on milled biomass effluent. What seems clearer is the need for characterization and testing of different biofilms, which could potentially lead to better MEC design and operation. The additional gaps that should be addressed in the path forward are how scale will affect the operations (both at fermentation through mixing and at the MEC step) and the lifetimes of the membranes and electrodes. From the TEA slide, it is clear that the cost of hydrogen is quite significant, so lifetime/frequency of replacement should be important. The TEA does not indicate the replacement rate assumed, and the future plan does not specify if/when/how this parameter will be evaluated.

- The project's proposed future work will continue the ongoing development and has presented a good continuation plan.
- The NREL consortium is planned in a logical manner. Some uniformity in approaches to TEA should be identified. The TEA will help compare funded projects as technologies mature.
- The project should be open to exploring developments being made in other MEC projects, such as new electrodes.

Project strengths:

- The project develops technologies that would provide pathways for utilization of low-cost lignocellulosic biomass or negative-cost organic wastes for hydrogen production. Development and commercialization of these technologies will allow decentralized hydrogen production through waste biomass utilization.
- The project conducts a comprehensive investigation, looking at the pathway in its totality. It appears that progress has been achieved in the three investigative tasks.
- The project has a strong focus on fundamentals with strong collaboration among national laboratories.
- The national laboratory leadership lends to the project's strength.

Project weaknesses:

- The project's future path is unclear, given the achieved stage. The presented TEA does not seem to be representing actual progress; it would be helpful for the TEA to include actual process/experimental parameters and inputs as factors in the analysis to clearly guide the experimental work toward the most impactful steps.
- It is not clear how synergetic the technologies are. Overall integration strategies should be considered early in the project to promote optimization of each individual technology's performance in a way that benefits the other components.
- The project does not engage potential commercialization parties and could look at including an advisory board.
- The TEA is a project weakness.

Recommendations for additions/deletions to project scope:

- Steps/actions in the TEA have been recommended, specifically comparing alternative pathways for feed and potential impact of successful completion of the overall target's next steps. The study of scale effects and lifetime of electrodes/membranes should be included in the path forward. It does not seem that the planned optimization of the lab fermentation reactor is needed at this stage, based on the information provided, and scale and strain developments may deem this work irrelevant; it could be a candidate for deferment unless TEA shows otherwise. The tornado in the TEA indicates that improving above 175 g/L loading has a relatively small effect on the hydrogen cost. If the target has been achieved, clarification is needed on why work is continuing on solids loading. The TEA uses a base case of 66 A/m^2 (current case), while the experiments indicate that only 40 A/m^2 has been achieved. If so, the current case should adjust for the lower current density. The project should clarify how realistic it is to project a higher (300-500 A/m^2) future state if only 40 A/m^2 has been achieved. Clarification is needed on the cost at the current demonstrated density. The project could clarify the impact of using unmilled biomass versus milled versus DMR biomass in the overall cost. Additionally, the project could clarify the issues related to using less treated biomass.
- Regarding the TEA, the project could be clearer about where and how CO_2 will be captured for the carbon capture and sequestration cases and how this project will lower feedstock costs. The project could also increase coordination between Task 1 and Task 2 since the reactor design may benefit from changes in microbe performance. Lastly, the project could consider including feedstock pretreatment options, such as are being championed by Idaho National Laboratory.
- The project could look at approaches that eliminate the need to buffer feedstock. The project could also outline an offtake pathway so it can be modeled and costed by all consortium members.

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

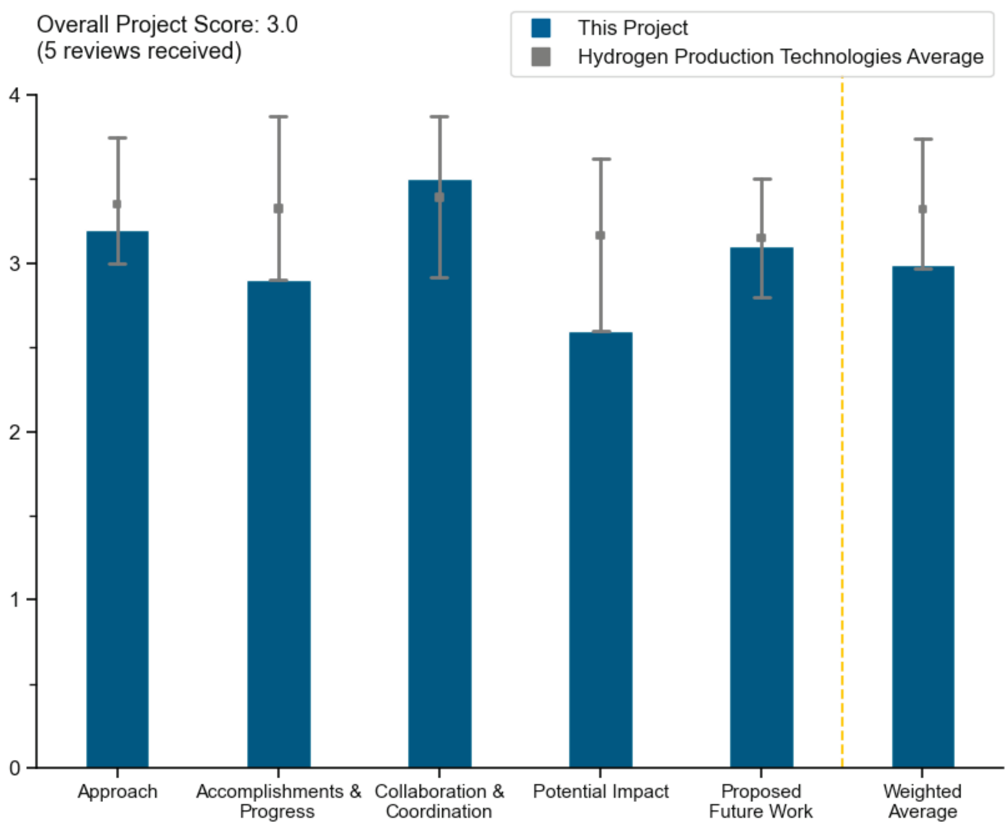
Hong Liu, Oregon State University

DOE Contract #	DE-EE0008844
Start and End Dates	10/1/2019–3/31/2024
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 DOE target).

Project Scoring



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

- Based on the data presented, the project team has made great progress on the topics of identifying, building, and testing less expensive electrodes in a microbial reactor. The project team has presented solid technical information in demonstrating the project's solution in the right scale.
- The project addresses MEC performance through better anodes and cathodes. The project does a good job of exploring some new ideas. Real waste streams were investigated, which exposed limitations and is commended. The team seemed open to investigating surprising results that lead to a novel additive-free approach to reducing the impact of hydrogen scavengers.
- The low current density in MECs represents the most critical barrier toward commercialization, and the current project aims at addressing these barriers by developing high-performance and inexpensive electrode materials and by focusing on the reactor scale-up. The project is well-defined and -designed.
- The project objectives are to develop MEC components that provide significant cost reduction to the anode and cathode of the cell and to increase operation current density, which together would reduce the capital cost of the MEC system. Building a demonstration of a system having multiple cells at 10 L reactor size is ongoing. These are reasonable objectives to the MEC development. The project needs to better assess the cost and conduct life cycle analysis of carbon nanotube production to determine whether this technology can be scaled up to higher production levels.
- The critical barriers to $2/kg H_2 via microbial electrochemical reactor development have been clearly identified by Oregon State University (OSU). This project is in its final stage, with many of the milestones having been successfully completed. A few tasks will be tackled within the next year, but the project might be underspent. A more detailed review of funding might be appropriate at the next technical review.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and DOE goals.

- Progress has been made in developing a lower-cost anode and cathode. Replacing carbon cloth material with Ni mesh on the cathode appears to reduce the cost and increase the current density. High current density in the cell was demonstrated in fresh wastewater but rapidly decreases with time. The project indicates that pre-fermentation of the wastewater would be required to sustain high-current-density operation. The cost of this additional pre-treatment step needs to be estimated.
- The project is proceeding well toward the planned milestones. However, the decrease in current density with real fermentation effluents can be problematic. The need to add buffer capacity to the solution (either by adding salts or basifying the solution to self-generate a bicarbonate buffer) can limit commercial-scale application with real wastewaters. The low performance with large volatile fatty acid (VFA) variability represents another obstacle.
- OSU has about a year to complete the project. It is not clear whether the project will meet the cost target of $2/kg H_2. OSU has made good progress in developing a reactor, as well as testing microbes to make hydrogen. As outlined in previous reviews and answered by the principal investigator, OSU has made progress on updating the techno-economic analysis (TEA), as well as in reactor durability.
- The progress toward the project objectives is obvious.
- It appears solid work has been done, but the project has not yet pulled together to demonstrate overall improvement in cost or productivity. This should be a focus for the next Annual Merit Review.

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 collaboration between OSU, Texas A&M University (TAMU), Pacific Northwest National Laboratory (PNNL), and Mazama Brewing seems to have been fruitful. OSU shows good interactions between its partners. Mazama Brewing should allow for a good demonstration of the proposed reactor. The project could have identified an off-take customer. The project could identify a local off-take customer for follow-on of this work.

- The project has close working collaboration between OSU, TAMU and PNNL. The industrial brewery partner has been identified to supply the wastewater for 10 L reactor testing and for further technology commercialization.
- The project has collaborations on new materials, electrode performance, and waste feedstock. The project may want to add a collaborator if waste stream pre-treatment is an axis that needs to be explored.
- The project has good synergy between the different entities.
- The project appears to have reasonable collaboration, although this is difficult to judge from a single presentation.

Question 4: Potential impact

This project was rated **2.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Inherently, MECs will be a niche H_2 production pathway. The main objective of this project is to develop improved electrodes, but it is unclear how much of an impact this will have. The project's TEA suggests that most revenue for the system operation arrives from the credit for reduction of biochemical oxygen demand (BOD) of the brewery wastewater discharged into public wastewater treatment facilities. It was also suggested that the MEC technology cannot fully clean the wastewater, and further discharge to the public facility would still be required. Yet full credit for the wastewater cleanup was taken in the TEA.
- The project indicated that this MEC technology would be applicable to medium-size breweries with capability to produce about 1,000 kg H_2/day. While this may be a significant amount for local application, the number of facilities where this technology would be applicable is fairly low, so this will remain a niche market. Further purification of H_2 was not accounted for either.
- Impact may be reduced by the limits of the system due to the need to increase buffer capacity. The fact that the current drastically decreases with real effluents can limit impact. The final goal for H_2 cost relies heavily on credits.
- OSU has proposed a careful program to address the DOE goals for hydrogen production through biological methods. Without an off-take approach, it is difficult to rank how well this effort aligns with the Hydrogen Program and DOE research, development, and demonstration goals and objectives.
- The data and analysis presented in the package have not demonstrated how relevant the delta is in the cost of the hydrogen from the lower electrode cost, which, based on some information in the presentation, can be estimated as quite small. So, although lower cost is always good, it is not convincing that the low-cost electrodes pursued will be crucial toward the pathway of lowering the hydrogen cost. This reviewer is looking forward to information to be convinced otherwise.

Question 5: Proposed future work

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

- OSU has effectively planned the project to address the DOE goals for hydrogen production through biological methods. The program has been executed well against its project plan. The technical achievements may not be met within the next year. Although addressed by the principal investigator, the TEA may still need revision to achieve the fidelity found on other projects. When completed, this project will serve as a baseline for other efforts to generate hydrogen through biological pathways.
- The proposed future work is well planned and can further advance the project. However, the variability of the wastewater compositions has been overlooked. Only one effluent has been used and tested, which is not representative of the variability in effluent chemistry and compositions.
- The plan appears to be set to bring all the elements together.
- The proposed future work is reasonable for continuing technology development.
- The next phase should demonstrate the stability/lifetime of the system at a relevant scale. The plans indicate that, but they are rather economical on the specificity. In any case, the economics assume a "3 years for anode and 5 years for cathode" lifetime, so this should be a target. The plan for the next phases

indicates (Milestone 5.1) a 72-hour test, which does not appear long enough. The project should clarify how the long-term stability will be established in realistic feeds.

Project strengths:

- The project addresses the critical barrier of increasing MEC current density and performance. The project is aiming to develop novel, inexpensive material, which is critical to reaching the goals set for MECs. The team is working synergistically toward the completion of the specified goals.
- The project has an innovative approach to electrode materials and is receptive to new opportunities to improve MEC performance. Dropping the lignocellulosic biomass fermentation aspect was a good thing, as it allowed the project to focus on materials and challenges for less controllable waste streams.
- The project made good progress in lowering the cost of MEC electrodes and in increasing the current density.
- The project strengths are highlighted by the leadership provided by OSU. Identifying an industry sector and brewers to partner with could lead to the distribution of this technology.
- The project has good technical information and good documentation.

Project weaknesses:

- Most of the initial work was focused on synthetic media, overlooking the complex composition of real media. Only one wastewater type and composition appears to have been tested to date. The impact of the wastewater composition (low buffer capacity that needs to be increased by adding salts or generating bicarbonate in solution, VFAs) on performance can limit impact of the proposed work.
- The project weakness can be identified by not having clearly defined an off-take for the produced hydrogen. Off-take would ultimately define the price of hydrogen and thus help with determining whether the cost target of \$2/kg H_2 is adequate.
- It is not apparent how the several workstreams will come together to produce an improved MEC device. The project needs to clarify which electrode approach is better and how robust these developments will prove to be when put into a working device.
- The project is still in a very low technology readiness level, and it is not clear how much commercial interest there would be for technology application.
- The project has weak economics (based on the incomplete information this reviewer has).

Recommendations for additions/deletions to project scope:

- The project scope should make sure that the technology is evaluated with actual feeds to establish the long-term stability, especially compared to the more expensive alternative. A cheap electrode that does not last that long will not be the economic solution. The economics on slide 4 are somewhat confusing. The effect of the electrode material and production cost per kilogram of hydrogen is not clear. The project should clarify how significant the reduced-cost electrodes are per the \$/kg H_2. (The table suggests a capital cost contribution of \$1.2/kg, but it is likely not only electrode cost.) The project needs to clarify the electricity use per kilogram of hydrogen. (It shows cost, but there is no kWh/kg information or \$/kWh cost assumed.) Although the principal investigators have addressed another reviewer's question on the credits, this reviewer does not consider the credit applicable. Likely, BOD reduction can be achieved by fermentation alone in a waste treatment plant, so the electrolytic approach cannot use this credit that exists simply in the base case. Electrolysis allows the additional production of hydrogen, at the expense of power and electrodes. It is not clear if the cost applies to the electrolytic (additional) hydrogen or to the total (including the fermentation one). This needs explanation. According to the stoichiometry on slide 4, theoretically, only two-thirds of the hydrogen is due to the electrolysis (the rest is simple fermentation). Further from the data, slide 13 says, "Cathodic hydrogen recovery indicated that over 97% hydrogen was produced via the fermentation process, rather than the MEC process." One would then question what the benefit of electrolysis really is. It is not clear what the effect is of electrode lifetime per kilogram of hydrogen. This information is likely crucial, so an indication is needed. In addition, it appears that "[b]utyrate and propionate are found to decrease the maximum attainable current density and could not be utilized in MECs," and as a result, treatment is necessary. The project should clarify how the cost of hydrogen produced here (including hydrogen separation/purification cost, sludge treatment, pre-treatment, etc.) compares to electrolytic hydrogen from water derived from the same wastewater (after necessary pretreatment).

- The project should engage PNNL (or other national laboratories) to do a detailed TEA, including all known non-energy operating and manufacturing costs (e.g., nutrients and buffers). An outcome of that analysis would be how sensitive the hydrogen production cost is to the cost of electrodes. Also, as presented, one might conclude that the main utility of MECs is a waste stream (partial) treatment technology, with hydrogen as a side hustle; the project should address this.
- The main suggestion is to implement tests with different wastewater types/sources. If brewery wastewater is the main target, effluents from different companies need to be tested in the MECs.
- No change of scope is recommended.
- The reviewer has no additions or deletion to the current project scope.

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

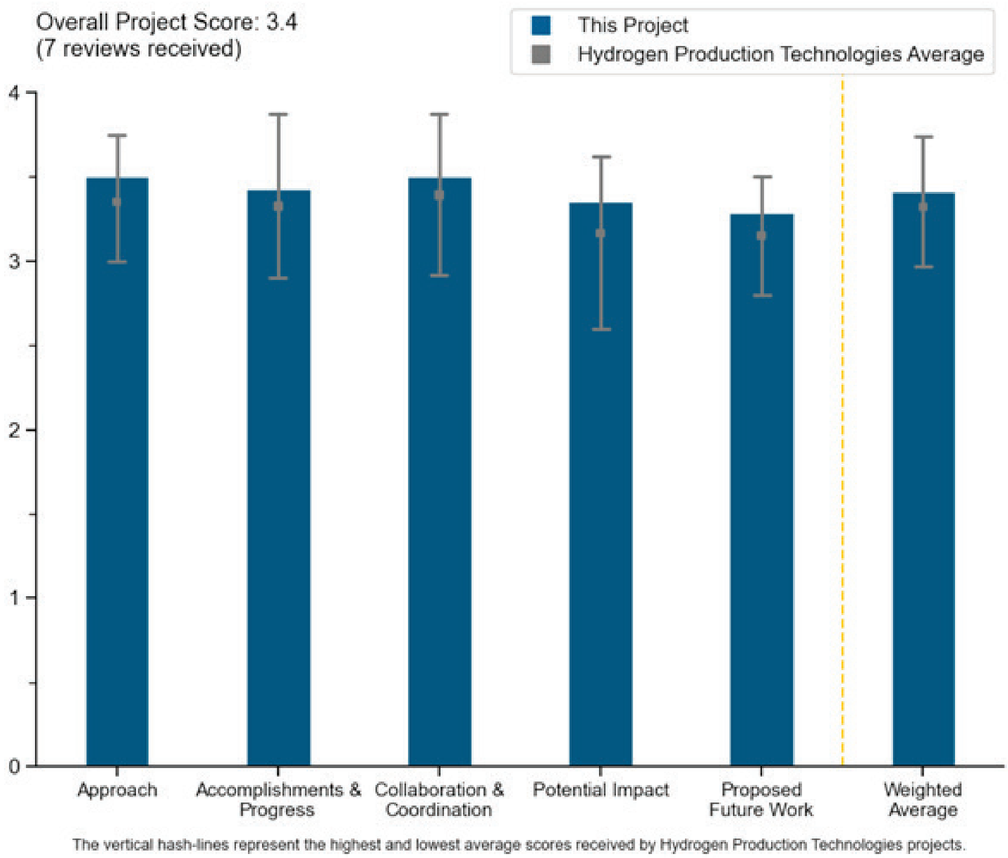
Bryan Pivovar, National Renewable Energy Laboratory, and Richard Boardman, Idaho National Laboratory

DOE Contract #	multiple
Start and End Dates	1/1/2020
Partners/Collaborators	Argonne National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, National Energy Technology Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, National Institute of Standards and Technology, SLAC National Accelerator Laboratory, University of California, Irvine, Carnegie Mellon University, Colorado School of Mines
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 2026. H2NEW is studying both low-temperature electrolysis (LTE), based on proton exchange membrane (PEM) and liquid alkaline technologies, 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



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 needed work to meet the hydrogen production cost target: a consortium that includes multiple national laboratories to bring in experts to address technology barriers, with input from industry stakeholders. The H2NEW consortium, led by Drs. Boardman and Pivovar, is a great example of massive collaboration between large cross-functional teams across national laboratories. It was a pleasure seeing such a large effort and progress; this is well done. Developing cells, stacks, and testing stands for larger systems is going to be beneficial for the industry—and mostly for start-up companies, academia, and national laboratories. The project could consider incorporating a top-to-bottom approach across the H2NEW consortium regarding understanding what customers need, who will be buying hydrogen, and what operators/owners who will be running hydrogen plants will need to meet customer demands. Major effort is spent on the technology but not enough on who would be buying, incorporating, or financing such technology. Developing such relationships or hiring industry consultants who can provide some guidance would be beneficial. Variable operation is an important consideration covered in the presentation. Perhaps the team could consider variable operation from the perspective of boundary conditions of the entire hydrogen production plant, not just the electrolyzer system. The team could reconsider levelized cost of hydrogen (LCOH) cost calculations, especially capital and operating expenditures, depending on the type of hydrogen off-take agreement (whether the customer will accept any interruption/variability in hydrogen supply and how such interruptions are accounted for in the LCOH). The project team could consider a side-by-side analysis of how development of alkaline technology in the United States compares to mature alkaline technology and technology deployment in the rest of the world.

- The National Renewable Energy Laboratory (NREL) has developed the H2NEW consortium to overcome the barriers of hydrogen production via electrochemical pathways. The critical barriers for each technology have been identified and are being addressed. The project is well defined and seeks to compare electrochemical hydrogen production technologies on the basis of LCOH. H2NEW has a steering committee, which comprises the top industry leaders in electrochemical hydrogen machinery. The committee enables H2NEW to address any challenges uncovered during the mass manufacturing of electrochemical hydrogen machinery.
- The lead for the HTE solid oxide electrolyzer cell (SOEC) part of H2NEW has been able to piece together an excellent team and appears supportive to team members. However, the SOEC should benchmark the PEM work, primarily at NREL, which has an excellent organization and structure. Key issues have been methodically isolated and effective strategies developed there. Approach focus in HTE must be on quickly lowering cost, lowering area-specific resistance (ASR), increasing the current (hydrogen production rate), improving longevity and heat addition into the SOEC, and disseminating the results to real energy system integrators. Given the state of progress, the approach for LTE should be in performance, manufacturing, durability, and dissemination of results to energy system integrators.
- The project has clear evidence of a fully developed approach that shows a pathway from bench-testing to scale-up verification.
- This is a very comprehensive and complex project that needs tremendous leadership and coordination from the principal investigators. The low-temperature water electrolysis (LTWE) part covers important components such as catalysts, membranes, and porous transport layers (PTLs). However, new catalyst (TiO_2 supported catalyst) and thinner membrane (e.g., Gore 80 micro membrane) are not included. The ink stability and coating study is meaningful for the scale-up and manufacturing (slide 28). Alkaline water electrolysis is a new plus. However, the principal investigators need to consider the challenges of the integration between the intermittent renewables and the electrolyzer. Advanced diagnostics tools, such as x-ray absorption spectroscopy (XAS) and neutron imaging, have been implemented to pinpoint mechanisms. LTWE and high-temperature water electrolysis (HTWE) are quite different in terms of materials, approaches, and technology readiness levels (TRLs). Therefore, it is not logically reasonable to combine them into one presentation. They can be split into two different projects or presentations.
- The team has done excellent work. A wide range of accomplishments were reported. However, it is unclear how the approach has been selected for each task.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- Great accomplishments have been made in the past year, including benchmarking baseline proton exchange membrane water electrolysis (PEMWE) performance across different laboratories, mechanisms for Ir oxidation and dissolution, PTL interface, and membrane thinning. Liquid alkaline water electrolysis (LAWE) has been added to the scope of work. Baseline performance has been established rapidly. LAWE performance using stainless steel is higher than using Ni, but it is hard to interpret the data. The benchmark PEMWE performance decay rate (4,000 hours) 28 μV/h is still high. The decay rate should be 10 times lower (3 μV/h). Oxygen crossover and contamination are two different subjects and should be on different slides. For the HTWE part, the work of identifying stressors is meaningful to analyzing degradation mechanisms. For HTWE on slide 56, nano-computed tomography (nano-CT) shows high-quality pictures of interface densification. It is really a great job. The project could consider how LAWE can be integrated with the renewable impermanency. Reverse current during shutdown can lead to fast decay of the electrodes. In addition, shunt current is a great challenge. The project needs to report Faradaic efficiency.
- The H2NEW consortium has achieved several significant milestones in the development of low-temperature electrolyzers, including basic science approaches to durability and approaches to calculating the LCOH. The work on understanding utility pricing of electricity is also prized, as it is used by industry when considering hydrogen plant locations. Each of these accomplishments is a step that enables DOE to meet the $1/kg H_2 goal.
- Accomplishments have shown significant progress toward understanding most aspects of cell and subcomponent design, related to cost and durability. Testing has been done to simulate real-world

environments to project how LTE devices will respond under the cycling conditions expected in applications tied to renewables.

- Significant progress has been made. However, because of the large amount of information and many details given in the presentation, it is difficult to assess the effect of the accomplishments/progress toward the project and DOE goals.
- The project has made very good progress. However, the frequency of meetings to seek stakeholder input is unclear.
- Excellent progress was made in LTE and HTE.

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 H2NEW consortium hosts technical reviews and steering committee meetings to interact with each of the consortium members. These meetings often comprise breakout sessions to best collect input to refine H2NEW programs.
- The project has clear demonstration of successfully collaborating and leveraging the different lab, academic, and industrial partners.
- The project appears to be well coordinated to bring in expertise from a variety of laboratories and industrial partners.
- The project has excellent collaboration among national laboratories and universities.
- The collaboration for this project is really strong between national laboratories. However, the participation from the universities and industries is weak, although some industrial members sit on the advisory committee.
- The presenter did not provide examples or describe the approaches/procedures to ensure full participation of every member of the consortium and have appropriate coordination/strategy of the activities between many members of the consortium working on different tasks and different technologies.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has clear evidence of the potential impact. The project has a cost analysis included in technical progress to show areas of focus needed to drive $/kg down to the targets needed for broad electrolysis deployment. Technical work has shown significant progress toward development of materials and understanding that work toward DOE cost targets for hydrogen.
- The H2NEW consortium is critical to the Hydrogen Program and has potential to significantly advance progress toward DOE research, development, and demonstration (RD&D) goals and objectives. This is specifically found in the efforts to rank emerging technologies against LCOH metrics. This ranking can help DOE better plan future funding opportunity announcements to ensure the Department's RD&D goals and objective can be effectively met.
- Addressing key technical and cost barriers would be critical in transitioning the energy sector toward renewables.
- The project aligns very well with the Hydrogen Program and DOE RD&D objectives.
- This project is very impactful because of its substantial investment from DOE, the scope of work, and some insightful results. However, the project can become more significant if it can come up with solid strategies for performance improvement and degradation mitigation. Given the substantial DOE investment, it is very much to be hoped that the project can produce transformative results rather than incremental improvements. Technology transfer efforts and outcomes are not strong.
- The Idaho National Laboratory presenter mentioned the proton-conducting solid oxide electrolysis cell (P-SOEC) and alkaline technology development. The protonic P-SOEC technology, whatever advantages it may eventually have, once validated, has a low TRL and Faraday efficiency and no industrial partner in the

forefront of development. It is uncertain whether the project should continue to be pursued, other than as an academic curiosity. DOE has driven three or four fuel cell technologies to demonstration. The cost of developing a fuel cell technology to the demonstration stage has historically taken at least a $1 billion and decade(s) per technology. Developing to demonstration or market such a low-TRL (incredibly small millimeter scale) and unvalidated technology such as P-SOEC will take a billions of dollars and decade(s). There are eight years left to 2030 and only limited funding to reach the Hydrogen Program goals. There will be insufficient time for such protonic technology to impact 2030 or perhaps even 2050 goals. HTE proton-conducting technology should clearly be beyond the scope of HydroGen and H2NEW. The alkaline appears to have already been commercialized to some outside the United States.

Question 5: Proposed future work

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

- The H2NEW consortium is planned in a logical manner. The consortium has the appropriate decision points to update its focus if an emerging technology shows promise.
- Proposed future work clearly identifies remaining challenges and high-level goals for future work.
- The project appears to be on track to accomplish the stated objectives.
- Proposed future work at SLAC and other locations to focus on in operando degradation work is exploratory in nature, may not ever be relevant, and may detract (in a funding-constrained program) from the real purpose. The focus of all the research in the Hydrogen and Fuel Cell Technologies Office (HFTO) is to drive to the 2026 goals of low ASR, high current, and rapid acceleration to deployment to meet 2030 and 2050 goals.
- The proposed future work is just a list of project tasks. It does not highlight most imminent challenges or provide priorities of the future work.

Project strengths:

- This project has many strengths. In HTE, Pacific Northwest National Laboratory (PNNL) is providing solid contributions toward material characterization, standardization, and testing. Industry, per se, is not likely to share its own information and may shut out others, reducing the speed of their own commercialization and the meeting of HFTO goals. A basic shared understanding and information transfer (Data Hub) and distribution across all Hydrogen Program areas will help achieve HFTO goals and objectives. PNNL is correctly focusing on standard technologies and materials sets. Some researchers think it would be great to do endless investigation into promising alternative materials. However, continuously jumping around and changing materials sets (with low or no repeatability) leads to new and more developmental challenges each time and to ever-longer development cycles and not to meeting HFTO goals.
- The project has a strong and capable leadership team and is addressing the most important elements of LTWE and HTWE. Great accomplishments have been made in the past year, including benchmarking baseline PEMWE performance across different laboratories, mechanisms for Ir oxidation and dissolution, PTL interface, and membrane thinning. LAWE work has been added to the statement of work.
- The H2NEW consortium strengths are found in the industry-based steering committee. The focus on the LCOH as a metric also aligns the consortium to enable DOE to meet its goals.
- The project has strong collaborations and well-planned technical work, which is supported throughout with a techno-economic analysis to identify areas of focus.
- The project has a broad range of activities addressing various aspects of different hydrogen technologies. The project involves many experts in different areas from national laboratories.
- The project team make-up is the biggest strength.

Project weaknesses:

- No major weaknesses are identified in the H2NEW consortium. A consortium weakness could develop as the number of projects it oversees continues to grow.

- At this stage, the project appears to be fixed on a certain cell design and materials. Incorporation of new and emerging materials is valuable and expected to happen soon.
- The collaboration with the industry is weak at this time, with national laboratories playing a dominant role. Technology transfer outcome is weak, and the results are incremental, not transformative.
- The use of accelerated testing may have limited usefulness. Focus must be on lowering cost, lowering ASR, increasing current (hydrogen production rate), and improving longevity and heat addition into the SOEC.
- The priority for the different project activities is not well defined. It appears that activities/focus areas have been selected based on expertise at national laboratories. There is a need for broader participation.

Recommendations for additions/deletions to project scope:

- The H2NEW consortium showed leadership in developing a reference design for a liquid electrolysis system, which was required, as liquid electrolysis is showing promise of maintaining dominance as electrochemical machinery for hydrogen production. It is proposed that the H2NEW consortium develop a reference design for a gigawatt to help guide industry in this development. Also, establishing pathways to hydrogen off-take can also aid industry.
- Highly integrated synchrotron x-ray diffraction (XRD), with questionable relevance to well-developed commercial materials sets and to the real cell operational conditions, may be beyond the scope of this effort, with such limited funding being available. The goal is to quickly lower ASR, increase the current density, and improve heat addition into the SOEC to meet 2026 HFTO goals. The project is still performed solely by national laboratories, so industry participation is largely missing. Industry participation is a key aspect of HFTO; all work needs to be integrated with industry.
- Regarding the collaborations with universities and industry, some tasks can be undertaken by universities at lower cost and by industry at larger scale. Technology transfer needs to be strengthened. The results need to be adopted by industry. In the future, the project can be divided into two projects, LTWE and HTWE, which can be presented separately. Fundamental investigations are good, but the project’s insights on performance improvement and degradation reduction need to be specified.
- More focus, defined priorities, and broader participation are recommended for this project.
- Near-term, highly focused efforts are needed.

Project #P-197: Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzers

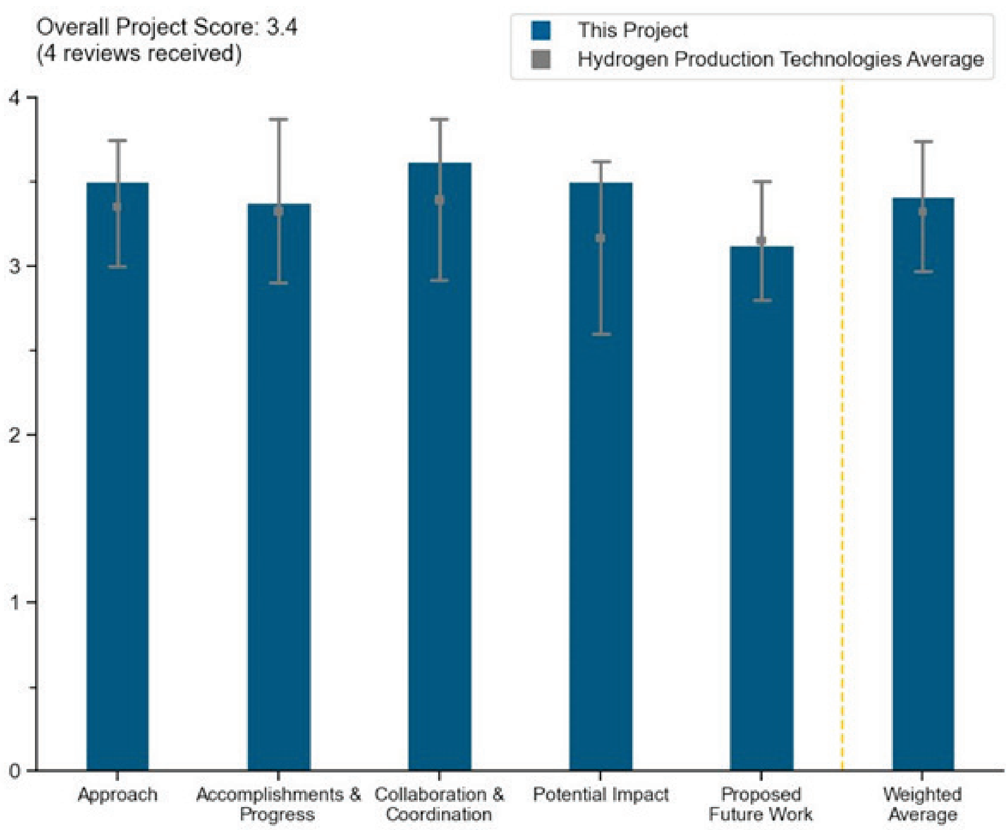
Andrew Steinbach, 3M Company

DOE Contract #	DE-EE0009237
Start and End Dates	1/1/2021–9/30/2024
Partners/Collaborators	Giner, Inc., Plug Power Inc., National Renewable Energy Laboratory, Oak Ridge National Laboratory
Barriers Addressed	• Capital cost • Manufacturing

Project Goal and Brief Summary

This project aims to develop manufacturing processes for reproducible and uniform proton exchange membrane water electrolysis (PEMWE) components at commercial scale, specifically for an oxygen evolution reaction (OER) catalyst, electrode, and thrifted catalyst-coated membranes. Once developed, these processes will be scaled up to gigawatts per year, and component production will begin. The produced components will then be assessed and validated for efficiency, durability, power density, and low iridium content in megawatt-capable stacks relevant for gigawatts-per-year deployment scale. If successful, this project's results will help satisfy industry needs for high-volume capacity PEMWE and reduced manufacturing costs for the necessary components.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production 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 timely and directly addresses the current needs for manufacturing gigawatt-scale catalysts and electrodes. The approach to developing low-iridium-loaded catalyst-coated membrane manufacturing, while also demonstrating the performance and durability in high-pressure differential operation, is addressing the barriers and is on the right track.
- The team is taking a strong technical approach based on addressing the most important needs for improved water electrolysis, including reducing Ir loading, increasing performance at high current, and improving durability.
- The Ir/nanostructured thin film (NSTF) has proved to be very promising as the OER catalyst for PEMWE. The NSTF has demonstrated great performance and durability simultaneously. The scalability of the Ir/NSTF powders, electrodes, and membrane electrode assemblies (MEAs) has been investigated. The catalyst cost has not been studied. 3M has been using its own membranes. For a comparison, 3M may need to test its catalysts with the Nafion™ membrane.
- The approach slide did not have much detail. The milestones were only in the back-up slides, and even those lacked details. It would also be good to compare the cost of this process to that of conventional catalysts.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- The team is making excellent progress in the efforts to develop improved NSTF-based electrolyzers, and the work is highly beneficial to the larger Hydrogen and Fuel Cells Technologies Office (HFTO) program. The 2,000-hour, steady-state durability test and the variable renewable energy test showed promising results, as did the highly accelerated stress testing on the modified catalyst. Overall, the NSTF powder approach seems to be achieving promising results.
- The project has made significant advancement in meeting the milestones. The project has also taken steps to address the drawbacks presented in the previous year. The project has met milestones regarding performance, durability, and loading targets and is on track to meet the manufacturing rate milestone.
- The 1,000-hour testing (5 A/cm^2, 300 psi) at Giner progressed very well. The MEA is very stable. However, the sudden H_2 crossover after 1,000 h increase is under question. A repeat needs to be done as soon as possible. The Ir/NSTF catalyst can achieve performance of <2.3 V at 10 A/cm^2 with low Ir loading (0.5 mg/cm^2) and with low decay rate of 1 µV/h. This low decay rate at high current density is particularly meaningful. The short stack data has not been demonstrated. The cost analysis of the catalyst and MEA has not been conducted.
- Excellent progress was shown on various aspects of the project. Excellent performance and durability data were shown. Two critical manufacturing steps still need to show progress toward project goals.

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 involves good interactions between the lead (3M) and several subs, including characterization at Oak Ridge National Laboratory (ORNL) and National Renewable Energy Laboratory (NREL), durability testing at NREL, and testing/validation at Giner and Plug Power.
- The project demonstrated excellent collaboration with national labs and industry, leveraging their capabilities for diagnostics and further development of the MEA.
- There is excellent collaboration with Giner, Plug Power, and the National Renewable Energy Laboratory (NREL). The presentation does not show the contribution from Plug Power.

- There is good partnership with Giner, Plug Power, and NREL to cover all aspects of the project. If 3M is exiting polyfluoroalkyl substance (PFAS) manufacturing, then other partners need to be identified to provide PFSA membranes and ionomers.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project is very impactful because of its distinctive approaches, and encouraging results were demonstrated. The Ir/NSTF can become a new commercial catalyst if its cost can be reduced.
- Excellent durability and performance were demonstrated. If the project can show cost and manufacturing feasibility, it will have a very high impact.
- The project is highly relevant to HFTO efforts in development of gigawatt-scale manufacturing of electrolyzer catalysts and electrodes.
- If all continues to go well in this project, it could have a substantial impact by enabling higher-performing and more durable electrolyzers with reduced Ir content. Overall, the impact of the project could be quite positive. On the other hand, since the NSTF approach is highly specific to 3M, there is some question about how impactful the work will be to the broader community and some risk that the work could go to waste if 3M ultimately does not pursue commercialization.

Question 5: Proposed future work

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

- The proposed work on addressing the manufacturing barriers related to rate and catalyst layer uniformity will help overcome the barriers in meeting the milestones.
- There is excellent proposed work with demonstrations in Giner and Plug Power stacks.
- A small, short stack (Giner) and large stack (Plug Power) are included in the future work. Economic analysis should be included in the project. 3M can work with Strategic Analysis to expedite this process.
- The future work makes sense and represents a logical path to addressing the project challenges, but the project would be more valuable if it included future work with a more science-focused effort that would be broadly beneficial to the electrolyzer community outside 3M.

Project strengths:

- The Ir/NSTF approach to make OER catalysts for PEMWE is very innovative. Remarkable PEMWE performance and durability have been demonstrated. The project has assembled a strong team that includes 3M, Giner, Plug Power, NREL, and ORNL.
- The work builds on a long history of NSTF development at 3M and excellent capabilities for manufacturing NSTF-based materials. The principal investigator is highly experienced and has an excellent focus on meeting project goals and pushing the technology forward.
- Excellent durability and performance were shown at low loadings. Thorough work was shown with durability testing under various conditions, including on/off and constant current over >1,000 hours.
- The main strength of the project is the development of capabilities to manufacture high-performance and durable electrolyzer MEAs. The team is capable of delivering on the targets.

Project weaknesses:

- The sharp focus on NSTF means that the project does not have much impact on approaches outside of NSTF, thus limiting the value and impact of the project in the wider community.
- The project needs to address the additional cost of NSTF manufacturing and demonstrate that the additional cost can be tolerated with improved performance or durability.

- The team needs to address the higher Ir dissolution rate with the low-loaded Ir MEAs. The benefit of Ir/NSTF over Ir/IrO_x nanoparticles is unclear.
- Economics analysis is needed to understand the cost of NSTF materials.

Recommendations for additions/deletions to project scope:

- Economic analysis should be included in the project. 3M can work with Strategic Analysis to expedite this process. Further Ir loading reduction to 0.25 mg/cm^2 and 0.1 mg/cm^2 is recommended. At low Ir loading, the effect of some contaminants needs to be investigated.
- The project would benefit from utilizing the capabilities of the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium to understand the Ir catalyst durability, for example, Ir dissolution of the NSTF catalyst using techniques such as online inductively coupled plasma mass spectrometry (ICP-MS).
- The project should add cost projections for NSTF and compare them to those of conventional MEAs.

Project #P-198: Enabling Low-Cost Proton Exchange Membrane Electrolysis at Scale Through Optimization of Transport Components and Electrode Interfaces

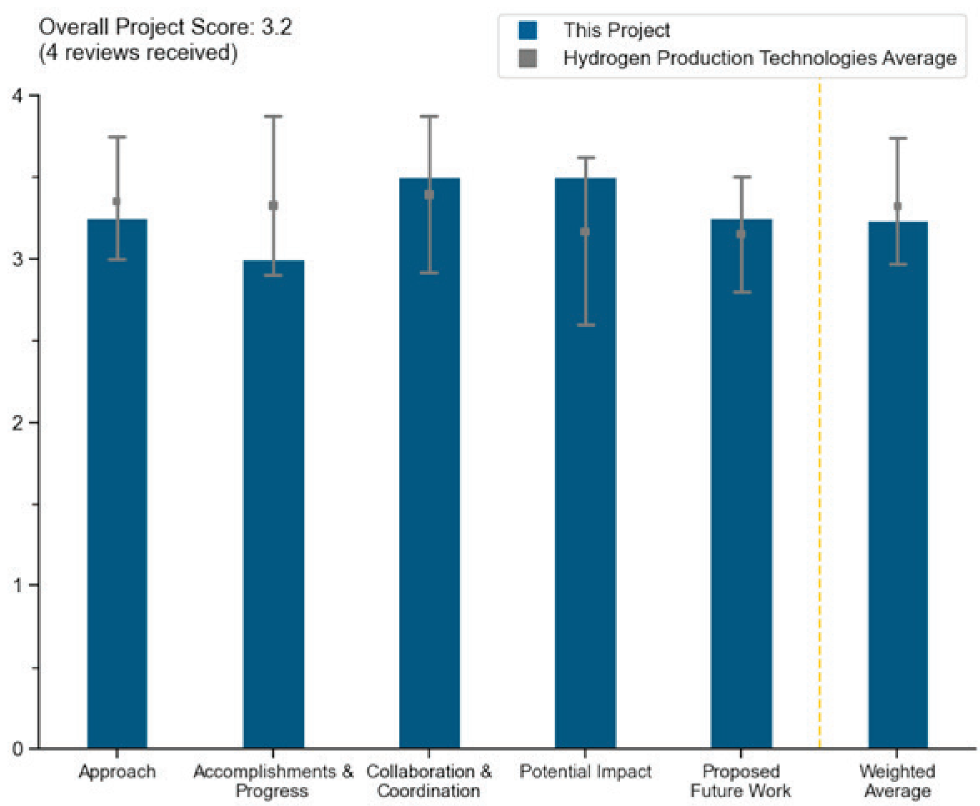
Chris Capuano, Nel Hydrogen

DOE Contract #	DE-EE0009238
Start and End Dates	10/1/2020–4/30/2024
Partners/Collaborators	National Renewable Energy Laboratory, Oak Ridge National Laboratory, De Nora Tech, LLC, University of California, Irvine
Barriers Addressed	• Capital cost • System efficiency and electricity cost

Project Goal and Brief Summary

This project aims to develop an optimized porous transport layer (PTL) designed for an electrolyzer system and upscaled to manufacturing level. The PTL serves many purposes: the distribution of water flow across the cell, the removal of gaseous oxygen from the anode, the establishment of contact between the anode and current collector, and the provision of mechanical support for the membrane. At present, available PTL materials are adapted from other industries' materials and not optimized for electrolysis. The addition of a microporous layer (MPL) to the existing design will provide a more closely packed pore structure immediately adjacent to the catalyst layer, balancing porosity with contact area. Porosity will also be balanced against mechanical strength to support hydrogen pressure. These improvements will enable good fluid management while providing a uniform interface to the catalyst and membrane. The PTL will enable integration of advanced membrane electrode assemblies (MEAs) in service of advancing electrolyzers toward the DOE cost goal of $2/kg.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production 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 approach focuses on developing improved PTLs for proton exchange membrane water electrolyzers (PEMWEs), including MPL approaches that could provide improved catalyst utilization and higher durability. This project is addressing some of the most important barriers to clean hydrogen production. While the listed tasks are focused on PTL development, the presentation included several slides on seemingly unrelated work on catalyst characterization, ink properties, and testing of a large number of MEAs with different catalysts and loadings; the relevance of this work to the project seems limited.
- The project goal is to develop a PTL with an MPL. The project utilizes computational modeling and x-ray characterization in optimizing the PTL substrate and MPL morphological properties. The project is also developing coating methods to thrift platinum group metal coatings.
- This project works on the PTL and its interface with electrodes, which is a critical area for PEMWEs. The x-ray computed tomography (CT) is a powerful tool to investigate PTLs. DN catalysts do not have information. It is unclear what their differences are. This is a PTL project. It is not clear why IrO_2/NbO_x and IrO_2/oxidic support catalysts were investigated.
- There is a good, detailed approach with quantifiable milestones.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- The project is on track to the accomplish the milestones. Development of PTLs with MPLs is necessary for low-loaded anode catalyst layers needed to achieve Hydrogen and Fuel Cells Technologies Office (HFTO) targets regarding low-cost clean hydrogen. The project has demonstrated improved durability with low Ir loading.
- Significant progress has been made toward developing improved PTLs. Most importantly, the team has succeeded in demonstrating improvements in durability and reductions in Ir loading through the development and integration of improved PTLs. The characterization work at the University of California, Irvine (UCI) is providing valuable insight into the effect of pore size and porosity on oxygen removal. The work at De Nora Tech, LLC (De Nora) has yielded several promising PTLs, and the Nel Hydrogen work on developing coatings with reduced Pt content appears valuable, though a lack of any technical information about how the materials are made makes the progress of limited value to those outside the project team.
- Reasonable progress has been demonstrated, given the supply chain issues. The work at Oak Ridge National Laboratory (ORNL) (slides 12 and 13) and National Renewable Energy Laboratory (NREL) (slide 14) seems to be on catalysts and inks, while the main project is focused on MPL and PTL development. This needs to be integrated better. Longer-term durability tests are critical, and 100-hour testing might not reveal the true durability of these materials in the long term. Excellent short-term durability was demonstrated.
- The PTL has lower Ir loading. The MPL with Ir 0.1 mg/cm2 loading can achieve comparable performance to the baseline MPL with Ir loading 1 mg/cm^2. One major task is optimization of the MPL thickness, particle size, and porosity. No good data or progress has been shown. Not all the PEMWE performance is great. For example, the voltage is clearly 2.0 V at 1.8 A/cm^2. A partial reason could be the low operating temperature of 50°C. It is unclear why a higher temperature was not used. The presentation did not show advanced PTL manufacturing. Perhaps this is a partial scope of work of 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 a well-coordinated team to achieve the project targets.
- The project features excellent interactions between the lead and several subs, though some of the work performed by the subs does not seem particularly relevant to the overall project.

- This project has a strong team, including Nel Hydrogen, UCI, NREL, De Nora, and ORNL. It is not clear what the role of De Nora is.
- The ORNL work needs to be better integrated into the project.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Development of improved PTLs is one of the greatest needs to enable low-cost, durable electrolyzers, and this project could potentially have a substantial impact in this area. If successful, the project could enable substantial reduction in Ir and Pt content, helping to accelerate widespread deployment.
- The project holds significant relevance in the development and manufacturing of PTLs with MPLs, as the project has the potential to enable low-cost electrolyzers by thrifting an expensive Ir catalyst by improving the contact between the catalyst layer and the MPL.
- This is high-impact work if a better MPL can be developed to enable lowering Ir by one order of magnitude.
- The project will be highly impactful if all the proposed tasks can be completed and milestones met.

Question 5: Proposed future work

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

- The planned work is reasonable and appropriate to meeting the project goals, though inclusion of more work scope that could provide improved understanding and thus benefit the larger electrolysis community outside the project team would be valuable.
- The proposed future work aligns with the project milestones. Adding a target for ex situ compressive and bending mechanical evaluation of the PTLs to future work should be considered.
- Generally, the project has a good future plan. The project needs to work on optimization of the MPL thickness, particle size, and porosity.
- Long-duration durability tests are planned.

Project strengths:

- This project has a strong team including Nel Hydrogen, UCI, NREL, De Nora, and ORNL. The PTL and interface with electrodes are important research areas. The project has demonstrated some good characterization data using x-ray CT. The project can reduce the Ir loading to 0.1 mg/cm^2 by adopting a new PTL design.
- Nel Hydrogen is a leader in water electrolysis, so the company's engagement in the Hydrogen Program through this project is of great value. The team includes fantastic expertise and can make a real impact on accelerating electrolyzer development and deployment.
- The project has a well-coordinated technical team that has developed PTLs with MPLs that show improved durability and performance, with a reduction in Ir loading in initial testing.
- The project has an excellent team, and MPL impact on performance is significant.

Project weaknesses:

- It is unclear how screening supported the Ir catalyst and how developing coating methods integrates into this project.
- Some proposed tasks—such as optimizations of the MPL thickness, particle size, and porosity—have not started.
- Some of the presented work seems irrelevant to the project goals.
- Long-term durability and stack testing are still lacking.

Recommendations for additions/deletions to project scope:

- The project needs to focus on effects on PTL properties, such as MPL thickness, particle size, and porosity. The project needs to investigate PTL manufacturing improvements. The project should operate cells at more standard conditions, such as 80°C, to make better comparisons with data from other projects.
- The project should explore the benefit of MPLs regarding the deformation of the catalyst layer and membrane at high-pressure operation. The project should consider testing the durability of the PTLs and the coating under cycling conditions.
- The work on catalyst characterization does not seem to fit in this project. The work on ink coating and ultra small angle X-ray scattering (USAXS) also seems to be of little relevance. The resources could be better spent focusing on the core PTL work.
- The project should integrate the ORNL catalyst work into the project or redirect to PTL/MPL work.

Project #P-199: Integrated Membrane Anode Assembly and Scale-up

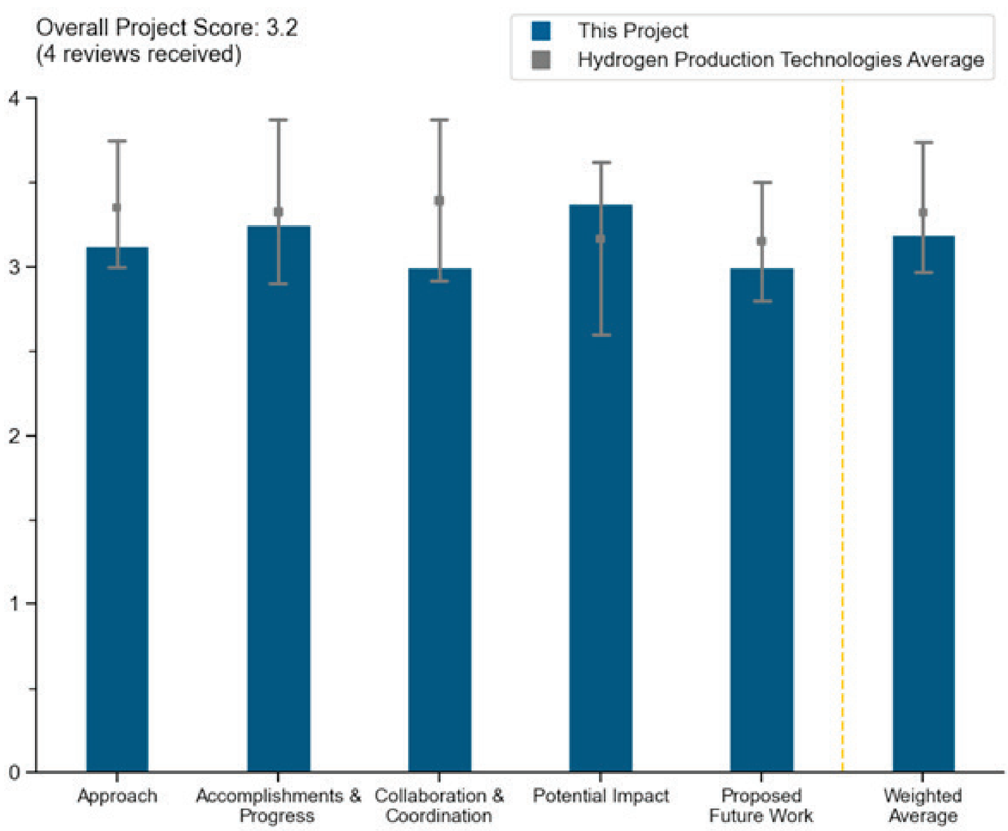
Adam Paxson, Plug Power Inc.

DOE Contract #	DE-EE0009236
Start and End Dates	8/1/2021–10/31/2024
Partners/Collaborators	University of Tennessee, Colorado School of Mines, Oak Ridge National Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Production volume • Component cost

Project Goal and Brief Summary

This project will develop and fabricate a single-piece, integrated membrane anode assembly with the aim of reducing electrolyzer capital costs. The status quo involves a time-consuming manufacturing process and expensive components. This project will implement innovative manufacturing processes and architectures to reduce the cost and fabrication time of the anode support structure and membrane electrode assembly (MEA), the most expensive components in an electrolyzer stack. Researchers will create a single-piece anode support structure (SPASS) and catalytic and ionomeric coatings. The coatings will be applied to the anode support structure's surface to form the integrated membrane anode assembly. The project will then scale up and demonstrate the production process.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production 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 focuses on addressing key barriers to proton exchange membrane electrolyzer deployment through development of anode assemblies with reduced cost and increased performance. The exploration of multiple routes to improvement, including catalyst deposition through ink-based methods and electrodeposition directly on the porous transport layer (PTL), provides a promising route to increased performance, though an increased focus on reduction in Ir loading would be beneficial.
- The proposed approach of coating catalyst layer directly onto a PTL reduces the interfacial contact issues between the catalyst layer and PTL. Further coating of the intermediate ionomer layer with a gas recombination layer reduced the contact issues with the catalyst layer and membrane.
- It is not clear how the lattice Boltzman modeling ties to the rest of the project. It is unclear why Ru is being used since its long-term durability is known to be an issue. The SPASS design looks very promising in terms of lowering cost while improving performance over the baseline. The project needs to add membrane durability testing since the cast 2-mil membrane on a porous electrode will probably not have the mechanical strength of a similar free-standing membrane.
- The reviewer supports the innovative thinking behind the project, but it is not apparent how much this approach will impact the installed cost of an electrolyzer, much less the cost of hydrogen production. It is not clear whether the impact is through lower-cost materials or lower-cost manufacturing—and how much lower.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The project has demonstrated progress in development of methods for direct deposition of oxygen evolution reaction (OER) catalysts on the PTL, including extensive studies of the effects of alternate deposition methods. The excellent characterization results from Oak Ridge National Laboratory, which clearly show the morphology and elemental distribution of the resulting porous transport electrodes, are highly valuable. There was not enough data on durability, aside from the work on electrodeposited IrRu, which has known durability challenges.
- The project is on track to meet the project milestones after overcoming certain barriers related to ink penetration into the PTL. The project has the potential to reduce the interfacial resistance in MEAs while also reducing the manufacturing cost to meet the DOE Hydrogen Shot targets.
- This project has a challenging objective. The project seems to be behind in its timeline since it should have optimized and scaled up design at this point. The team may need to revise objectives to allow time to understand what is and is not working instead of pushing ahead to demonstration.
- The project has demonstrated good progress toward validating SPASS design. However, the baseline material seems to have the best performance in 50 cm^2 testing. This should be reconciled with the 5 cm^2 data showing improvements over the baseline.

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 good collaboration with national laboratories for catalyst coating strategy and characterization. It is not clear how the University of Tennessee modeling contributes to the success of the project. If it is to guide a fundamental change in cell geometry (rather than reproducing the same geometry with a new manufacturing process), then more information needs to be provided.
- The project has overall good interactions between the team members, especially in the realm of characterization. The role of the modeling effort in driving progress on integrated anode assemblies is not very clear, though.

- The project has good collaboration between the partners but should tie the modeling better to the experimental work.
- The project included partners from national laboratories, with universities providing technical expertise needed to accomplish the project targets.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project is addressing some of the most important barriers and could have a large impact on electrolyzer development and deployment, though an increased focus on reducing Ir loading is needed to maximize the impact.
- The project has the potential to meet the large-scale manufacturing of the electrolyzer MEAs, which is also timely and necessary to meet the Hydrogen Program and DOE targets.
- It seems intuitive that simplifying the stack manufacturing process will lead to benefits, but a techno-economic analysis (TEA) is needed to validate and quantify this view.
- High project impact can lower manufacturing cost while improving performance and durability.

Question 5: Proposed future work

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

- The proposed future work is well structured for overcoming the barriers and meeting the milestones.
- Most of the future work makes sense, but there was no mention of the catalyst electrodeposition effort or the plans for durability testing. A more detailed description of future work is recommended.
- Minimizing bleed through demonstrating 300 cm^2 stack performance will be critical to the success of this project.
- Moving to scale-up and demonstration at this point is not the best way to prove the utility of an integrated assembly, based on the remaining fundamental challenges that have been found to date.

Project strengths:

- Plug Power Inc. is one of the leaders in electrolyzer development, so engaging the company in the Hydrogen Program through this project is highly valuable. The strong efforts in development of catalyst deposition methods, as well as the excellent characterization, are key strengths.
- If all the milestones are met, the project has the potential to reduce the cost of MEA manufacturing, leading to low-cost electrolyzers.
- The project is ambitious, with an innovative idea to make a step change in stack design.
- The project has a good team with a very strong approach.

Project weaknesses:

- A stronger focus on Ir loading reduction and durability improvement is needed. While increasing OER activity and decreasing Ir loading through incorporation of Ru could be attractive, development of an approach to stabilized Ru is needed, given the well-known instability of Ru on electrolyzer anodes.
- Integration of the computational model to the SPASS is unclear, and durability improvement of conventional catalyst-coated membranes over SPASS is not well presented.
- The project has not conducted a TEA to calibrate the impact of innovations.
- The project’s modeling is not tied into experiments.

Recommendations for additions/deletions to project scope:

- The project should de-emphasize multiphase transport modeling or clarify why this aspect of the project is on the critical path for success. Potential tradeoffs with efficiency and/or durability should be addressed.
- The role of the modeling work is not very clear; shifting the associated resources to support other parts of the project should be considered.
- Membrane durability needs to be demonstrated with some on/off experiments.
- Stability of the catalyst layer coatings at high-pressure operation should be explored.

Project #P-200: Low-Cost Manufacturing of High-Temperature Electrolysis Stacks

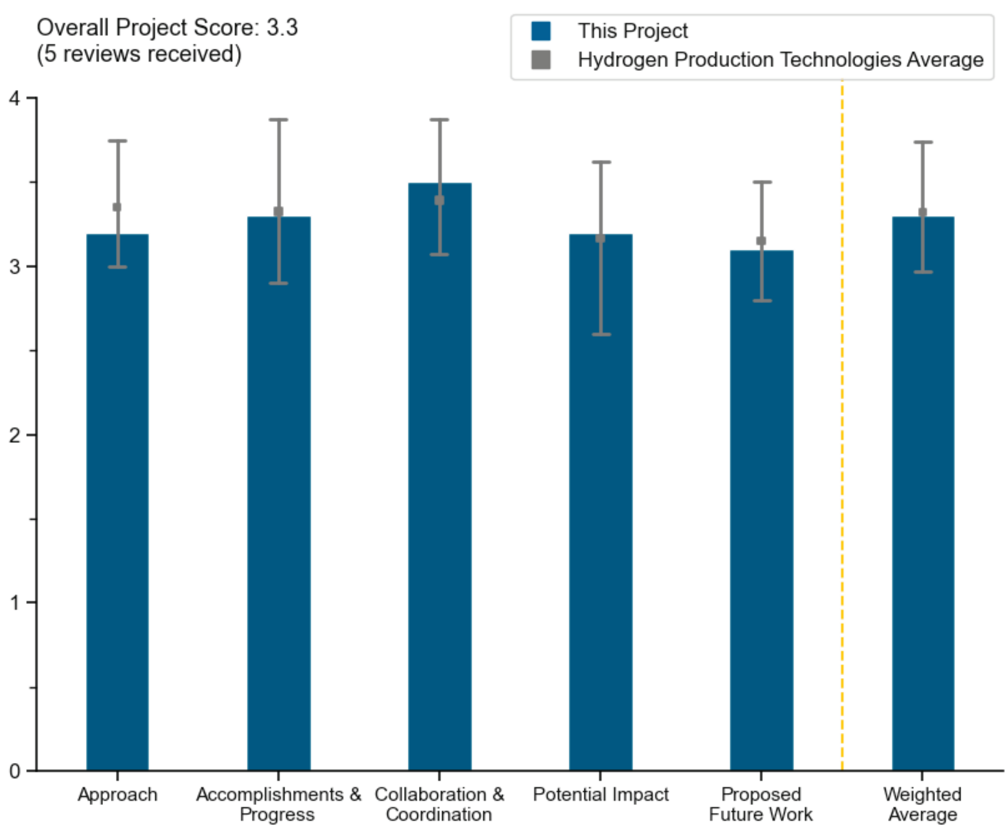
Scott Swartz, Nextech Materials, Ltd.

DOE Contract #	DE-EE0009621
Start and End Dates	4/1/2022–3/31/2022
Partners/Collaborators	Idaho National Laboratory, Strategic Analysis, Inc.
Barriers Addressed	• High-temperature electrolyzer stack cost • High-temperature electrolyzer electrical efficiency • High-temperature electrolyzer stack durability • Hydrogen production cost

Project Goal and Brief Summary

The project's goal is to develop cell and stack manufacturing technologies for high-temperature electrolysis (HTE) stacks. The primary objective is to achieve stack manufacturing costs below $100 per kilowatt, with a 15% reduction in cell costs through design optimization. The project will address key barriers, including high-temperature electrolyzer stack cost, electrical efficiency, and durability, by enhancing cell performance, stack durability, and manufacturability. The approach involves developing innovative cell and stack designs, reducing manufacturing costs, and conducting rigorous testing and analysis. Work in the second year encompasses updating baseline cost models, reducing electrolyte thickness to improve cell performance, implementing two stack cost reduction approaches, and testing stacks.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production 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 approaches that have been proposed and employed to reduce the solid oxide electrolyzer cell (SOEC) manufacturing cost are reasonable and feasible. It is very good to recycle the materials to further reduce the cost. The team also demonstrated that recycling materials can reduce the cost.
- In this project, the team identified several key areas that can reduce the cost of SOECs: changing electrolyte materials, recycling the tapes, and changing interconnect alloys. If the project is successful, the stack cost can be significantly reduced.
- The approach of conducting the cost study, performing various activities to reduce cell material and manufacturing costs, and confirming cost reduction via third-party validation is effective, and the work is well coordinated.
- The cost reduction processes are generally reasonable. However, the operating temperature (800°C) is still too high for metal interconnect loaded stacks. This could lead to fast performance decay. The team should consider ways to improve the cell performance to lower the temperature in the future. The approach involves tasks to reduce cell and stack cost on the Nexceris FlexCell. Many aspects will be addressed: validate low-cost interconnect alloy material, conduct long-term stack durability testing, reduce the number of components in the stack repeat unit, and automate stack component manufacturing. Nexceris is not an established solid oxide cell developer/marketer with competitive cell/stack performance, even after many years of DOE support. There is no competitive commercial prototype/product from Nexceris. For this project, it can only be hoped the FlexCell results from Nexceris can be useable across the solid oxide fuel cell (SOFC) industry.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The team has validated the proposed work and demonstrated the proposed methods for reducing SOEC manufacturing cost.
- Excellent progress has been made toward meeting the project objectives and targets.
- The project has demonstrated good progress on the three aspects of the proposed work.
- Progress was modest. Supply chain issues hindered progress of the effort. In the words of the speaker, only the best results were shown. The largest cost reduction opportunity is replacing scandia-stabilized zirconia (ScSZ-6) with yttria-stabilized zirconia (YSZ-3) in the support layer. The second largest opportunity is green tape recycling. The high area-specific resistance (ASR) of 0.65–0.70 Ω-cm^2 is totally unacceptable. The claimed high current of 2 A/cm^2 is not presented—and not presented over the long term anywhere at the cell level.
- The team seems to have found a way to lower the cost, but the high operating temperature could jeopardize the lifetime of the stack. The 10-cell “rainbow” stack testing results were shown only with the best set of voltage readings. The team should report the other nine cells’ voltages, too.

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 was good collaboration. Pacific Northwest National Laboratory (PNNL) helped do post-test analysis. Testing is planned at Idaho National Laboratory (INL).
- There was good collaboration with project partners INL and Strategic Analysis, Inc.
- Collaborations with national laboratories and industry are noted.
- PNNL is doing the scanning electron microscopy (SEM)/energy dispersive spectroscopy (EDS) for the Nexceris stack after a 4,000-hour test, which was funded by the DOE Office of Fossil Energy and Carbon Management. It is unclear whether this is part of proposed activities for the DOE Office of Energy

Efficiency and Renewable Energy (EERE) project. If so, it is unclear whether this should be considered baseline results or new findings from the EERE project.

- It would be better if the team could collaborate with additional institutions, for example, universities and national laboratories, to better understand the materials and manufacturing processes.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The achievements and proposed work are very important for reducing SOEC manufacturing cost. It will certainly help to achieve the DOE targets and goals.
- The project focuses on cost reduction for stack manufacturing, thus aligning well with the Hydrogen Program.
- If successful, the project can make great progress on reducing Nexceris' SOEC stack costs.
- The project will help achieve the Hydrogen and Fuel Cells Technology Office (HFTO) goals if the manufacturing knowledge gained can be transferred to an established developer and commercializer. HFTO must be the integrator. In general, the company is excellent in generating/supplying powders and will sell cells for others to stack and test. It is not desirable to create yet another SOEC manufacturer/marketer. DOE has driven three or four fuel cell technologies to market. Historically, the cost of developing a fuel cell corporate technology to the demonstration stage has taken at least a $1 billion and decade(s) per technology. There are eight years left to 2030 and only limited funding to reach the Hydrogen Program goals.
- Without further reducing the operating temperature, it would be a challenge to improve the lifetime of the stack, which is a critical barrier for HTE technology.

Question 5: Proposed future work

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

- The near-term plans are good: (1) exercise Strategic Analysis' cell and stack cost models to identify additional cost reduction opportunities, (2) build and deliver an HTE stack for validation testing at INL, and (3) conduct a 1,000-hour stack test to close out the first go/no-go milestone. However, there are only eight years left to 2030 and only limited funding to reach the Hydrogen Program goals. Funding yet another SOFC developer/marketer may be impossible. The impact of this technology will not impact the 2026 or 2030 goals.
- The proposed future work is feasible and important. It would be better if the project could do a better study of the interconnect materials.
- Degradation studies should be proposed. Ways to reduce the operating temperature should be investigated.
- The proposed future work is broad, lacking specifics, e.g., "to identify additional cost reduction opportunities."

Project strengths:

- The project strength mainly relates to the approach to conduct detailed cost analysis to identify appropriate cost reduction opportunities.
- The entity has the capability to partner well with the national lab complex, especially PNNL and INL. The work is very valuable to Nexceris.
- The team has all necessary expertise to conduct the proposed work. The researchers have demonstrated good progress on research and development.
- Recycling the materials reduces the SOEC manufacturing cost.
- Some ways to lower the cost have been identified.

Project weaknesses:

- The project needs transformative (rather than incremental) approaches/ideas to further reduce stack costs.
- Instead of weaknesses, the reviewer poses two points for clarification:
    - Cost estimation: Slide 4 shows the Nexceris stack cost was $426/kW (as of the proposal), and it can be reduced to <$100/kW if this project is successful. In the later slides, it shows the stack cost will be $123/kW. With all the estimated savings presented in the slides, it seems like the cost and cost-saving numbers do not add up.
    - Interconnect ASRs: Slide 18 shows the new alloy's ASR was continuously reduced from ~400 hours until the end of the test, and since this is after 400 hours, it was not the so-called "burn-in" effect. An investigation into what happened will be really useful.
- Cost reduction and manufacturing knowledge gained may be too specific to be widely useable by the industry.
- No intentions have been shown to further reduce the operating temperature to improve the stability.
- No weakness was identified.

Recommendations for additions/deletions to project scope:

- It would be better if the team could perform additional work to study the interconnect materials.
- The project should study ways to lower the operating temperature.
- There are no recommendations for additions or deletions to project scope.

Project #P-201: Automation of Solid Oxide Electrolyzer Cell and Stack Assembly

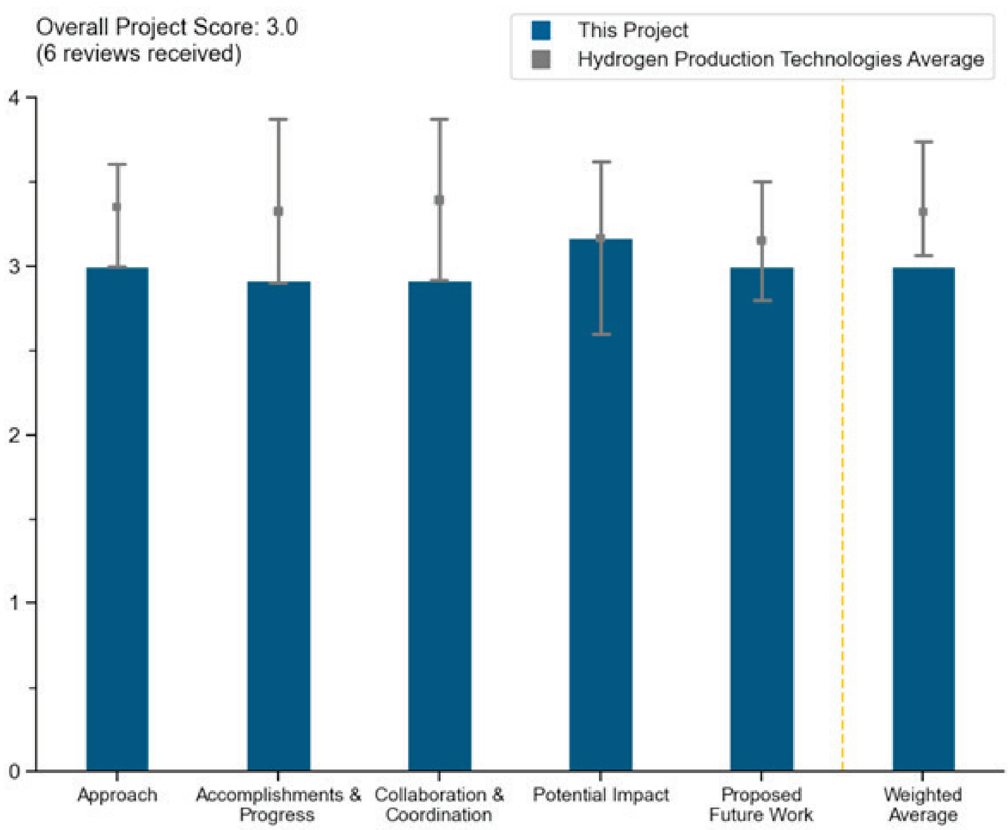
Todd Striker, Cummins Inc.

DOE Contract #	DE-EE0009622
Start and End Dates	8/1/2022–1/31/2025
Partners/Collaborators	
Barriers Addressed	• Traceability: processes corrupt barcodes • Meeting capital investment budget • Space: the solutions provided fit within 15 ft^2/MW

Project Goal and Brief Summary

The goal of this project is to develop high-volume manufacturing and quality control processes for solid oxide electrolyzer cells (SOECs) and stacks. The project aims to achieve targets such as an 85% reduction in direct labor, a 63% decrease in cycle time, and a 15 ft^2/MW annual capacity, which will contribute to reducing the cost of goods sold and support the Hydrogen Shot “111” goal. The project’s accomplishments include baseline and preliminary requirements, process and gauge developments, automation development, traceability improvements, and equipment down-select. The next steps involve risk reduction, equipment installation, facility integration, commissioning, and steady-state operation to demonstrate project manufacturing targets.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production 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 is at its early stages, and unfortunately, the principal investigator could not attend the Annual Merit Review. Stack production and assembly automation is imperative to reducing overall stack costs. The reviewer is looking forward to future updates. Perhaps the team could consider including the following for the next update:
    - A description of the equipment (to the extent possible) and the complexity of identifying equipment that can be bought off the shelf versus equipment that needs to be designed with vendors for a specific application.
    - The major differences, if any, for automation of an SOEC production line versus a solid oxide fuel cell (SOFC) production line. For example, scale of systems/stacks might play a major role in the difference of equipment needed.
    - The equipment that is the most complex to incorporate, why, and how such risks could be reduced through design and installation.
- The Cummins Inc. (Cummins) team has identified key areas to reduce the SOEC stack manufacturing cost through automation.
- Cummins will leverage its limited SOFC experience. However, the project will utilize Cummins' core manufacturing competence, expertise, initiatives, and supply chain and will emphasize quality control and traceability for a predictable product.
- Standard industrial automation processes have been designed, and quality control procedures have been documented. It is unclear how many cells have actually been processed to test out the automation and quality control systems.
- One important aspect of this project is large-scale manufacturing demonstration. However, more details, especially on process operation and integration, should be given on barriers and approaches to overcome those barriers.
- The presentation is very general (or superficial) and lacks specific details for technical evaluation. The fabrication processes/steps seem to be routine and reasonable. The uniqueness and advantages of the fabrication process were not well articulated, nor were the critical barriers/challenges and the proposed approaches to overcome them. There is room for improvement in sharpening the focus on critical challenges.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and DOE goals.

- The manufacturing improvements work is clearly not tied to SOEC performance. SOEC performance, even short-term, is not presented at either the cell or stack level. Lack of SOEC performance makes the SOEC manufacturing work possibly drop into the categories of "the irrelevant." The project may become a mere manufacturing exercise. Cummins appears to be committed to the underlying solid oxide cell (SOC) technology, and DOE welcomes such commitment. With excellent facilities and a large number of experts with diverse expertise within Cummins, Cummins could easily become a major SOEC player if the company is open-minded to different SOEC technologies. Indeed, Cummins is an important electrolyzer player in proton exchange membrane electrolyzer cell technology and could be in SOECs if its efforts are connected to a successful underlying technology that establishes SOC performance.
- It appears that some reasonable progress has been presented. However, it is not clear how the cells or stacks produced by the automated fabrication processes may perform under typical operating conditions. Perhaps it is still too early to ask this type of question since only a small amount of the budget (~$331,000 of $5 million) has been spent on the project so far.
- During budget period (BP) 1, the team did the analysis and identified key supplies, which is the go/no-go point.

- Significant accomplishments and progress are reported on process development; however, it is not clear how these contribute toward the overall project and DOE goals.
- The project's slow progress was caused mainly by supply chain blockage.

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 presentation did not cover this topic, other than to state that vendors and equipment have been identified, so collaboration is difficult to evaluate.
- The project has limited collaboration, with no subrecipients on this award. Domestic suppliers have been engaged where and when possible.
- Although the project has no subrecipients, no information or discussion was provided on how the project activities are coordinated and how various suppliers are engaged.
- It seems that Cummins does not have a partner institution for this project.
- The slides did not mention external collaborations.
- The project has no collaborations.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- If successful, the automated fabrication process developed may reduce the capital cost of cells and cell stacks, thus contributing to achieving the Hydrogen Shot "111" goal.
- The project's new automation and quality control systems could benefit cost-effective mass production of cells in the future.
- The project focuses on large-volume manufacturing demonstration and cost reduction, and most aspects support the Hydrogen Program objectives.
- Automation is a very important aspect of SOEC/SOFC production. The wider audience would appreciate a more detailed description of equipment and the fabrication line so that lessons learned by Cummins can be applied across the industry.
- If successful, the Cummins stack cost would be significantly reduced.
- The manufacturing improvements are clearly not tied to SOEC performance, which limits relevance and impact.

Question 5: Proposed future work

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

- Reasonable tasks have been outlined for future work, and proper approaches have been proposed to address the remaining challenges and barriers. Examining the electrochemical performance of the fabricated cells and stacks to ensure that their quality is sufficient for cost-effective commercialization would be beneficial.
- Project lead times are still turbulent, as the schedule will have some dependence on equipment delivery. Integrating equipment with reliable traceability and integrating with the manufacturing execution system still carry some risk. Most of the project's work will be dominated by execution when equipment arrives. Cummins is still exploring materials and process development to reduce the drying space required.
- The proposed future work lacks specifics (e.g., ship equipment in 2024 does not have any information on the key pieces of equipment or estimated shipment date).
- It is unknown when the supply chain issue can be resolved.

Project strengths:

- The project's automation and quality control systems for mass production of electrolysis cells, stacks, and systems are its greatest strengths.
- The project will utilize Cummins' core manufacturing competence and expertise, initiatives, and supply chain and emphasize quality control and traceability for a predictable product.
- Automation of the fabrication process has the potential to reduce the cost of SOCs and stacks, although many challenges seem to remain.
- The strengths of this project include high-volume manufacturing demonstration, quality control, and cycle time improvements.
- Cummins is utilizing its strength in the manufacturing and automation of SOEC manufacturing.

Project weaknesses:

- During BP 1 (nine months), the team spent ~$331,000, which is about 6%–7% of the budget. During the question-and-answer session, if understood correctly, the presented indicated that the majority of the Phase II budget will be on equipment purchasing. It would be helpful to know the total cost of the equipment.
- The project is still in the early stages, so it is difficult to assess the degree of the project's success. It seems there is still a long way to achieving the project goals.
- The manufacturing improvements are not tied to SOEC performance, which limits relevance and impact.
- The project lacks testing of the designed automation system because of the backlog of parts.
- The project lacks innovations and appears to rely on conventional approaches for process improvement.

Recommendations for additions/deletions to project scope:

- Careful evaluation or inspection of the electrochemical performance of the fabricated cells/stacks would be helpful to quality control of the automated fabrication processes.
- The project should commission and qualify the designed systems with a sufficient number of cells.
- There are no recommendations for additions or deletions to project scope.

Project #P-202: Novel Microbial Electrolysis Cell Design for Efficient Hydrogen Generation from Wastewaters

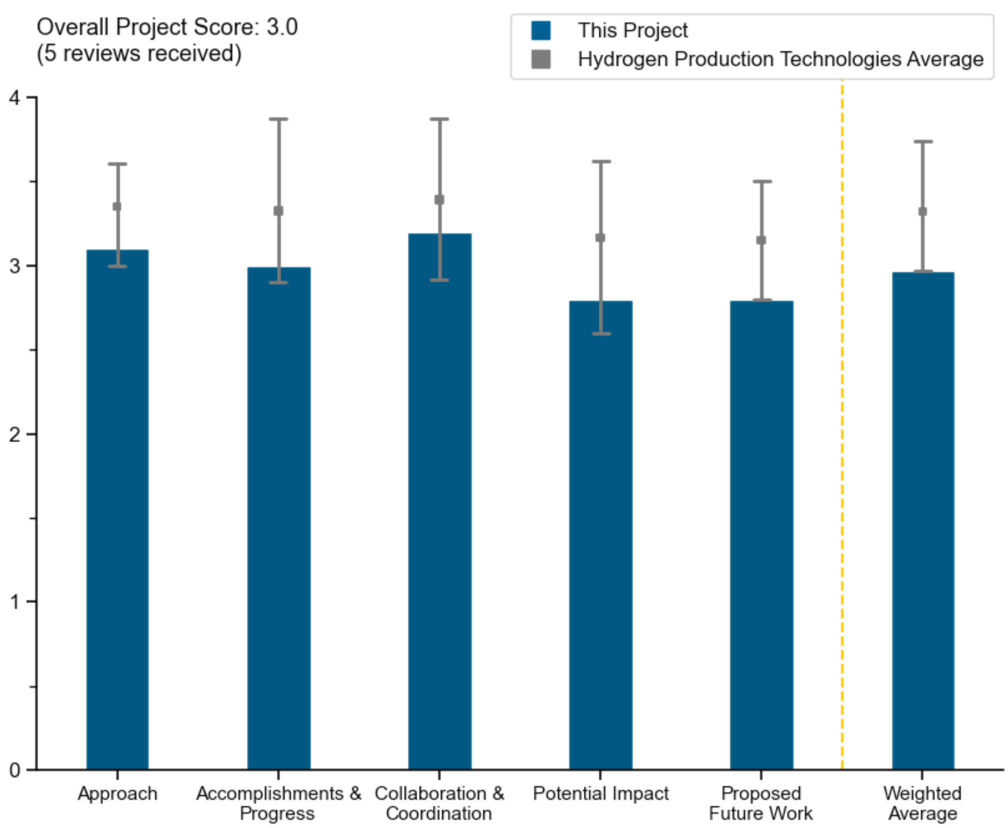
Bruce Logan, The Pennsylvania State University

DOE Contract #	DE-EE0009623
Start and End Dates	9/1/2021–9/30/2024
Partners/Collaborators	Johns Hopkins University, National Renewable Energy Laboratory, Island Water Technologies
Barriers Addressed	• Low cell efficiency • Small current density • High cathode cost and poor H_2 production

Project Goal and Brief Summary

This project seeks to offer a cost-effective method to generate hydrogen, utilizing wastewater as a renewable resource while reducing feedstock costs and environmental impact. The primary objective is to develop a novel design for a zero-gap bench-scale (100 cm^2) microbial electrolysis cell (MEC) that efficiently produces high-rate hydrogen from wastewaters. The innovation involves combining an anion exchange membrane (AEM) and eliminating the use of a liquid catholyte, resulting in improved current density, hydrogen production rates, and pH stability. Activities include testing hydrogen production from various feedstocks and optimizing the fermentation process, as well as validating and optimizing MEC performance. Additionally, researchers will prepare cathodes free of platinum group metals (PGMs). The ultimate aim is to demonstrate a pathway for hydrogen production at scale using wastewater feedstock, while addressing cost, performance, durability, and scalability challenges.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production 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 Pennsylvania State University (Penn State) has clearly identified the critical barriers for a microbial approach to generating hydrogen at a cost of \$1/kg H_2. There is some confusion as to whether the DOE goal is \$1 or \$2/kg H_2 for hydrogen generation via microbial pathways. This should be clarified at the next Annual Merit Review (AMR). The Penn State milestone schedule indicates the project is well designed and feasible. Partnering with Island Water Technologies (IWT) gives Penn State a pathway to developing an off-take customer for hydrogen, as wastewater treatment plants are being developed for both renewable natural gas and hydrogen generation. The wastewater treatment plant could have a direct path to placing the hydrogen in pipelines.
- The project uses a novel MEC design strategy (a zero-gap membrane with vapor feed at the cathode), which is a different approach that should definitely be explored. The results could change the game for MECs.
- The project team is going to a vapor feed for the anode, which is a good choice and should lower overall cell potential. The research on a non-PGM catalyst for an alkali system seems very reasonable. The AEM membrane research will be difficult. There is not a stable AEM for regular water electrolysis, and this system will be harder. There will likely be reactant crossover (ethanol, formate, lactate, etc.), which could be a potential problem. The separation of the formate, ethanol, and lactate from the fermentation broth will likely be very expensive. A cost analysis should be done. It is surprising that Hydrogen Analysis (H2A) was not included in the approach. The approach adds a second separation for the buffer recycling. Addition of two new unit operations may increase the cost.
- There was great demonstration of the progress achieved so far, for an innovative new idea. The performance of the system indicated an encouraging high hydrogen productivity but at a small scale. It appears that the system has limitations in the concentration of certain organic compounds, but the presentation did not provide any indication of the effect or how it changes with the concentration. The project also did not discuss whether the same compounds affect the alternative configuration.
- The project is developing a zero-gap MEC cell with a PGM-free cathode and with vapor feed to the cathode to replace liquid catholyte. From the presented concept and results, it is not clear how the vapor feed for the cathode will be generated and how vapor condensing within the cell will be avoided. The expected performance conditions—temperature, pressure, and flow rate—should be reported, as well as a schematic process flow diagram (PFD) for the whole system integrating the MEC.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- Penn State is making good progress toward achieving the project objectives. The team has well-defined metrics and good comparisons to other existing microbial electrochemical cells. Greater discussion on off-take pathways might allow for better assessment of achieving DOE goals for microbial hydrogen generation, specifically in estimating production cost. At an estimated program execution of 58%, this project may be underspent. It is proposed that project spending be reviewed at the next AMR.
- By separating out the formate, lactate, and ethanol from the broth and using only those organics, this is now very similar to other work in electrolysis reported elsewhere. The separations cost may be significant. The DOE Bioenergy Technologies Office program has a consortium dedicated to separations. The identification of the NiMo catalyst was a good accomplishment. Identifying a good buffer for the MEC is an important accomplishment. The use of a buffer may increase the operating and manufacturing (O&M) costs. At the voltages applied and with the carbon felt (which is a catalyst), the project may be doing electrochemical destruction of the organics. The principal investigator reported high durability. This may be a bit premature since the technology has not run for long periods. Long-duration (1,000+ hours) needs to be done to ensure no biofouling. It would be interesting if the project could report the half-cell potentials; since the project has a reference electrode, this should be easily done. An impedance spectroscopy is recommended to better understand the limits of the cell.

- The project is a contribution toward the goals of the DOE Hydrogen Program and has achieved and exceeded the productivity target—but only at small scale so far. Moreover, there was no estimate on how this productivity gain, but in a different system, will affect the cost of the produced hydrogen.
- The project performance has been delayed by Dr. Rossi's moving from Penn State to Johns Hopkins University (JHU). The necessary project modifications have been completed, and the work should be resumed at JHU. High current density for the MEC performance has been observed, though testing was done with very small cells, and it is not clear how much this performance can be sustained for larger cell size and for multiple cell stacks.
- It would have been good to see at least initial attempts at getting results on a real wastewater feed at this point in the timeline. The project should make sure to do so before the next AMR, as outlined in Future Work.

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.

- Penn State has shown good collaboration with the National Renewable Energy Laboratory (NREL) in developing biological buffers for microbial feedstock. Discussions about the status with IWT could be helpful in determining the project's impact. The project could engage IWT to outline possible hydrogen off-take pathways. This may have been addressed in the proposal and could perhaps be provided in the backup slides at the next AMR.
- The team has well-defined roles, the members have worked together before, and they seem to be doing well.
- Good collaboration is established between Penn State and JHU and NREL. The project is also working with IWT for wastewater supply for testing and for technology commercialization.
- It is nice that the project is working with NREL, but so far, it is only to obtain a model wastewater feed and advice. The project has not yet benefitted from collaboration with IWT.
- The project appears to have good collaboration, at least on paper.

Question 4: Potential impact

This project was rated **2.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project led by Penn State has an excellent alignment 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. Per the discussion on the team, IWT has been identified to promote the technology. It might be beneficial for IWT to outline a hydrogen off-take pathway. If successful, this project may advance progress toward the DOE RD&D goal of hydrogen production of $1 or $2/kg H_2.
- The objectives of the project appear to align with the Hydrogen Program goals and the DOE RD&D goals. The outcome will likely enhance knowledge and understanding of the process, even if at the end, the proposed system will be abandoned. However, the presentation did not provide any indication of how the system could move toward the cost targets that have been set. Thus, it is difficult to fully characterize the alignment with the totality of the goals.
- MECs will be a niche production pathway for hydrogen, but within this space, the project is novel and has the potential to maximize the utility of MECs.
- Production of hydrogen from fermentation of waste streams fits within the Hydrogen and Fuel Cell Technologies Office portfolio. By adding additional unit operations, the researchers have lost the simplicity of the original MEC. The new unit operations (there are two separation steps, one for the substrate and one for buffer recycle), along with the buffer, will likely add cost and may make it difficult to achieve the goal of low-cost hydrogen. The Remaining Challenges slide states that acetate is the ideal substrate and that the ethanol, formic acid, and lactic acid are difficult. The team's mitigation of this is dependency on other projects to genetically engineer strains to increase the acetate and minimize the other compounds. This seems to say that the success of this project is dependent on other projects. The other projects have been working on genetically engineering strains to eliminate production of the other compounds for a long time.

- The project needs to conduct a techno-economic analysis (TEA) to determine cost of hydrogen production. Apparently, most revenue for the system operation would arrive from the credit for wastewater cleanup and treatment. A TEA should determine what the contributions are of the wastewater cleanup, the MEC system cost, and the consumed power in the cost of hydrogen. It is likely that MEC technology would be primarily applicable to cleaning small-size water streams, and it is not clear how much the technology can be scaled up to match the available feed streams. It is not clear how pure the hydrogen produced by the MEC is and how the requirement for further purification would affect the cost of hydrogen.

Question 5: Proposed future work

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

- Penn State has effectively planned the project to address the DOE goals for hydrogen production through biological methods. The program has been executed well against its project plan. The proposed solutions for the remaining challenges and barriers may be successful. There is some concern the approach to TEA may not be inclusive of all costs. The project is asked to outline the factors to the TEA at the next AMR. If a TEA task does not exist in the project, perhaps it can be added with support from the national laboratories.
- On the positive, the presentation indicated that the team has identified barriers to the success of the product, such as the variability of buffer concentration in a real system, the presence of organic compounds that could affect system productivity, and the requirement of a pretreatment step to remove solids. It seems that the team plans to test some solutions to these issues, but the presentation provides only milestones and should clarify the target stability. It is not clear whether the advantages of zero-gap MECs will hold in a real system. It is not clear how stability/lifetime will be evaluated or how the buffer variation will be simulated.
- The project needs to add an H2A analysis and show a reasonable pathway to achieving the hydrogen cost targets. The project team does not mention the challenge of biofouling, which has historically been a challenge to MECs, and should clarify whether the problem has been solved. Long-duration flow-through tests are needed. The AEM fouling needs to be studied. In addition, there may be crossover of the substrates. The impact of crossover (if it is happening) needs to be understood.
- The focus on moving to real wastewater feeds from NREL and IWT is commendable.
- The proposed future work is reasonable on continuing technology development.

Project strengths:

- The team is very strong and includes industry, as well as academia and a national laboratory. The project has identified a non-PGM catalyst. The approach has the potential to use a very low-cost, perhaps even free, feed stream. The use of an AEM has potential to lower costs.
- The project adequately studies MEC operational parameters on performance (although from the presentation, it is unclear why these parameters, and not others, are being studied). The convincing comparison with other studies seems to document the advantages of the system at lab scale.
- The project strengths are highlighted by the teaming between Penn State and IWT. The connection to NREL is also prized and could grow if a TEA is also pursued.
- The project has a novel approach and a fundamental understanding.
- The project made good progress in demonstrating high-current-density operation.

Project weaknesses:

- The path to \$2/kg H_2 is not identified. This is particularly important since the project is adding several unit operations. In chemical processing plants, separations are the most energy-intensive process. The addition of the AEM may work, but the principal investigators did not mention the risk of biofouling or substrate crossover with the membrane or electrolysis work. AEMs have not had excellent durability. The project's success seems to be dependent on the success of other projects to genetically modify strains to increase the titer of the desired substrates and the development of stable AEMs.

- Per discussions during the reviewer questions at the AMR, there are questions as to the performance of the microbial electrochemical cell. Carbon corrosion could be skewing the energy consumption. A greater weakness may be the need for buffering. The cost of buffering should be reviewed, as it might have a big impact on achieving the DOE cost targets.
- The project is small-scale at the moment, and there is no indication of longer-term operation/lifetime. The industrial partner's contribution is unclear. The project has no quantification of the effect of higher productivity on the final cost.
- The novel approach may lead to wastewater quality specifications that limit the range of wastewater feeds that can be used. The question of how broadly applicable the approach can be, should be addressed soon—if not in this project, in the next.
- The project is still in a very low technology readiness level, and it is not clear how much commercial interest there would be for technology application.

Recommendations for additions/deletions to project scope:

- The project should provide data to quantify the effect of organic compounds at different concentrations. Perhaps the system is more sensitive than alternatives to these compounds. With a target of 20 L H_2/L-reactor·day and achieved productivity of 70 L H_2/L-day, it seems that there might be some room to give. The study of the design at a larger scale should be done quickly (if indeed that is the projected size) to demonstrate that the advantages will hold at that scale.
- The project should develop a PFD for the hydrogen production system that would integrate the MEC stack and analyze the mass and heat balance, particularly associated with vapor generation. A detailed TEA should be performed to estimate the cost of hydrogen production.
- An H2A analysis is needed, with reasonable (not overly optimistic) assumptions for the capital and O&M costs of adding the additional unit operations and the cost of buffers.
- The project should outline the factors to the TEA so it can be added with support from the national laboratories.
- The project should consider exploring the potential to pressurize the vapor on the cathode side, as mentioned in the question-and-answer session.

Project #P-203: Novel Microbial Electrolysis System for Conversion of Biowastes into Low-Cost Renewable Hydrogen

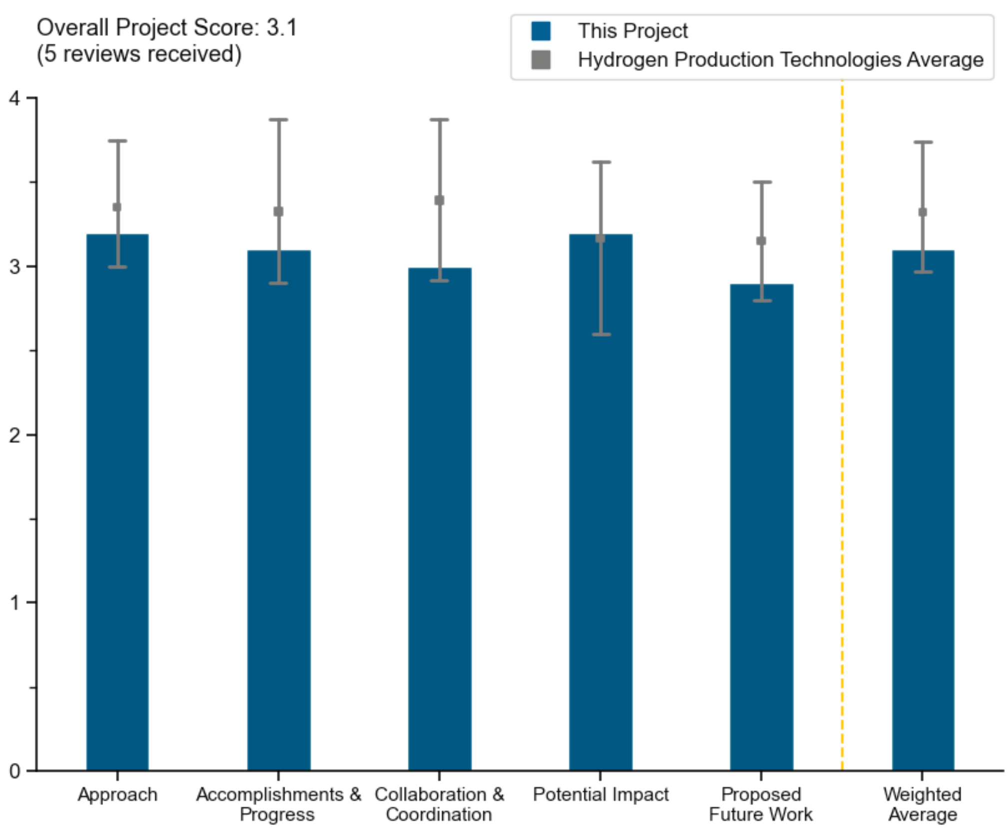
Noah Meeks, Southern Company Services, Inc.

DOE Contract #	DE-EE0009624
Start and End Dates	11/1/2022–10/31/2025
Partners/Collaborators	Electro-Active Technologies, Inc., T2M Global
Barriers Addressed	• Scale-up • Performance • Durability • System/process engineering

Project Goal and Brief Summary

The project aims to identify critical scale-up parameters and develop a microbial electrolysis cell (MEC) stack to achieve target hydrogen productivity (>20 L/L-day). It also focuses on demonstrating the stability and durability of MEC technology and developing an integrated waste-to-hydrogen system using commercial food waste. The project seeks to enable distributed hydrogen production, increase hydrogen yields in MECs (>40%), and provide a renewable source of hydrogen while abating waste management costs. By the end of the project, the project team will demonstrate an integrated waste-to-hydrogen system using commercial food waste to produce hydrogen with end use in fuel cells.

Project Scoring



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

- Southern Company Services, Inc. (Southern Company) has proposed an effective approach to overcoming the barriers of hydrogen production via a microbial pathway. Some of the data reviewed needs further explanation—specifically, the drop in efficiency and current density as the microbial electrochemical cell is scaled to 10 L. The team being led by Southern Company has strong analysis, technology partnership, and off-take in Southern Company Gas.
- The project focuses on scale-up and commercialization of hydrogen production by MCE technology previously demonstrated by Oak Ridge National Laboratory (ORNL) and Electro-Active Technologies, Inc. Conducting detailed techno-economic analysis (TEA) and life cycle analysis (LCA) and understanding biomass yield and degradation mechanisms will be a significant part of the project. The project outlines all the important parameters in the process that will be optimized throughout the period of performance.
- The project team is demonstrating a scale-up approach for a specific MEC system. Unfortunately, the system factors are not included (catalyst, anode/cathode material, etc.). It is unclear from the presentation whether the results shown are applicable to other systems (smaller cell size with multi-cell systems) or whether other systems simply have to follow a similar (to this project) approach to determine their optimal configuration. Thus, the work presented does not seem to "Identify critical scale-up parameters and development of MEC stack to achieve target hydrogen productivity," which is listed as the objective of this phase. The authors are clearly aware of the various parameters affecting MEC biofilm optimization and MEC optimization, as some introductory slides demonstrate, but the presentation (at least) does not show how the team identified the critical parameters through the project. Instead, the presentation gives the impression that the team followed a predetermined scale-up approach (which is useful on its own but as a demonstration).
- The team is using Hydrogen Analysis (H2A) to help determine a pathway to low-cost hydrogen. The team is licensing a fermentation technology, which means it is more mature than having to start with trying to discover or genetically engineer one. The scope is ambitious for the budget. The project does not include the biofilm fouling of the membrane. The use of the membrane with food wastes will likely result in biofilms. It is not clear that the approach has work scope to address or mitigate this risk. The team is planning on subcontracting out the TEA and LCA to another company and will do it based upon some scale-up, which will result in a better TEA.
- The main barrier this project seems to be addressing is demonstration of a commercially viable continuous MEC system. In this regard, it appears the focus is to engineer an MEC system. The plans to do this seem reasonable, but it is hard to tell how robust they are. The target waste stream (generically referred to as food waste) is unclear.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- The project team has made excellent progress, considering the project started in the fall of 2022, and has identified some optimal operating conditions. The high hydrogen recovery in the 2,000 ml and 10,000 ml reactors suggests that the project team is splitting water and may want to talk with some electrochemists. There may be simple designs that would eliminate this. The selection of 80 ml volume cells may result in stacks with a large number of cells in a real system, which is significant because it will result in higher manufacturing costs than if larger-volume cells were used. There is a reason the fuel cells and electrolyzers are scaling their active area to reduce costs. Slide 12 has the target impedance of <0.8 dkohm-cm^2, and it is not clear that the project team has validated this. For slide 10, it is not clear how long the system was operated ore what the operation conditions were. There are additional questions: whether the feed was recycled, what the temperature was, and what the flow rate was. In addition, the project is asked to define cathode efficiency. For slide 11, for the impedance, the project is asked to explain why the impedance increased with volume, i.e., perhaps it was an increase in ohmic. It is not clear what the mass transfer was. It would be helpful for the project to integrate a reference electrode to run the impedance and other tests. There is no data on lifetime operation. It is not clear how the performance changes.

- Although the presentation does not seem to fully address the project objectives, the work is quite useful as a practical demonstration of the scale-up of the MEC systems. The drawback is that there is no explanation (in the presentation) of why the criteria were selected (maybe an explanation will be shown in a later report) and how/if the approach should be followed at each MEC system. Irrespective, this work could be used by other programs, based on laboratory results, to test and understand scale-up. Although (after trying multiple scales) this project seemed to settle in a multicell 80 ml system, other projects in the Hydrogen Program (the Program) are targeting the higher scale. It probably suggests a gap in the knowledge transfer among the Program's projects.
- The project started about two quarters ago and has developed scale-up strategy and demonstrated cell scale-up by about a factor of 125. Significant decrease in cathode efficiency and hydrogen production per liter reactor was reported for larger reactor volumes, which suggests that uniformity of the reactant and current distribution across the cell remains a challenge. The project needs to carefully analyze the scaling-up factors to resolve this issue.
- Southern Company is making good progress toward achieving the project objectives. The project has well-defined metrics. Southern Company could include a summary chart to better highlight the milestones and progress on tasks.
- The project has reasonable progress for the first six months, with components being built and tested.

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.

- Southern Company has good collaboration with its partners. Southern Company has enabled Electro-Active Technologies to scale up the project technology and provided a pathway to off-take hydrogen when production is available. Southern Company has also partnered with T2M Global (T2M) and a consulting company for the environmental resources management to support the TEA and provide the levelized cost of hydrogen being produced from the microbial system.
- There is no indication of a less-than-good collaboration. The team seems quite familiar with work in the area and builds on that.
- Close collaboration between Southern Company, Electro-Active Technologies, and T2M should lead to fast commercialization of the technology if design performance is demonstrated.
- It is not clear how Southern Company is involved, while Electro-Active Technologies is doing most of the work. The reviewer is looking forward to seeing the TEA from collaboration with T2M.
- The team includes a system manufacturer and end users; however, the roles and responsibilities are not clearly presented.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project led by Southern Company has excellent alignment with the 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 TEA should provide DOE with a clear status as to the maturity of microbial pathways for hydrogen production.
- Commercialization of an MEC system has the potential to provide two-pronged societal benefits of abating waste management costs, while producing a renewable local source of hydrogen for use in fuel cell equipment. While conducting TEA and LCA, the project should focus on determining the optimal scale at which the MEC technology could be deployed and commercialized, what types of waste streams can be processed, how much hydrogen can be produced, and how much downstream purification would be required.
- The project aligns with the Hydrogen and Fuel Cell Technologies Office's goals. The project will co-produce CO_2. There will be competition for the food waste since food waste can be converted to biocrude via hydrothermal liquefaction, which can then be made into products such as bioplastics and other bioproducts.

- Investigating and demonstrating how lab-scale results can hold up upon scale-up is crucial in the development of this and any technology. To that end, this is a useful project in the overall Program, particularly around MEC.
- Inherently, MEC will be a niche production pathway for hydrogen. This project meets DOE objectives of accelerating deployment of new technologies.

Question 5: Proposed future work

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

- A Gantt chart or some critical path for the future work, rather than "execute on the remaining scope," would be helpful to see. The project is doing an H2A analysis. The future work would benefit from using the H2A analysis to identify the research and development areas that would make the largest cost reductions. The project does not include the biofilm build-up on the membranes as a potential risk. In other work in this area, formation of biofilms has fouled the systems, which is even worse for units that use a separation membrane. The use of the membrane with food wastes will likely result in biofilms. The project needs to report on long-term operation.
- The proposed future work described in slides 16 and 17 of the presentation raises the right questions (durability, different feedstocks) but lacks specificity. This gap makes it very difficult to comment on whether the project has effectively planned its future. For example, the project could clarify which feedstocks can test or "stress-test" the "stability and durability of MEC technology" and how they will be selected. The project should also clarify whether the size of the cell (selected on impedance analysis) is the optimal scale for durability. The future plan could address this question.
- The project's presentation was thin on plans for future work, so it was hard to judge. It is good to see that Southern Company will get more involved. If future work indeed includes looking at landfill gas as a feedstock (an odd choice), the project will need to compare other ways to utilize this feedstock to make hydrogen, such as modular reforming or pyrolysis.
- The future work is centered around evaluating business cases around specific Southern Company projects, which should promote fast-track commercialization of the technology.
- As this project is in an early stage, Southern Company is focused on executing on project scope. It is assumed risk analysis and risk mitigation will be available as the demonstrations progress.

Project strengths:

- The project has made excellent progress. The work scope looks like the project team is focused on the correct areas. The project team has included an H2A TEA analysis. The team has a manufacturer and end users. Electro-Active Technologies is a spin-out from ORNL, developed in the I-Corps program. This program would give Electro-Active Technologies a good foundation upon which to build.
- The project strengths are in identifying an off-take for hydrogen and the focus on the TEA.
- The project is practical and has useful demonstration data on system performance at different scales.
- The project focuses on demonstrating commercial viability of MECs.
- The project has a strong commercialization component.

Project weaknesses:

- There are no project weaknesses at this stage of execution. There is concern issues can exist with microbial reactor scaling. More discussions are suggested as to the decrease in performance when scaling from 16 mL to 10 L.
- It is recommended a reference electrode is used in the electrochemical tests to better understand the performance of the cells. The reference electrode can inform on which reaction is limiting, if the limits are due to kinetics or mass transfer, and better elucidate failure mechanisms.
- The project does not indicate whether the project findings on "optimal scale" are universally applied. It would have been useful to discuss/explain the rapid deterioration of the system performance with scale. An

estimate of the economics of the hydrogen based on the findings is missing (there is a graph from a reference paper but not a direct estimate from the findings here).

- The project needs to address the biofouling and mitigation. Long-term operation needs to be reported. The TEA and LCA need to be completed.
- There is a potential for fundamental challenges (e.g., feedstock heterogeneity, fouling, hydrogen separations) to derail the project.
- The project just started, and it is difficult to evaluate the results obtained up to date. Initial results on MEC scale-up suggest significant loss of efficiency at larger scales, which may be a challenge.

Recommendations for additions/deletions to project scope:

- A close inspection of the current densities listed in table 10 (dimensionless) and comparison with the estimated current densities (by cell area and current) on slide 12 show that they are not the same (for the same scale). The project should clarify if these are different sets of experiments and why. The data in slides 10, 11, and 12 for the 80 ml volume are all different. In fact, the 30 A/m^2 at an 80 mL scale is not achieved in slides 10 and 12. Some discussion is necessary since achieving this current density is shown as the key selection factor for the cell size. On slide 10, summary results are seen at five scales, but there is no attempt to discuss the dependency of the responses to the scale or what would be a way to develop some predictive approaches, which would be a useful contribution. Moreover, simple inspection of the data in slide 12 shows that in addition to the scale, the five experiments have different cell area-to-volume ratio (~2.5 cm^2 per ml at small scales to 1.25 cm^2 per ml at the higher volumes). The project does not discuss whether the ratio has an effect and, if yes, how this ratio will be used during system performance optimization. Discussion is needed. At least, one would have expected that the ratio should have stayed constant upon scale-up. Although the four cells in the photographs on slide 10 appear to be similar in the relative ratios of their dimensions (avoiding any additional complication in the interpretation of the results), it is quite possible that the exact dimensions of the cell (height, width, depth) may be important (instead of the volume alone). It would have been nice to have some commentary on that. An estimate of the economics of the hydrogen based on the findings is missing (there is a graph from a reference paper but not a comparison with the findings here).
- The project needs to address the biofouling and mitigation. Long-term operation needs to be reported. The TEA and LCA need to be completed. It is recommended that the team use a reference electrode in electrochemical tests to better understand the performance of the cells. The reference electrode can inform on which reaction is limiting, if the limits are due to kinetics or mass transfer, and better elucidate failure mechanisms.
- The project could consider how the hydrogen will be used locally, or brought to market, if production units remain at the scale being considered.
- No changes in scope are required.
- The reviewer has no additions or deletion to the current project scope.

Project #P-204: Hydrogen Production Cost and Performance Analysis

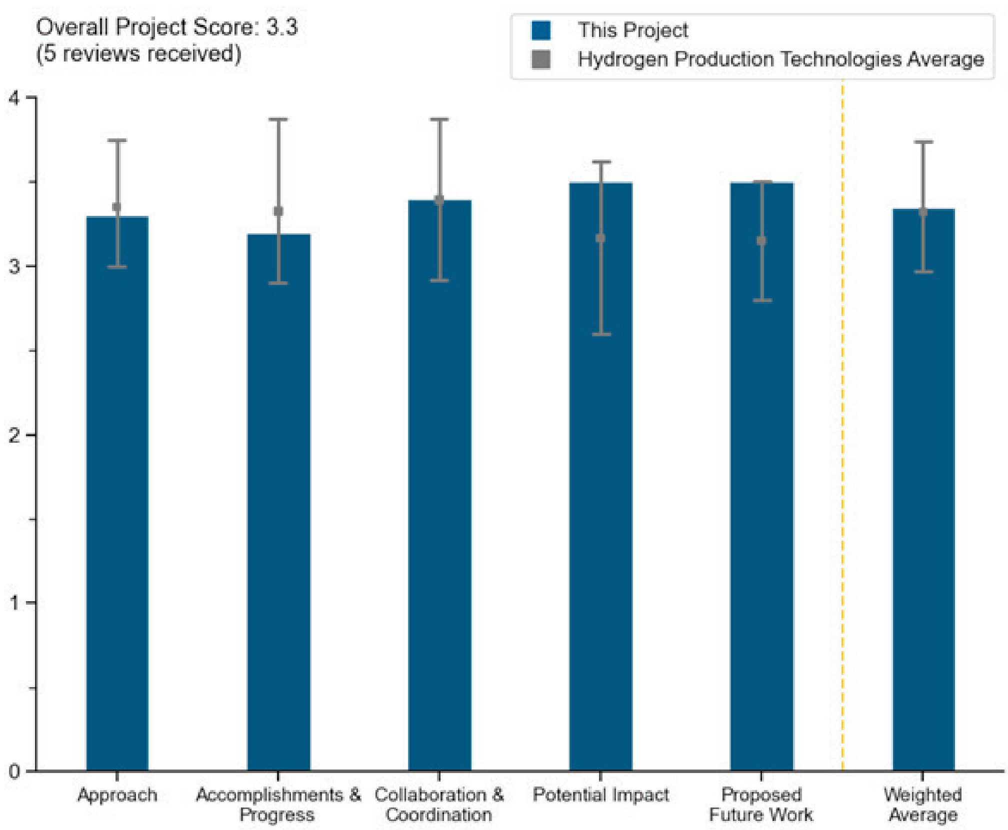
Brian James, Strategic Analysis, Inc.

DOE Contract #	DE-EE0009629
Start and End Dates	10/1/2021–9/30/2024
Partners/Collaborators	National Renewable Energy Laboratory, Idaho National Laboratory
Barriers Addressed	• Hydrogen generation by water electrolysis: • Capital cost • System efficiency and electricity cost • Manufacturing

Project Goal and Brief Summary

The project aims to conduct a techno-economic analysis (TEA) of various hydrogen production pathways, including electrolysis and photoelectrochemical methods, to evaluate the cost of hydrogen production. It utilizes Design for Manufacture and Assembly (DFMA®) techniques, heat and mass balances, and Hydrogen Analysis (H2A) discounted cash flow models. The goal is to estimate the cost of hydrogen production based on state-of-the-art technology at central production facilities (50–500 tons per day) and measure the cost impact of technological improvements in hydrogen production technologies. The project will provide a comprehensive pathway analysis, identify cost drivers, guide research and development efforts, and support the Hydrogen Shot goal of achieving $1/kg hydrogen production cost. The approach involves collecting data, conducting cost analysis of proton-conducting solid oxide electrolysis, and collaborating with experts and research institutions to ensure transparency and accuracy.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production 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 to the analysis and objectives for the project, system boundaries, and operating parameters have been clearly identified. The approach to the analysis of the anion exchange membrane (AEM) water electrolysis is similar to the ones used in analysis of other hydrogen production technologies, which allows making consistent back-to-back comparisons of the cost of hydrogen production by different methods.
- This is a great effort in estimating the stack cost and deployment costs of alkaline electrolysis (ALK) hydrogen plants and comparing to proton exchange membrane (PEM) systems, mainly leveraging the National Renewable Energy Laboratory model. Perhaps the team could consider the following suggestions to further tighten/improve the models since the project has only one year remaining:
    - Incorporate capital expenditures (capex) for ALK systems deployed worldwide to date; verify the capex cost of PEM and ALK stacks and full systems, and do one-to-one comparisons in terms of balance-of-plant (BOP) (what is included and what is not to be allowed for accurate comparison).
    - Verify efficiency curves with electrolyzer original equipment manufacturers (both PEM and ALK) and BOP providers as function of production capacity.
    - Verify engineering, procurement, and construction (EPC) costs with Tier 1 EPC firms.
    - Conduct sensitivity analysis for higher electricity costs, different electrolyzer and balance-of-stack availability, utilization, etc.

  Furthermore, ALK is mature technology that has been deployed in gigawatts worldwide; it would be valuable to explain why it is more expensive than PEMs, which are lagging in maturity, supply chain maturity, and deployment scales.
- This is a good approach that has proved to work well in the past. The approach is a to do a bottom-up analysis, which raises questions about whether some of the assumptions are bottom-up or top-down. The assumptions on slide 6 for future performance need to be validated. Where they came from is not clear. The assumption for degradation that the AEMs will approach PEM performance degradation does not seem to be realistic, given that these are very different systems (one is acidic, and the other is alkaline) and that AEM degradation mechanisms are different from Nafion™ membrane degradation mechanisms. It would be better if performance could be tied to a scientific reason that would allow for overcoming degradation mechanisms rather than "industry thinks we can do this..." The same is true for slides 7, 10, and 14. It is not clear why the performance improvements in the future case were chosen.
- TEA is critical to keep DOE focused on the most important challenges. Strategic Analysis takes a rigorous, mostly transparent approach to developing benchmark costs with industry input. The exceptions are when that industry input needs to be protected (e.g., polarization curves) or when engineering judgement is required because of lack of data (e.g., EPC costs).
- There is a well-defined approach for cost analysis. Assumptions are clear. The approach is aligned with the project goals.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- Significant accomplishment toward goals is demonstrated. Numerous scenarios were explored and cost representations created to show major influences for dollar-per-kilogram reductions. Trades were conducted between low-temperature electrolysis (LTE) hydrogen generation technologies.
- The project made very good progress in evaluating cost of hydrogen production by AEM operating with KOH and with a water feed. Comparison with other technologies has been made, and the crucial cost factors have been identified.
- The TEA identified priority focus areas for AEM systems to lower the cost of hydrogen production.
- The current state of AEM performance seems optimistic, especially the AEM water scenario. It is not clear where the data is coming from because there are no commercial stacks to use as a reference. If the team is referring to literature data, then it would be better to put some references in the document. The DFMA and

flow sheeting were well done, assuming the assumptions that were used are correct. The projected AEM current–voltage (I-V) curves seem optimistic. The solid oxide electrolysis cell (SOEC) current density on slide 24 is low. SOEC Hydrogen and Fuel Cell Technologies Office (HFTO) work has shown SOEC current densities in excess of 1 A/cm^2 (see various past Annual Merit Review presentations by FuelCell Energy and others on SOECs). It was unclear why the current life was projected to be 35,000 hours (slide 8) when slide 25 says it is less than 9,000 hours. It was unclear whether the performance assumptions were for end of life or beginning of life—in other words, whether the stack will operate at 3 A/cm^2 at 1.8 V for the 90,000 hours.

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 collaborates with all major stakeholders in water electrolysis development: DOE, national laboratories, electrolyzer developers, and manufacturers.
- There is a good combination of labs and industry to get at real costs, operating conditions/parameters, and degradation rates.
- Strategic Analysis obtains feedback from commercial manufacturers, which is critical to this type of analysis.
- The team has well-defined activities and contributions.
- Close collaboration with EPC firms and vendors could help tighten the model.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has significant impact on development of the Hydrogen Program through accurate comparison of the cost of hydrogen production by different technologies and through identification of the most critical cost components that require further development efforts.
- Cost breakout for stack and system subcomponents was done well and provides guidance for areas to focus for the largest cost-reduction opportunities. It is important for researchers to understand so they know the highest-value areas to explore and improve.
- The projected performance predicts one set of targets that would enable AEM to achieve the cost targets.
- Interest in AEM will only grow. DOE-sponsored analysis like this will be taken as a benchmark.

Question 5: Proposed future work

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

- Next steps planned for the project, conducting cost sensitivity analysis and coming up with strategies for reducing stack cost and operating costs, are well defined and provide logical continuation for the project.
- Proposed future work shows follow-up for incomplete AEM scenarios. Efforts are also realigned to see the viability of achieving $1/kg targets established for electrolysis after project start.
- There are plans to publish the H2A case and DOE record (the latter is important because it allows a deeper explanation of the analysis). The team should show the sensitivity of results to input assumptions. DOE has a low-grade reputation for optimistic cost assumptions, so the sensitivity analyses are important, including those where more than one variable is changed at a time. The cross-comparison of LTE options published is recommended as well. Preparation of the proposed Hydrogen Shot scoping study is strongly recommended. It may be best to show that as a standalone study, but DOE should rapidly shift to a total-cost-of-supply metric, including storage, transmission, and distribution.
- The future work seems appropriate.

Project strengths:

- The project provides analysis of new and rapidly developing AEM water electrolysis technology for hydrogen production. Many new hydrogen projects and startup companies have recently been formed to develop and commercialize the technology. Providing publicly available TEA and performance metrics for the technology will allow for better comparisons of different commercial systems and will provide targets for system development and assessment by DOE.
- This is very important work. It is needed for HFTO to create appropriate performance targets. It is imperative that Strategic Analysis provide very honest and transparent analysis. Strategic Analysis has an excellent process for doing this and well-qualified staff.
- The project has a strong prime contractor in this area of research who is well regarded in the field. Good collaboration is shown between national laboratories and the prime contractor. The industry partner input adds validity to modeling efforts.
- Rigorous bottom-up analysis is a strength. Assumptions are transparent; work is published.

Project weaknesses:

- The team needs to provide more documentation on the current and future performance metrics. Saying "we found this in the literature" should be accompanied with the literature references. If the team surveyed industry, there should be error bars showing the variation between responses. The team has done this in the past, so it was surprising not to see it in this presentation or in the background information.
- Optimistic assumptions are made about EPC costs. The team should talk to EPC vendors. It is not clear whether the analysis actually does guide DOE decisions on research and development to fund. If possible, the team could show evidence of the impact of past analyses.
- It would be nice to get similar input from industries in the comparison technologies and not just AEM. It is possible this was done, but that was not clear in the presentation.
- No specific weaknesses were identified.

Recommendations for additions/deletions to project scope:

- The project needs to more fully document its assumptions. Currently, it looks like the future performance targets were selected to achieve the DOE goals (top-down) and not based upon a bottom-up analysis of what the physics says can be reasonably done. Stating that AEM target durability can be achieved because PEM can do it is not a strong argument.
- It would be good (and does not seem difficult) to show the projection of future costs compared to a learning curve approach. It would complement Strategic Analysis's bottom-up approach and help some stakeholders put the results in context.
- No modifications to the scope of the project are recommended.

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

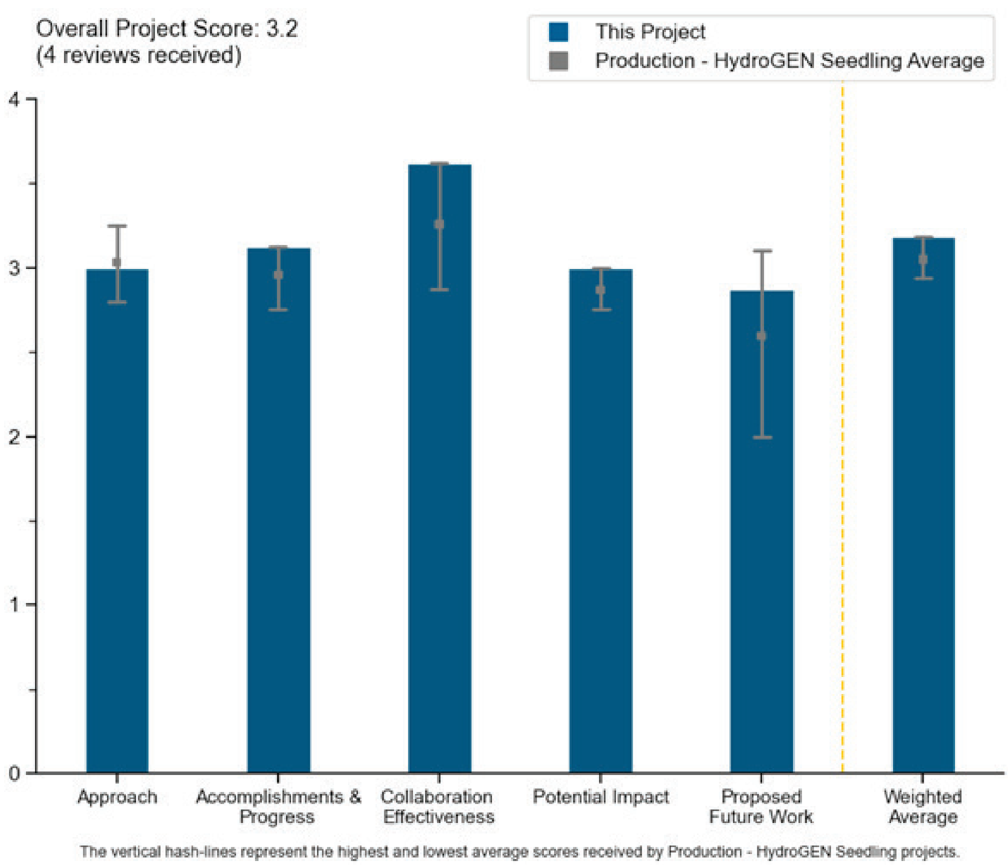
Kevin Huang, University of South Carolina

DOE Contract #	DE-EE0008842
Start and End Dates	4/1/2020–3/31/2024
Partners/Collaborators	University of Massachusetts at Lowell, Idaho National Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Delamination and chromium poisoning of oxygen electrodes

Project Goal and Brief Summary

The two leading causes for oxide ion conducting solid oxide electrolysis cell (O-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, delamination-resistant, and chromium-resistant oxygen electrode for durable, high-efficiency, and high-rate hydrogen production via intermediate-temperature SOECs (≤700° Celsius).

Project Scoring



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 and feasibility.

- It is always a pleasure to listen to Dr. Huang's presentations, and new ideas keep coming. The project's use of the required presentation template for the updates is appreciated. In general, the work in Europe has shown that electrode delamination, which many groups have addressed, is mainly a function of processing and application on cells. Likewise, major electrolyzer original equipment manufacturers (domestic and abroad) demonstrated long operation in solid oxide fuel cell (SOFC)/SOEC/reversible solid oxide cell (rSOC) stacks/systems without oxygen electrode delamination. The following comments are shared in the hopes of helping to guide current and future work with a more focused approach:
  - Perovskites and composites are well-known oxygen electrodes operated in large systems (in Europe and the United States) for extensive periods without any major delamination issues. The principal investigator (PI) also mentioned no delamination was observed when measured in fuel cells. However, delamination does occur in symmetric cells; thus, perhaps it is worth considering whether symmetric cells are the right tool to measure electrode delamination or any kind of long-term electrochemical operation. Perhaps it would be worth questioning how or if such data/behavior could be reproduced in full cells.
  - The SCT (strontium cobalt tantalum, or $SrCo_{0.9}Ta_{0.1}O_{3-\delta}$) coat is an interesting approach to help with electronic conduction and as Cr getter. It would be helpful to understand whether it is economically more feasible to coat all cells with SCT or apply scaled, well-understood, manufactured-at-scale, Cr-resistive coatings to bipolar plates. Perhaps it is worth considering whether application of SCT (an additional cost) is necessary if there are Cr-resistive coatings on the stack and doing the job. If SCT's primary role is to serve as a current-collecting paste and will replace another current-collecting paste, then further investigations are warranted.
  - On slide 14, the baseline lanthanum strontium cobalt ferrite–gadolinium-doped ceria (LSCF-GDC) cell shows extremely low performance, while there are many literature sources clearly showing that such electrodes perform at least 2x to 4x better (commercial inks). Perhaps it would be beneficial to explain why such a low-performing cell was used for comparison against the highest-performing cell with LSCF-GDC/SCT. If another highly conductive current collective paste (e.g., lanthanum strontium cobalt [LSC]) is used for a baseline cell, then it would be helpful to know the difference in cell performance. Perhaps it would be beneficial to conduct such a study to ensure an accurate one-to-one comparison.
  - Using the same materials in planar cell configuration leads to substantially lower degradation than in tubular cell configuration. Perhaps it would be beneficial to explain this difference.
- Cr tolerance of oxygen electrodes is an important degradation mechanism that needs to be resolved. The project considers a Cr-tolerant coating over the LSCF-GDC electrode. The selected coating layer has excellent oxygen exchange properties, as discussed by the PI. The symmetrical electrode test method is a good approach to measuring the exchange current density and is skillfully used to monitor the change in the exchange current density over time.
- Both experimental and computational methods are employed to study the oxygen electrode, which provides a clear and deep understanding of the novel electrode the project developed.
- The approach is adequate except for operating at too low of currents. Delamination and Cr poisoning of oxygen electrodes are the two leading causes for the performance degradation of SOECs.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals, as well as the HydroGEN Consortium mission.

- The team has validated that the bilayer oxygen electrode can help to improve performance and durability. Both experimental and computational studies have been conducted to confirm the results. The accomplishments meet the proposed goals.

- Time to delamination is calculated empirically based on change in exchange current density with time. Combining multi-physics modeling, materials process development for coating, and experimental validation shows the well-rounded approach of the project's research group.
- The project's progress is adequate but appears slow.

Question 3: Collaboration effectiveness

This project was rated **3.6** for its collaboration and coordination with HydroGEN and other research entities.

- The project is working with two national laboratories. It shows that combining the strengths of the university with the core capabilities of two laboratories is beneficial.
- The team has very good collaborations with universities and national laboratories.
- The project has excellent collaboration, with five national laboratories supporting the effort.

Question 4: Potential impact

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

- The overall objective is good. Adding another layer over the oxygen electrode appears to provide Cr tolerance and reduce delamination. Many groups seem to have addressed the delamination problem (to the extent it is published), but extending the solution for high-current operation as an objective is worthy of exploration. It is somewhat unclear whether the coating needs to be continuous to gain the Cr tolerance and whether the top layer has the same functionality as the underlying LSCF-GDC opposite. Testing the concept on commercial tubular cells is a good approach, although the cycle-to-cycle degradation seems high, but a solution will help the industry.
- Even in the reversible mode, currents of 3 A/cm^2 or higher for SOECs will be needed. The tubular technology, whatever advantages it may have, has inherently lower current designs. The effort is concentrating on tubular SOFCs, which has no industrial partner in the forefront of development. It is uncertain whether the project should continue to be pursued, other than as an academic curiosity. DOE has driven three or four fuel cell technologies to demonstration/market. The cost of developing a technology to the demonstration stage has taken at least $1 billion and decade(s) per technology. There are eight years left and limited funding to reach the Hydrogen Program goals to indulge every distraction. Developing to demonstration or market such a technology (tubular SOECs) will take a billion dollars and decade(s). It may be too late for these Seedling projects to impact DOE 2030 goals.
- The success of this project will certainly advance the SOEC program at DOE and help to achieve durable SOEC cells, stacks, and systems.

Question 5: Proposed future work

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

- The project has a good approach and plan.
- The project should complete the work at the highest currents possible.
- The proposed future work is reasonable.
- Perhaps it would be beneficial to consider experimental direction change.

Project strengths:

- This project addresses two common degradation mechanisms, namely Cr poisoning and oxygen electrode delamination. The project understands the mechanisms and formulates solutions elegantly.
- Both experimental and computational methods are employed to understand the bilayered electrodes.
- The research is an excellent academic contribution with important commercial SOFC experience.

Project weaknesses:

- It appears the project's effort is avoiding degradation, delamination issues, and exploration by operating at low currents. Even in the reversible mode, currents of 3 A/cm^2 or higher for SOECs will be needed. The tubular technology, whatever advantages it may have, has inherently lower current designs.
- It is unclear whether the layer needs to continuously cover the electrode and whether it needs to be uniform. It was stated that the isostructural layers will not delaminate at the interface, but the project needs to convincingly demonstrate this as fact.
- The project has no apparent weakness.

Recommendations for additions/deletions to project scope:

- Certain accelerated tests, such as rapid thermal cycling, will give a better understanding of the stability of the bilayer electrode. Perhaps an evaluation of a discontinuous or partially covered layer on its capability for Cr tolerance would be helpful.
- The project should operate at higher currents.

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

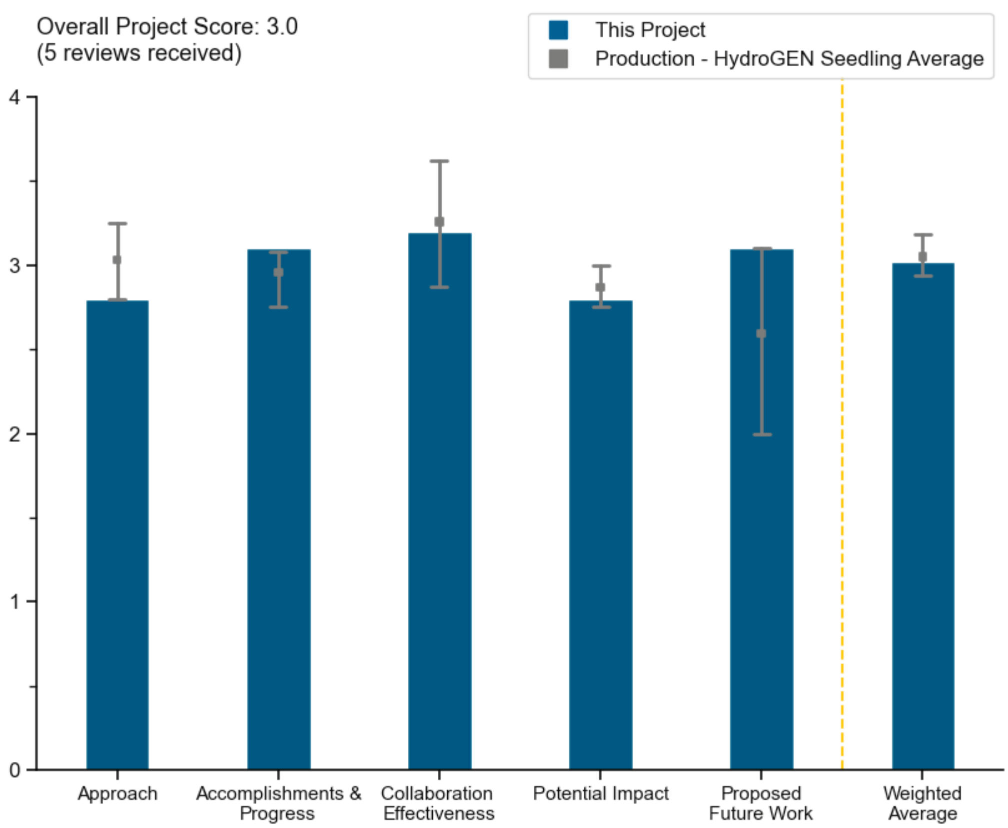
Yanfa Yan, The University of Toledo

DOE Contract #	DE-EE0008837
Start and End Dates	10/1/2019–9/30/2023
Partners/Collaborators	National Renewable Energy Laboratory, Lawrence Livermore National Laboratory
Barriers Addressed	• Materials Efficiency – Bulk and Interface: Identification of absorber composition and interfacial materials for efficient hydrogen generation • Materials Durability – Bulk and Interface: Investigation of intrinsic stability of perovskites; development of durable protection layers • Configurations: Tandem film stack 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 $1/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 Production - HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **2.8** for identifying barriers and addressing them through project innovation, as well as for project design and feasibility.

- The team is focusing on improving the durability of low-cost perovskites for PEC water splitting. The solid-state efficiency of the proposed material class is already comparable to that of III-V systems while offering much lower manufacturing costs. The fact that narrow e_g perovskites do not possess the same intrinsic stability as wide e_g ones is a challenging issue, but ongoing research efforts in the photovoltaic (PV) community to address these problems, including in the principal investigator's group, will eventually translate to PEC systems.
- Tandem perovskite "photoelectrodes" offer an attractive approach to achieving high solar-to-hydrogen (STH) using potentially low-cost, solution-processed materials. The emphasis on durability tests is appreciated, as this is a critical barrier to overcome. Sealing the tandem perovskites behind a metal foil is also likely to be an effective approach to ensure those components are not exposed to the electrolyte. The performance of the perovskite photo-absorbers is impressive, but it is not obvious that Type III PEC devices (panel configurations) have a competitive advantage over PV electrolysis using PV panels made of the same photo-absorbers.
- The use of perovskites may enable low-cost materials. The project uses the HydroGEN nodes well. From slide 5, it looks like the project team is making a mixed hydrogen and oxygen gas, which is a separations and safety challenge. The project will be using a membrane to solve this problem, but this was outside the work scope. The membrane will increase the impedance, so the project will get lower STH efficiencies than reported. The project team needs to be testing the materials in a configuration that better simulates what the final device will be to truly understand the performance. The tandem configuration is a good approach.
- The project has a good approach that allows for inexpensive tandems for water splitting. There is a balance between detailed understanding and testing, although improvements are needed. It is not clear why a buried bandgap material is used in a PEC configuration compared to PV electrolysis. The project is focused on the photoelectrode, but the test cell should be a viable system that can be tested to ensure equitable comparisons.
- The project's vision projects an increase in efficiency (>20%), decrease in cost (<\$200/m^2), and durability of >1,000 hours. The current state of the art has 18% efficiency, a cost of \$20,000/m^2, and durability of 100 hours. The project suffers from a chronic stability problem with water-soluble materials. The project's targets are well stated, but it is clear that insufficient thought is given to some of the key issues with implementation. Highly effective PV cells do not necessarily make for cheap hydrogen if there are catalyst, stability, and engineering issues that are intractable.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals, as well as the HydroGEN Consortium mission.

- The project has made good progress in terms of understanding fundamental mechanisms for degradation and figuring out ways to overcome them. The project examined different metals and catalysts and obtained efficiencies that are relatively high (although not the highest reported). However, the system should be less expensive. The stability has improved, but the project still has a long way to go to be commercially competitive. There still appear to be significant challenges.
- The project has demonstrated impressive STH efficiencies for Type III PEC devices (>18.5%). The project has also demonstrated ~240 hours of stability, although the project is unlikely to achieve the 1,000-hour target, based on presented results. While significant progress has been made, it is not obvious that this approach presents a realistic pathway to achieving the DOE Hydrogen Shot goal of < \$1/kg H_2. The discussion about the perovskite stability challenges/mechanisms is appreciated.
- The project team was able to achieve high STH efficiency of >22%, but this was in a cell that produced stoichiometric H_2:O_2, which is not safe. The real STH will be lower when a membrane is used to prevent the stoichiometric H_2:O_2 gas generation. The project team was able to develop a suitable conductive paste. The project was able to achieve suitable performance of 280 hours. The open-circuit voltage of 2.13 V is very good and is suitable for water splitting. Overall, the project team made very good progress to exceed

the project goals. The team is using an IrO_x counter electrode, which is suitable for an experimental setup but is not going to be suitable for a commercial cell.

- The project benchmark to improve is the state of the art. The project should probably use silicon and proton exchange membrane (PEM) and not 3/5 PEC. The project has three months to go and has not achieved 500 hours with 80% activity retention. The PV curve looks good, with 28% power conversion efficiency and open circuit voltage of 2.13 V. The presenter did not say what catalysts are needed for the system. The advantage of Si and electrolyzers is intensification of the electrolysis step and lower platinum group metal (PGM) demand for hydrogen production. The implementation does not consider gas separation or scale-up and could refer to DOE studies.
- The project has made some good progress regarding STH efficiency. With respect to stability, T90 = 240 hours was demonstrated. It is not clear whether the T80 of 1,000 hours can be met using the current device architecture, especially considering the project is in its final year.

Question 3: Collaboration effectiveness

This project was rated **3.2** for its collaboration and coordination with HydroGEN and other research entities.

- The project has effective collaboration with NREL (PEC measurement, atomic layer deposition interconnection, and protection layers) and LLNL (x-ray analysis).
- The lead organization uses the HydroGEN nodes well.
- The project seems to be utilizing the capabilities in the network to address the perceived issues.
- Numerous Energy Materials Network nodes are listed on slide 4, and the interaction with NREL's perovskite team is apparent (with one joint paper published in *Science*). It was not clear whether STH efficiency values were validated by the NREL PEC node. The interaction with the LLNL group was limited to one figure on x-ray spectroscopy analysis on slide 24. More information on how these data are used to improve perovskite properties would have been welcome.
- The project is leveraging HydroGEN labs successfully, although additional interactions and modeling to inform future work would be good. The interactions were not really shown, though—just mentioned. The project should be leveraging test cells from HydroGEN in all testing.

Question 4: Potential impact

This project was rated **2.8** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN Consortium mission.

- The project has a good approach in terms of inexpensive materials for PEC. If the technology were to be widely deployed, PEC could perhaps meet the goal, but it still needs improvement in terms of stability and scale-up. The test cells are not viable or representative, so it is hard to judge actual impact.
- Perovskites are clearly dominating the PV field and could have a huge potential for low-cost PEC hydrogen production, assuming durability issues (let alone in dry conditions) can be solved.
- The project presents a good introduction to why perovskites are of interest and has a simple solution-based film deposition.
- High-efficiency demonstrations and long-term durability tests are very valuable to the field. One of the biggest risks is long-term stability. Degradation of lead halide perovskites themselves is the biggest concern. This is especially concerning for some of the more exotic wide bandgap perovskites needed for the tandem designs. Some techno-economic analysis (TEA) work was carried out, but it was not clear that there is a realistic pathway toward <$2/kg or inherent techno-economic advantage of these device concepts compared to decoupled PV electrolysis (e.g., a PV-PEM electrolyzer). Specifically, achieving a 10-year lifetime is a major reach. It is concerning the TEA on slide 21 appears to have not taken into account the cost of the membrane. It is great that the projected photoelectrode cost might have a pathway to <$30/$m^2$, but the membrane that will be required to separate the O_2 and H_2 should also be considered. Mass-produced cation exchange membranes are often >$300/$m^2$. Utilizing these membranes at a current density of only 15–20 mA/cm^2 makes this alone an unfavorable proposition versus a PEM electrolyzer using the same/a similar membrane but with two orders of magnitude higher current density per area of the membrane.

- To meet the long-term goals of >$2/kg H_2, the project will need to use a counter electrode different from IrO_x and increase STH efficiency and durability. The mixed gas generation is a very significant challenge. The use of a membrane may solve the mixed gas challenge, but it will lower the STH efficiency. Mixed H_2 and O_2 gas generation is a safety issue.
- The project's understanding of the required performance seems adequate, but the cost of system components (especially the catalyst) is not really considered. It is hard to see how this could hit $1/kg with the complex fabrication, PGM dependency, and limited lifetime that seems inherent with such materials.

Question 5: Proposed future work

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

- Measuring temperature-dependent performance and running tests with separated cell compartments are both interesting and important analyses to perform. Demonstrating durability up to 1,000 hours is also key; however, it is not clear what changes will be made to the tandem structure to achieve this goal. With the current structure, the perovskite cells are physically isolated from the electrolyte, and loss in performance may come from the materials themselves, not the electrochemical process.
- The focus on long-term stability tests and TEA is appropriate during the remaining two to three months.
- The 1,000-hour test is a good experiment. The Hydrogen Analysis (H2A) production model would be useful to determine what the current projected cost of hydrogen would be with the device. The project needs to do testing with a membrane to better simulate a real cell to measure true STH efficiency.
- It is clear there is a way to go to achieve the project performance target in a rather limited remaining time, but this is at least understood.
- The project is ending, but there are still significant things to get done to prove stability.

Project strengths:

- The cells the team has produced can clearly generate the current densities required for high STH efficiencies. The team also has excellent knowledge in the physical and chemical properties of the class and is participating in efforts to improve the durability not only for PEC but also PV applications.
- The project focuses on stability of perovskites, which can be a less expensive tandem with high efficiency. The project has made good progress, although in more ideal cases, and has a good focus on the fundamental understanding that can be leveraged into improvements.
- High-efficiency PEC demonstrations and long-term durability tests are very valuable to the field. The perovskite tandem cells might have commercial potential in the PV field.
- The project looks at materials with high STH potential.
- There is nice progress on PV performance.

Project weaknesses:

- It was not clear that there is a realistic pathway toward <$2/kg or inherent techno-economic advantage of these device concepts compared to decoupled PV electrolysis (e.g., a PV-PEM electrolyzer). Also, long-term (5- to 10-year) stability of wide-bandgap perovskites is a major technical risk. While there was nice progress related to perovskite materials/photoelectrodes, efforts related to incorporating photoelectrodes into devices and thinking about scale-up considerations were underwhelming.
- The materials the project uses are sensitive to water. The project team is testing the cells in a configuration that is not representative of what a final device will look like, which results in higher performance than what will be seen in a real cell. The project has not done an H2A or other TEA analysis. The project uses IrO_x, which is extremely expensive, and there will be considerable competition for this valuable critical material.
- The test conditions were ideal, so it was hard to judge the actual efficiencies with practical cells and non-photoelectrode materials. The stability is still not sufficient. There are still major barriers in the various materials, and detailed strategies to overcome them were not presented.

- In terms of cell design, it is unclear why metal foils are bonded to the back of the cell, instead of coating catalysts via direct deposition (physical vapor deposition or chemical vapor deposition). The use of conductive paste and resulting gaps between the cell back side and foil could be a point of ingress, leading to degradation.
- Multiple issues still exist, implementation issues are not considered, and no consideration is given to the catalyst.

Recommendations for additions/deletions to project scope:

- If this work were to be extended, the cost of fabrication should be realistically assessed to establish meaningful targets. It is likely to be a long time before PEC is a viable technology; this a low technology readiness level. The assertion that the $1/kg target is achievable with this technology is questionable, and the assumed cost of electricity for PEM to achieve $1/kg is not achievable at the required capacity factor. Maybe $2/kg could be acceptable, but there should be some realism about what might be possible instead of unsubstantiated claims of what is achievable without any TEA being provided to inform the key performance metrics.
- The project is ending. The project could use HydroGEN cell testing and validation of PV electrolysis versus PEC because of stability issues.
- The project needs to do a TEA. The researchers need to do their tests with a membrane to separate the O_2 and H_2 production. The project needs to identify a better material than IrO_x.

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

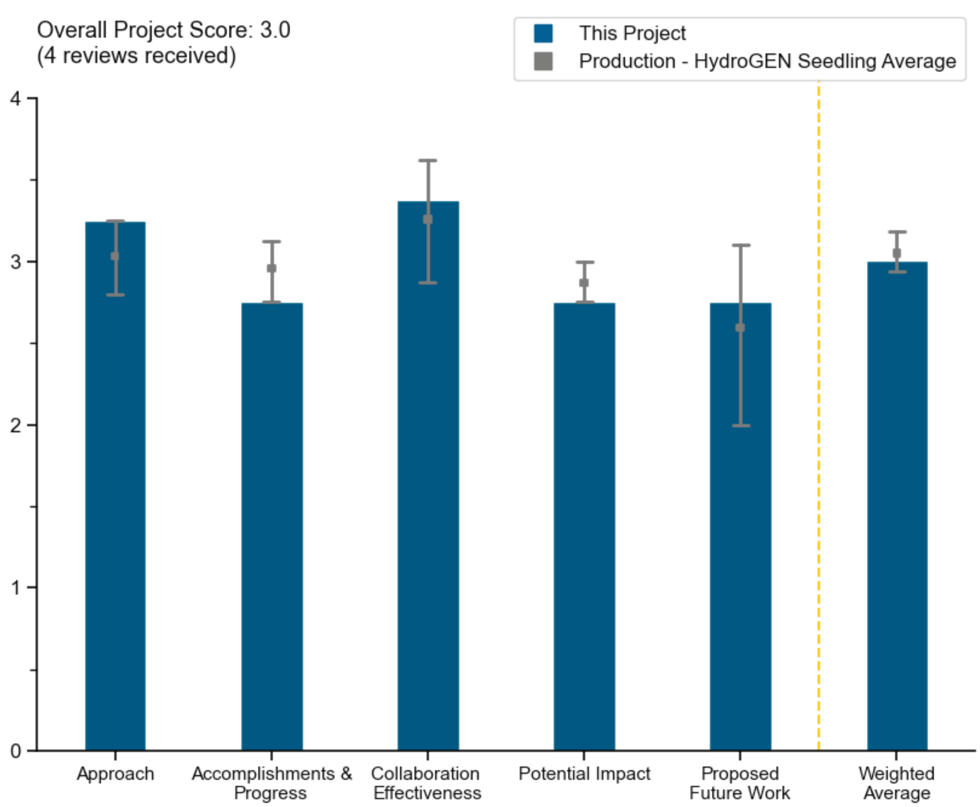
Shane Ardo, University of California, Irvine

DOE Contract #	DE-EE0008838
Start and End Dates	10/1/2019–10/31/2023
Partners/Collaborators	University of Michigan, Columbia University, National Renewable Energy Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratories, Strategic Analysis, Inc., Lawrence Berkeley National Laboratory, California Institute of Technology, Tokyo University Science, Shinshu University
Barriers Addressed	• Few composite particles that selectively evolve H_2 and O_2 instead of performing undesired redox shuttle back reactions • Design of ultrathin oxide coatings for selective reactivity and reactor dimensions for natural convective mixing, guided by empirical and numerical results

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 techno-economically viable photocatalyst reactors for solar water splitting.

Project Scoring



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

- The project aims at solving important challenges in PEC water splitting using so-called Type II (Z-scheme) reactors with suspended nanoparticles. Specifically, the team has targeted two key issues: reaction selectivity and the development of a low-cost reaction shuttle mixing process. Reactor design is driven from advanced modeling and simulations covering multiple physical (e.g., photon flux, particle diffusion) and chemical (reaction kinetics) steps. Overall, the approach and results presented are impressive. The team has clearly identified the main technological barriers with the technology and established clever solutions to address them.
- The approach uses Ir-doped $SrTiO_3$. Ir is extremely expensive, with limited supply, making it unlikely to be used at high volumes. In addition, there is a growing demand for Ir for other applications. Photoelectrochemical (PEC) particles in a Type II design is one pathway that has been proposed that has the potential to come close to \$2/kg H_2. The approach assumes the ability to keep the particles suspended. It also assumes natural convection for mixing, which is unlikely, given the diurnal mode of operation of this system and for the cases of multiple days without much sunlight (cloudy days, rainy or snowy days, etc.). The project needs to assume heating from the sun. The project may need to include cooling to ensure material integrity. The improved design increases the area for the ion transport between the oxygen evolution reaction and hydrogen evolution reaction (HER), which is vital for the success of this approach.
- The project may achieve 10% target efficiency. The particles need to remain suspended if not fixed film, which requires a good mixing of redox species. The project uses iridium-doped $SrTiO_3$. The project also uses two light-absorbing particle chambers. The redox shuttle species needs to diffuse/migrate through a barrier. There is a small area for redox shuttle to allow gas collection; perhaps there is a concentration gradient around this. The project could consider raceway tubes with larger ion bridges (slide 7). The project has undesirable back reactions and could consider Pt and IrO_x co-catalysts to help avoid other reactions on redox shuttle (Fe[III] reduction). The project team arguably has a good understanding of some of the key issues, although the practical implementation aspect, including catalyst loading, is conveniently ignored.
- This project seeks to develop high-yield photocatalysis with high selectivity. The project uses two separate catalysts for hydrogen, and oxygen evolution is studied.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals, as well as the HydroGEN Consortium mission.

- Great progress has been made in the project. For example, a coating that can prevent back reactions has been experimentally validated and backed up by simulations. Dopant discovery for strontium titanate has been successfully implemented via high-throughput screening. Characterization of a single particle with scanning electron microscopy is a noteworthy accomplishment. Demonstration of durability over 8 hours of testing is also reported.
- This project was started in 2019, so the lack of experimental data is a very significant failure. There were many simulations to aid in the selective coatings' selection. The simulations predict that solar-to-hydrogen efficiency of up to 10% may be achieved. The simulations were done at room temperature, but the temperature in the Type II configuration is likely to be substantially higher than room temperature because of the configuration and needs to be included in the calculations. The simulations assume the particles will remain in suspension. The suspension of particles for long periods of time has not been demonstrated and is unlikely to be achieved without some sort of mechanically induced mixing. The project is using Ir and/or Pt, which are critical materials; it is recommended that the project develop alternatives for both. Slide 12 seems to indicate that Rh was the preferred dopant, but the principal investigators (PIs) clarified that Ir was the best. The PIs needs to be clearer on what the best materials are, as this important finding is not clearly stated in the presentation. All the project slides need to clearly state what materials and conditions are used. The coating work is very encouraging. The idea of specific coating of the active sites is interesting but may be cost-prohibitive for manufacturing at large scale. The atomic layer deposition is an interesting approach, but its use for nanoparticles in high-volume manufacturing while keeping costs down may be a

challenge. The photo-deposition option may be better. The project did not do direct measurements but translated quantum yields through models. The project really needs to do direct measurements. For the proposed membrane, the project did not measure cross-over; the team only did calculations. The project needs to do more measurements to back up the calculations.

- The combinatorial screening looks really nice, but there are significant barriers to the success of the project, and it would seem that the targets are not going to be reached. The overall target (≥10 times larger H_2 evolution quantum yield than for uncoated particles) is not really enough to ensure this is a realistic technology and seems a bit narrow. Catalyst usage is not really addressed, although some thought is given to the design of a system.
- The project's accomplishments include rapid screening of catalysts and coating to suppress side reactions by using model and experimental validation.

Question 3: Collaboration effectiveness

This project was rated **3.6** for its collaboration and coordination with HydroGEN and other research entities.

- The project mentioned external partners early, and there seems to be a good deal of activity at different places. The combinatorial screening looks fantastic. The funds might be too thinly spread for effective work at each institution; coordination of such a large team would perhaps also be difficult.
- The team is supported by several Energy Materials Network (EMN) nodes, as well as international experts (Kudo and Hisatomi). Several joint publications include national laboratory scientists as co-authors. Overall, collaborations with external partners are effective and well-coordinated.
- The use of HydroGEN nodes was well done. The roles and responsibilities of the team members are not clear.
- The project appears to be interacting with various lab personnel and the research community.

Question 4: Potential impact

This project was rated **2.8** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN Consortium mission.

- The work performed so far is impressive. Although the project is focused on the development of particles and coatings, the milestones and go/no-gos have been established considering the whole Z-scheme process.
- Overall, the project is challenging, but success will provide another option for hydrogen production.
- The project simulations indicate possibly attaining $2/kg, but it is unlikely that the project will be able to get to a projected cost of $1/kg. The extremely critical material, Ir, is essential for the success of this technology. The project assumes that the materials can be suspended for long periods, which has never been demonstrated. The project team presented a good deal of calculations and modeling but not very much experimental data. This project was started in 2019, so the lack of experimental data is a very significant failure.
- It is not clear how this can lead to a workable system. Pumping was identified as a significant cost/energy penalty, and natural convection was postulated as a possible solution, but it is not clear how this would work on start-up/shutdown and intermittent insolation. The project's catalyst loadings could be enormous. The project has too much emphasis on modeling versus experiments.

Question 5: Proposed future work

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

- The proposed work seems a reasonable pathway to complete the work.
- The project seems to be coming to a close without really clear outcomes. "Continue to work with collaborators to obtain high-quality materials and evaluate particle properties using our suite of experimental tools, to support pathways to high-efficiency photocatalysis" and "continue to work with co-PIs/EMN project node experts to deposit ultrathin oxide coatings on nanoparticles and evaluate selectivity via HER quantum yield, to support pathways to high-efficiency photocatalysis" are too vague. The project

should really focus on what the key metrics are to meet a $2/kg goal and what the next stage would look like if the investigators feel this is a concept with merit.

- The proposed plan for future work is consistent with the project objectives.
- The project is ending this year.

Project strengths:

- The PI has identified two important barriers for PEC water splitting using Z-scheme Type II reactors. A team of experts with complementary knowledge has been assembled, and great progress has been made so far. The number of high-quality publications that resulted from this project is impressive. Good science will come out of this project.
- The project's concept provides a way to evolve hydrogen and oxygen in separate chambers. The use of coating is a good approach to limit secondary reaction.
- The project has a very interesting approach that avoids the limitations of the more common planar PEC configurations, and the modeling work was very interesting.
- The project is engaging with many people (25 researchers), is arguably creating many opportunities for scientific knowledge, and has some nice techniques.

Project weaknesses:

- There is nothing to report. The reviewer is looking forward to hearing how improvements made on particles and coatings will translate into a standalone Type II reactor efficiency in the near future.
- The project is unclear on crossover of hydrogen. Regarding extinction/transmission of light, the depth of reaction has very low quantum yields at 405 nm, which is less than 0.1%. The quantum yield target might be irrelevant if the percentage conversion is ridiculously low. Regarding single wavelength, it is not clear how this would translate to full spectrum. The project considers particle-scale effects but not the broader diffusion and light extinction/transmission issues. The project needs to build and operate something, as it is currently all calculation-based.
- The project did a poor job validating calculations with experimental work. The project assumed that natural convection would be sufficient to keep the particles suspended for long durations (years) without any other agitation, but this must be validated. It is an extremely unlikely scenario given the diurnal nature of the system and the obvious scenarios of cloudy days that would happen even in deserts.
- Selective deposition of coating will be challenging to implement.

Recommendations for additions/deletions to project scope:

- There are no specific recommendations. The team is capable, but it will be challenging to accomplish all the targets. Suspending particles needs more consideration in terms of particle size and surface characteristics. It is understandable if the project is hampered by limited time and other tasks take priority.
- The project must do experiments to validate the calculations. The project must prove that the assumptions on natural convection are sufficient to cause mixing, which must include start-up from when the particles are all on the bottom of the reactor. The project needs to find alternative materials to Pt and Ir, as these are expensive critical materials and there is tremendous competition among many industries, not just hydrogen production.
- Techno-economic analysis and experimental demonstration will be critical to the project's outcomes.

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

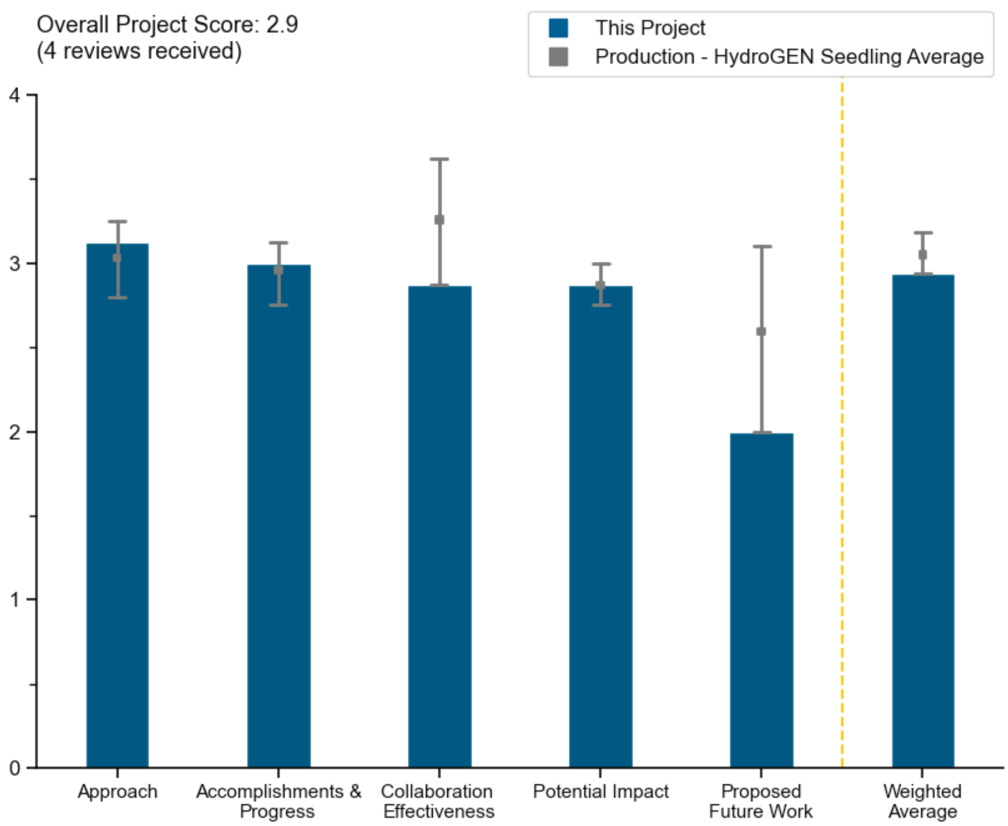
Aditya D. Mohite, William Marsh Rice University

DOE Contract #	DE-EE0008843
Start and End Dates	1/1/2020–1/1/2023
Partners/Collaborators	Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Stability of perovskite solar cells in aqueous media • Development of corrosion-resistant layers that are electronically transparent

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 and oxygen evolution reaction catalysts to demonstrate an integrated HaP-PEC cell with 20% solar-to-hydrogen (STH) 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 durable and efficient 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 Production - HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying barriers and addressing them through project innovation, as well as for project design and feasibility.

- Tandem perovskite photoelectrodes offer an attractive approach to achieving high STH using low-cost, solution-processed materials. The recyclability of the substrate and active components is also very attractive. The project incorporated a nice combination of materials development, device testing, and techno-economic analysis (TEA) that leveraged expertise at national labs.
- The project seems the most focused of the three PEC presentations. The project had the best articulation of the performance goals: 20% STH and 500-hour stability of HaP, this time using hydrophobic termination. Other photons can heat up the electrolyte and improve kinetics. (It is good that Sophia Haussener was mentioned.)
- The team is focusing on earth-abundant perovskite materials for PEC water splitting. Despite the material class's being notoriously unstable, the team managed to achieve good stability (~100 hours) with tandem structures.
- The team's approach investigates the major challenges for the technology. The plan has included a cost analysis portion to aid in the development. The water-stabile perovskites were an important focus.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals, as well as the HydroGEN Consortium mission.

- The project demonstrated record STH efficiencies for Type III PEC devices. The project demonstrated a recyclable platform, which is great to see from a lifecycle analysis standpoint, and very nice device demonstrations using a concept that is scalable, in principle. The project demonstrated ~100 hours of stability, although it is unlikely to achieve the 500-hour target, based on presented results.
- The project achieved high STH (15%) and life (100 hours), which was a little lower than the stated goal of 20% for 500 hours. The project should refrain from referring to 100 hours as "long life" when >40,000 hours will be needed for a technology to be considered. The degradation rate is still too high. The project needs to continue to better understand the degradation (delamination) challenge. The team is trying to decrease the use of Ir and other critical materials, which will be necessary for a commercially viable device. The conductive-adhesive layer accomplishment was very important and is a key enabler. The project team is working on scaling up the system size—the first time this has been seen. The heat harvesting to improve the efficiency is a novel approach. The demonstration of recycling the materials was a nice add-on to the work and is very interesting. The degradation rate is still too high, but 100 hours is progress. The researchers need to find alternatives to IrO_x. Ir is a critical material, and limited amounts are available. The researchers are looking at Ru with Ir, but these are not earth-abundant catalysts. The principal investigator claimed very good stability of the Ni and Ru in the acidic solution; however, this is unlikely for Ni. The project needs to look for the species in the solution.
- The project has made progress toward earth-abundant catalysts, recyclable components through solution-based extraction, a lifetime up to 2,000 hours, 98% conversion of electric energy to chemical energy, and Pt and IrO_x catalysts (slide 12). The technology shows 5- to 10-hour failure from ingress of ambient moisture, not from solution. Slide 17 shows progress with Ag. Slide 18 shows STH from 20.8% to 12.5%—not 15%, as stated in the presentation. Slide 21 shows results from IrO_2 catalyst delamination studies.
- Clearly, the team can produce high-efficiency solid-state tandem perovskite solar cells, and at face value, the STH efficiencies reported are impressive. However, it is apparent that no hydrogen has been collected so far at the system level. No information on the catalysts used for Faradaic efficiency calculations was provided. Also, it appears that this study was done on thin film catalysts, not the tandem cell. As such, STH values (calculated by multiplying current density x 1.23 V) constitute only the upper STH efficiency limit of the system. Also, for Year 2, the go/no-go decision point was a 15% STH for 100 hours; however, based on data provided (slide 15), it looks like efficiency dropped below 15% at around 50 hours.

Question 3: Collaboration effectiveness

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

- The project has effective collaboration with LBNL (degradation studies) and especially NREL (efficiency benchmarking/protocols, strategies for scale-up, input on TEA).
- The team members have well-defined roles. The lead organization effectively uses the HydroGEN nodes.
- The Energy Materials Network partners are LBNL and NREL. In the presentation, LBNL is credited once for the Faradaic efficiency calculation. LBNL is mentioned on slide 16 ("understanding of degradation"), but no data was included. Also, based on this presentation, it appears that the NREL node was not solicited for device benchmarking, despite being a part of the project. The latter is problematic, considering the high STH values reported by the team.
- The project's collaboration is satisfactory. The project has involvement from LBNL and NREL (slide 6) but may not connect as broadly with the HydroGEN community as other projects.

Question 4: Potential impact

This project was rated **2.9** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN Consortium mission.

- The potential impact of perovskites on PV and PEC is undeniable.
- High-efficiency demonstrations and long-term durability tests are very valuable to the field. One of the biggest risks is long-term stability; this project highlights some challenges associated with delamination/ degradation of catalyst and encapsulation layers, but the biggest concern is degradation of lead HaPs themselves (even in the absence of contact with the electrolyte). This is especially concerning for some of the more exotic wide-bandgap perovskites needed for the tandems. Some TEA work was carried out, but it was not clear that there is a realistic pathway toward <$2/kg or inherent techno-economic advantage of these device concepts compared to decoupled photovoltaic (PV)-electrolysis (e.g., a PV-proton exchange membrane [PEM] electrolyzer), even if electrolysis is carried out with earth-abundant electrocatalysts in an alkaline environment. Specifically, achieving a 10-year lifetime is a major reach, and it is not clear from the presented results that membranes were taken into account (it appears not).
- The reviewer does not recall what the statement "need 1000x times less material to absorb solar radiation" was using as the counterfactual, but this feels like hyperbole. Also, it is unclear why there are two charts for STH efficiency versus panel costs. The left one looks more credible, though from the presentation, it appears that some of the balance-of-plant costs were overlooked. It is not clear that any system requiring a low-iron glass can be realistically produced at or below $\$50/m^2$.
- The team is trying to identify a viable pathway to $2/kg H2 and proposed an ambitious pathway that may achieve \$1/kg H_2. The technology requires significant development such that it is unlikely to provide a pathway to \$2/kg H_2, let alone \$1/kg H_2, within the timeframe DOE states as its mandate.

Question 5: Proposed future work

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

- The project seems to be out of time (January 1, 2023, end date) with a number of objectives unmet.
- The project did not include a "Future Work" section.
- The project is ending this year.

Project strengths:

- The project has high-efficiency demonstrations and long-term durability tests and is very valuable to the field. The recyclability of the substrate and active materials is very attractive. The project incorporated a nice combination of materials development, device testing, and TEA that leveraged expertise at national laboratories.
- The project is looking at some very interesting materials that would decrease or eliminate the use of critical materials (Ir) and achieve longer lifetimes.

- The project appears to understand the broader implementation issues around pumping and platinum group metals.
- The project is based on high-efficiency solid-state and low-cost materials. Economical hydrogen PEC production could be achieved with perovskite, assuming durability can be addressed.

Project weaknesses:

- The cost of the membrane is unclear. Alkaline systems rates will decrease substantially. Ru is soluble in 1 M sulfuric acid; the project needs to check the solution chemistry: 200 mA/cm^2, p22 - 3 suns. Regarding the heat transfer from solar cell to electrolyte, some key operating conditions were omitted from the slides; it matters whether there is concentration or one sun. It is not clear what the next steps could or should be. This is fundamentally a tough technology to make work, and there is nothing here that shows a clear path to impact.
- It is not clear that there is a realistic pathway toward <$2/kg or inherent techno-economic advantage of these device concepts compared to decoupled PV-electrolysis (e.g., a PV-PEM electrolyzer). Long-term (5- to 10-year) stability of wide-bandgap perovskites is a major technical risk.
- The previous analysis done by Systems Analysis, Inc., for the Hydrogen and Fuel Cell Technologies Office suggests that it will be difficult for the planar design for PEC to achieve the low hydrogen cost targets DOE mandates.
- The project would greatly benefit from more rigorous PEC testing, which could add credibility to the technology.

Recommendations for additions/deletions to project scope:

- The “what next” was lacking.
- The project is ending.

Hydrogen Infrastructure Technologies – 2023

Hydrogen Infrastructure Technologies Subprogram Overview

Introduction

The Hydrogen Infrastructure Technologies subprogram focuses on research, development, and demonstration (RD&D) to reduce the cost and improve the reliability of technologies used to deliver and store hydrogen for a variety of applications in industry and transportation. Subprogram activities support development of hydrogen delivery and storage technologies to enable meeting the goals identified through the *U.S. National Clean Hydrogen Strategy and Roadmap*, the U.S. Department of Energy's H2@Scale initiative, the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law), and the Inflation Reduction Act. The subprogram addresses technical challenges through a portfolio of projects in two RD&D categories:

- 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 the conditioning, transport, and dispensing of hydrogen as a gas, as a cryogenic liquid, and as a materials-based hydrogen carrier. Processes and components of interest include liquefaction and hydrogenation/dehydrogenation processes, compressors, pumps, sensors, dispensers, and bulk transport equipment, including pipelines. Integration of components into complete fueling stations for medium- and heavy-duty vehicles and development of fueling protocols are also being pursued. 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 service. The HyBlend initiative investigates the potential of blending hydrogen into the natural gas 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, cryogenic liquid 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, development, and demonstration of breakthrough hydrogen storage materials.

In Fiscal Year (FY) 2023, the Hydrogen Infrastructure Technologies subprogram conducted scenario planning for energy storage applications, chemical/industrial applications, and medium- and heavy-duty hydrogen fueling to prioritize RD&D efforts and establish cost and performance targets. Liquid hydrogen transfer and fueling components and liquid hydrogen storage RD&D were prioritized because of their importance in enabling medium- and heavy-duty hydrogen fuel cell electric vehicles.

Goals

The Hydrogen Infrastructure Technologies subprogram aims to develop technologies so that clean, low-carbon hydrogen can be competitive with incumbent and emerging technologies across diverse applications. These applications include transportation, power generation, energy storage, and industrial and chemical processes. Specific subprogram objectives include the following:

- Develop hydrogen infrastructure technologies, including hydrogen delivery, storage, and dispensing, with the aim of meeting overall cost targets for delivered and dispensed hydrogen. For vehicle refueling, there is an intermediate cost target of \$5/kg H_2 and an ultimate cost target of \$2/kg H_2 for delivery and dispensing, resulting in a total intermediate cost (production plus delivery/dispensing) of \$7/kg H_2 and an ultimate cost of \$3–\$4/kg H_2 dispensed to vehicles.
- Develop low-cost, efficient, compact, and safe hydrogen storage technologies for use with end-use applications, including on board vehicles and at end-use sites. For vehicles, the objective includes meeting an intermediate cost target of \$9/kWh (\$300/kg H_2 stored) by 2030 and ultimately \$8/kWh (\$266/kg H_2 stored) for Class 8 long-haul tractor–trailers.

Key Milestones

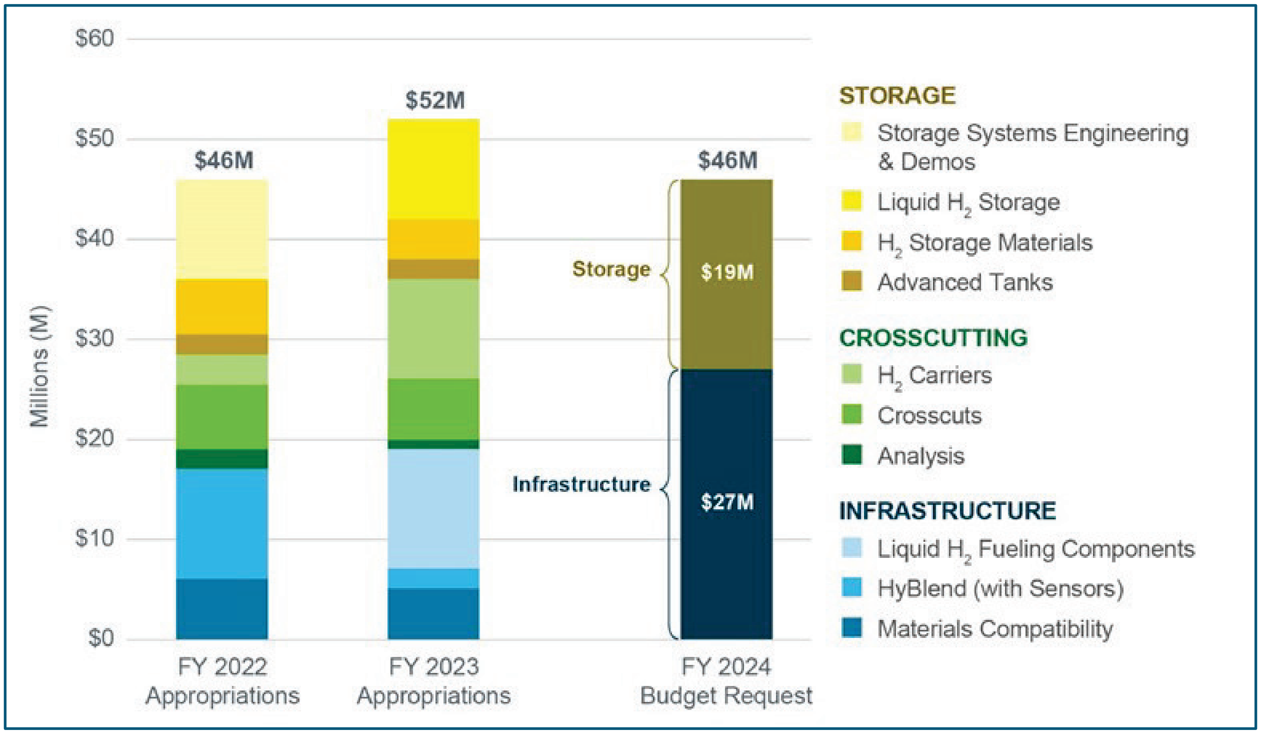
The Hydrogen Infrastructure Technologies subprogram has key milestones for each of the technology areas:

- Develop hydrogen infrastructure technologies for medium- and heavy-duty vehicle refueling to meet an intermediate delivery and dispensing cost target of ≤$5/kg H_2 and an ultimate cost target of ≤$2/kg H_2.
- Develop medium- and heavy-duty vehicle hydrogen refueling technologies capable of dispensing 700 bar hydrogen, either compressed or liquid, at an average rate of 10 kg H_2/minute, with a peak rate of ≤18 kg H_2/minute.
- Develop onboard hydrogen storage technologies meeting an intermediate cost target of $9/kWh ($300/kg H_2 stored) by 2030 and ultimately $8/kWh ($266/kg H_2 stored) for Class 8 long-haul tractor–trailers.
- Develop onboard hydrogen storage systems for Class 8 long-haul tractor–trailers capable of at least a 5,000-cycle life, with pressurized system components capable of at least 11,000 cycles.

Budget

The FY 2023 appropriation for the Hydrogen Infrastructure Technologies subprogram was $52 million. Allocations are shown in the chart below. New areas funded in FY 2023 include liquid hydrogen for onboard vehicle storage and liquid hydrogen fueling components.

The FY 2024 request is $46 million, with $19 million allocated to hydrogen storage RD&D and $27 million allocated to hydrogen infrastructure RD&D.



Annual Merit Review Results

During the 2023 Annual Merit Review, 54 projects funded by the Hydrogen Infrastructure Technologies subprogram were presented, with 20 Hydrogen Infrastructure projects and 6 Hydrogen Storage projects reviewed (a breakdown by budget category is shown on the right). The reviewed Hydrogen Infrastructure projects received scores ranging from 2.1 to 3.7, with an average score of 3.2. The reviewed Hydrogen Storage projects received scores ranging from 2.9 to 3.3, with an average score of 3.1. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

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

Number of Projects Reviewed by Budget Category	
Materials Compatibility (H-Mat)	7
HyBlend	2
Fueling Components	7
Fueling Stations	2
Liquid H_2 Storage	1
Advanced Tanks	4
H_2 Storage Materials and Carriers (HyMARC)	1
Analysis	2

Project #H2-041: H2@Scale Cooperative Research and Development Agreement: California Research Consortium (Reference Station, Fueling Performance Test Device, Station Cap Model)

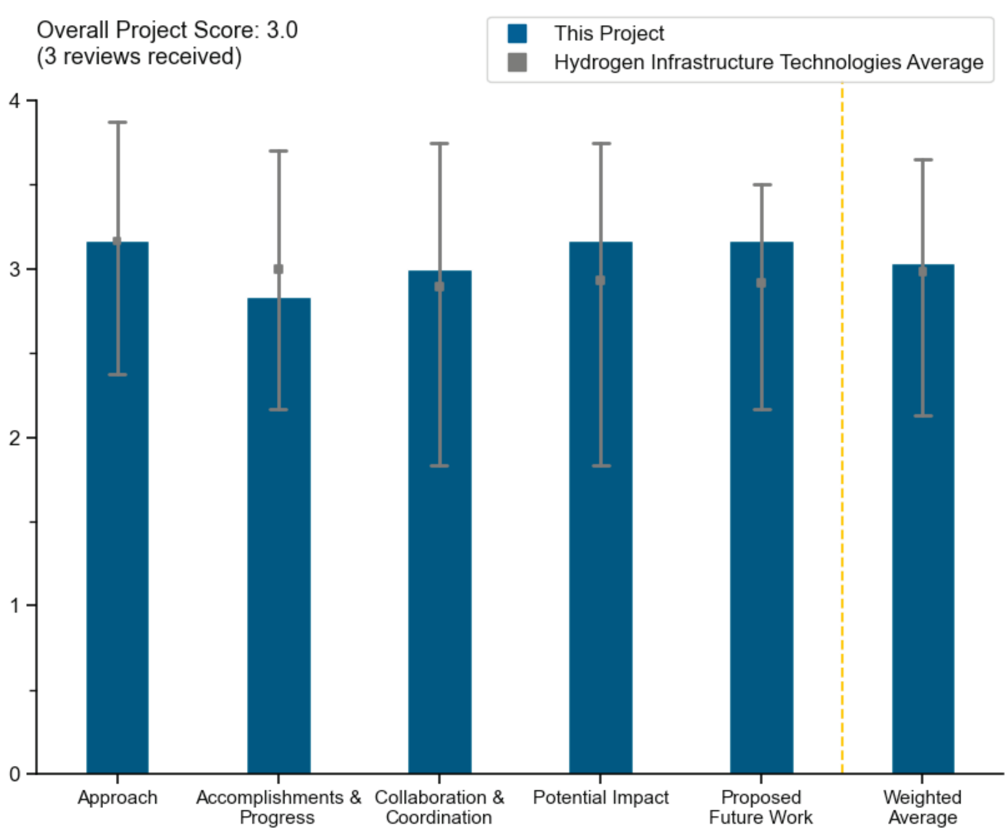
Sam Sprik, National Renewable Energy Laboratory

DOE Contract #	WBS 8.6.2.1
Start and End Dates	10/1/2021–12/31/2023
Partners/Collaborators	Sandia National Laboratories, Argonne National Laboratory, California Governor's Office of Business and Economic Development, California Air Resources Board, California Energy Commission, South Coast Air Quality Management District
Barriers Addressed	Lack of information on operation and evaluation of high-flow infrastructure for heavy-duty hydrogen vehicles including: • Infrastructure examples • Tools to evaluate designs • Test devices for performance

Project Goal and Brief Summary

This project aims to advance hydrogen fueling infrastructure for heavy-duty (HD) vehicles. Researchers will provide design considerations (by developing reference station designs) and risk analysis for HD hydrogen fueling stations. In addition, a model will be developed to evaluate station dispensing capacity. This project will provide tools and information that lead to more efficient design and commissioning of HD stations with greater capacity and higher flow rates.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure 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 presentation did a nice job of presenting information that has been discussed for the past five years but gives no indication of current technology developments or trends being identified for HD fueling. The information presented on the Hydrogen Fueling Capacity (HyCap) model is useful to know. Comparison of HyCap vs. the Hydrogen Station Capacity Evaluation (HySCapE) model is useful to understand.
- The focus on HD stations is much needed. The project has four focus areas: reference station design, risk analysis, development of a performance capability model, and development of a performance test device. The project could address the question of whether the performance capability model, which is trained on compressed hydrogen storage configurations, will also work for liquid hydrogen (LH2) storage configurations. Also, an explanation of the difference between HyCap and HySCapE would be helpful.
- The project approach seems good, but its description is unclear. On slide 5, the reports should be Deliverables, not Approach. The project could consider green hydrogen (GH2) in the scenario.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- It appears Year 1 is setting up a big payout in Year 2, and it will be a tall order, given the breadth of activities.
- Based on slide 2, Project Goals, there seems to be good progress on station modeling and efforts to make the tool available to the public.
- Slide 7 should be "Approach," not "Accomplishments and Progress." On slide 8, the three bulleted take-aways are information that the hydrogen refueling station community has been known for years. The project could provide more insights specific to HD, for example, defining exactly how those relationships are different from light-duty. On slide 9, the information is interesting, but more than just a few numbers was expected. For instance, the project could have provided a concise list of all the components that were listed, the number of sources that were used, and the confidence intervals for them. The project could be linked to the database. Slide 10 is interesting, but more data could have been shared, such as baseline hypothesis for hydrogen and electricity costs and/or a sensitivity analysis. It is not clear how that is different from the Heavy-Duty Refueling Station Analysis Model (HDRSAM). Slide 11 says "Approach" but should be "Accomplishments." The picture of a LH2 onboard tank for maritime is out of scope here. Also, it is unclear why GH2 delivery is considered here but not in the five scenarios. The bottom figure on slide 11 is also very well known and not needed. Slides 13–16 are validating the project's HD model with light-duty data. The differences between H2FAST, HDSRAM, Hycap, and HySCapE should be better explained to measure new progress from already existing models. The project has no Accomplishments and Progress on risk analysis and gaps with codes and standards (C&S), which were Year 2 deliverables.

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 appears to be strong collaboration with a national lab and California (California Air Resources Board [CARB], California Energy Commission [CEC], and South Coast Air Quality Management District [SCAQMD]). The absence of industry involvement is troubling and may be the reason the information presented looks dated.
- There is good collaboration between the three leading national labs. Interactions with Go-Biz, CEC, SACQMD, and CARB are not clear; it seems they are bringing only funding to the table. There is a lack of involvement, even anonymous, from the industry.
- The engagement of four California government agencies is appreciated, but their work contribution is unclear, and the same is true for Argonne National Laboratory.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project is focusing on key issues to build the confidence needed for industry players to invest in the hydrogen HD truck ecosystem.
- There may be useful impact through the development of HyCap.
- Although Potential Impact is obvious, it is not well presented in slide 4. Only the first bullet is relevant to the project, and it is difficult to relate to the rest, which is very high-level.

Question 5: Proposed future work

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

- Much of the project's work will be done in Year 2. One part of the Year 2 plan is the HD station risk assessment. The project could consider adding some context on how stations are proceeding today. Including LH2 storage configurations in the station performance model should be high-priority.
- Given the short time remaining, the project could downsize the proposed work to one or two topics, rather than the four topics presented on slide 20. The project should also meet with industry players (Chart, Nikola, Toyota, Linde, Air Products, Air Liquide, Pilot, Loves) to ascertain their thinking on station design.
- Future work consists mainly in finalizing ongoing work, except the test device. It is not clear why risk performance and C&S were postponed to Fiscal Year 2024, while the project is stopping by the end of 2023. Three-dimensional (3D) rendering is not needed.

Project strengths:

- The project has a great team that is focusing on critical issues for HD stations, and there is potential for useful insight from California agencies.
- Hydrogen for HD is certainly the most critical/important/obvious value for clean transportation. It is great that three main national labs are working on this together. There are great resources to use for pre-design.
- The project's objective is to advance HD station design for characterization and optimization.

Project weaknesses:

- The project has no Accomplishments and Progress on risk analysis and gaps with C&S, which were Year 2 deliverables. The project is not seeing the big picture, which is the difference between HyCap and other models, size and analysis of the database, and new information found through this funding.
- The project encompasses much important work across four different focus areas crammed into one two-year project. Several re-readings of the slides were needed to really grasp everything involved.
- The study is based on dated information but failed to present efforts to identify advancements from industry players.

Recommendations for additions/deletions to project scope:

- It is increasingly likely that many HD stations will have LH2 storage. The team might consider adding the potential for pressure to bypass low-pressure storage by taking advantage of pressurizing LH2. The project could also be more careful with economic analyses. The results are highly dependent on assumptions (e.g., the cost of delivered LH2) and perhaps are not the right forum for projecting station costs. HDRSAM serves this intended purpose. Perhaps the project could make a commitment that the developed designs will be reflected in the next update of HDRSAM.
- The project has no need for 3D renderings. The project should engage more of industry and share more about information collected (even if some of the information is confidential, there is still much to say). The code could be made available so that industries can tune their own versions (not limited to the web only).

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

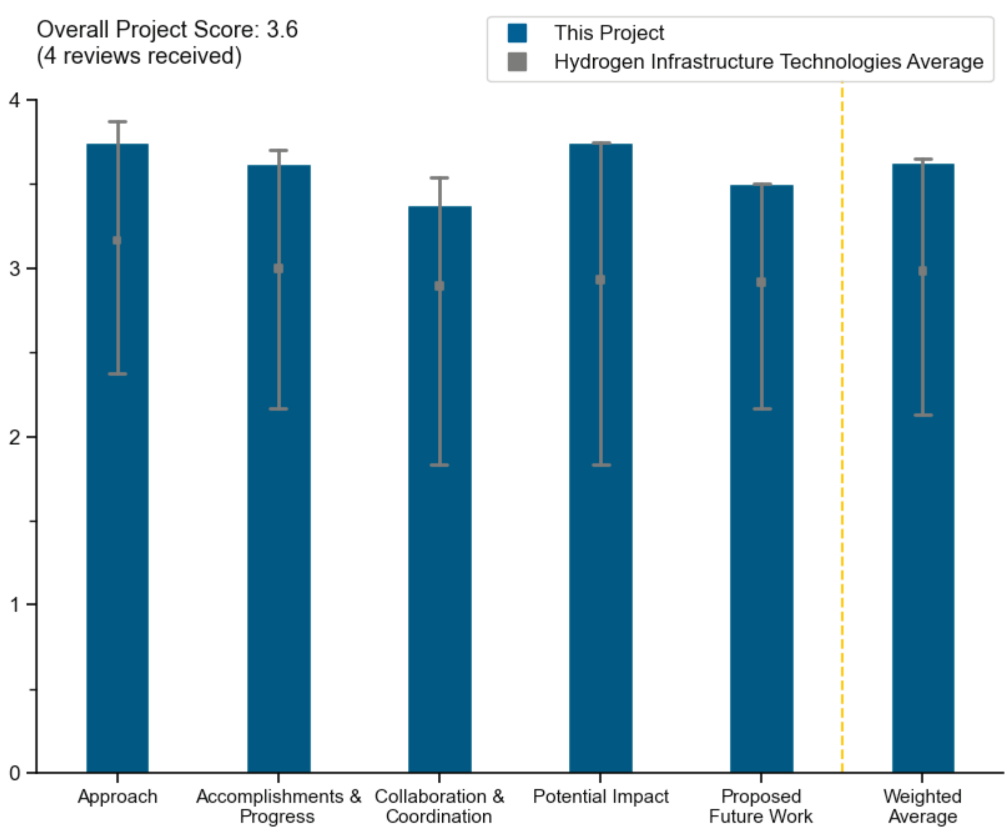
Chris San Marchi, Sandia National Laboratories

DOE Contract #	WBS 8.7.0.1
Start and End Dates	10/1/2018
Partners/Collaborators	Pacific Northwest National Laboratory, Argonne National Laboratory, Oak Ridge National Laboratory, Savannah River National Laboratory, Colorado School of Mines, Rutgers University, University of California, Davis, Swagelok, HyPerformance Materials Testing, LLC, Massachusetts Institute of Technology, University of Alabama, University of Illinois Urbana-Champaign
Barriers Addressed	• 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 primary objective of this project is to evaluate the potential for modern, high-strength steels to inform science-based strategies to design the microstructure of metals with improved resistance to hydrogen degradation. Specific goals are to (1) enhance performance and safety through improved understanding of materials compatibility and comprehensive materials data and (2) reduce the cost of infrastructure and components.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure Technologies 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 for this work includes materials and their evaluation by the participants of the Hydrogen Materials Compatibility Consortium (H-Mat). This includes five DOE national labs that lead the projects and approximately 40 industry and academic partners. The work addresses liquid and gaseous hydrogen, as well as the conditions and mechanisms for hydrogen embrittlement of high-strength aluminum alloys. The project addresses some of the known critical barriers that continue to slow down the acceptance of hydrogen, enabling it to become ubiquitous. The project clearly demonstrates hydrogen-compatible microstructures (aluminum alloys) and the possible limits for stress corrosion cracking in environments that use hydrogen. The presenter used easy-to-understand imagery that would appeal to a relatively broad audience. The presenter answered all of the questions posed. The presenter conveyed significant knowledge about the tests and outcomes. Using a consortium to evaluate the compatibility of materials with hydrogen is an excellent approach. The approach helps to connect this work to the relevant work addressed by the consortium's participants—or perhaps even to ongoing crosscutting work among the participants. The approach also helps to connect research with those who can use the outcomes of the research.
- The team has identified multiple clear areas of need, developed targeted objectives, and designed approaches that are reasonable for achieving those objectives.
- Regarding steel microstructures, many seem to have mixed morphologies (bainite and martensite), and it is not clear if the comparisons were 1:1. Also, more information is required about the microstructure(s) of the low-carbon samples. Instead of micrographs, presenting a table with the microstructure and corresponding properties may be more useful. It appears that austempered heat treatments were followed by tempering treatments. If that is the case, the reason is unclear, because austempering leads to a "tempered" carbide structure. Lower carbon implies less carbides, which implies that carbide "traps" may be deleterious to mechanical behavior in hydrogen. Regarding the aluminum project, the presenter provided inadequate reasoning for leaving AA6XXX alloys out of the test matrix but including 5083-O. Higher-strength AA6XXX alloys offer the most promise in hydrogen environments because of their resistance to both stress corrosion cracking (SCC) and hydrogen embrittlement. Additionally, low-Cu alloys will have better intergranular corrosion resistance and great formability. Regarding the initial fatigue crack, the project considered only slip (in pure metal) and simulations. Much more work can be done here with respect to inhomogeneous particles, grain size, etc. Finally, for the stainless project, the presentation of the results was unclear. The effect of hydrogen on the dislocation density, glide, and tangling was not well communicated.
- The approach is great, apart from initiation.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments and progress toward DOE goals of increasing the use and decreasing the cost of hydrogen include determining the most dominant influence on hydrogen-assisted fracture (strength), influences by microstructures and inclusions, and impacts of pressure on various concentrations of hydrogen. "Low-carbon steels appear to provide a good combination of strength and resistance to hydrogen-assisted fracture," as noted on slide 8 of the presentation. The scientists worked on a diverse range of aluminum alloys in high-pressure dry hydrogen environments and the impact of residual moisture on fatigue and fracture properties in hydrogen fuel cell applications. Expanding the applications of hydrogen fuel cells is another DOE goal, and this work continues to address how to confidently and safely use hydrogen fuel cells to reach their potential.
- The project seems to be making good progress and is advancing the science between metal–hydrogen interactions and behaviors.
- The project has made clear progress on all research thrusts, and the results are promising.
- The progress is impressive.

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 presenter explained the involvement in this project on the part of some staff members in national labs and industry/academic organizations in the H-Mat consortium. Some of these may have provided materials for the testing. This collaboration helps to resolve the uncertainty in the understanding of the interactions and life expectancy of materials that are exposed to hydrogen. National labs and industry partners could potentially collaborate on an inventory of the materials presently used in the natural gas pipeline, on materials that can be used in new hydrogen pipelines, and on tube trailers used for hydrogen delivery.
- The team is largely composed of national laboratory personnel, as would be expected, given the scope of work and nature of the proposal call, which limits funded collaborations with other partners. However, the team is active in engaging with other entities where able to do so.
- The collaboration is extensive and useful.
- Based on the principal investigator's (PI's) previous comments to the previous review questions on collaboration, it appears the project did not have a well-defined set of collaborators from the project's beginning. All the reviewers noted this in the past review, and instead of attempting to improve on this aspect for the project(s), the investigator seems to have overlooked the reviewers' comments.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Characterization of materials in hydrogen environments is critical for adoption of hydrogen technologies in commercial vehicle and industrial applications. The investigators are taking the right steps to improving the testing database and understanding the microstructural features that influence the behavior of metals in high-pressure hydrogen environments.
- The project highly supports and advances ongoing progress toward increasing the performance of hydrogen storage and delivery. It also significantly contributes to the potential for cost reductions of hydrogen storage and delivery through an improved and deeper understanding of materials compatibility and hydrogen-assisted fractures.
- The team has oriented the project objectives to address key questions in the Hydrogen Program. Project advancements will have direct impacts on pipeline safety and inform innovation in developing materials with improved hydrogen compatibility for infrastructure applications.
- The impact is high, except for initiation work.

Question 5: Proposed future work

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

- This project is renewed annually. The work, thus far, demonstrates progress, and the breadth of the membership of the H-Mat consortium demonstrates enthusiasm and support for the work. At present, the project is planned to end in September 2023. The 2023 milestones include looking at the stress–time relationships of subcritical fractures of high-strength pressure vessel steels. This is needed work, and the project has effectively planned its future logically to a very high degree. The testing is rigorous, and documentation techniques are exacting.
- Follow-on proposed work is well aligned with logical next steps for achievements to date. The only suggested modification from the proposed plan would be to evaluate near-Pa-level water vapor pressures in the Al alloys (as well as tempers known to be more susceptible, i.e., T6 for 7xxx and sensitized for 5xxx-series alloys).
- The proposed work is reasonable toward stated goals.
- The PI should consider looking at low-carbon steels, identifying how to get high-strength microstructures for these materials, and defining the properties in hydrogen. With respect to aluminum, more work on AA6XXX alloys is needed. These materials could be pushed into more service testing environments (collaboration). It is not clear how the design goes beyond criteria against dry and moist hydrogen environments. It is strongly recommended that the investigators pause testing on high-strength AA2XXX and 7XXX alloys until more demonstrations of 6XXX are in the market and the in-service environment and

failure modes are better understood. The focus should be on the types of defects (inclusions, porosity, etc.) and their influence on fatigue crack initiation. If pure slip (stainless/aluminum alloys) is looked at, then the project may want to model the effects of grain size on slip transfer. On dislocations in stainless steel and the effect of hydrogen, experiments to prove out the hypothesis are needed to provide better clarity.

Project strengths:

- This project hinges on highly innovative data analyses for material science. The project fills some of the highly influential gaps that are slowing the acceptance of existing materials that are presently used in natural gas pipelines, storage systems, and tube trailers and will possibly be used to store and distribute hydrogen. As people know, even the wrong valve can cause a safety event. In the past, workers used a non-compatible valve in a storage trailer, and as a result, hydrogen delivery was not only slowed but stopped for a significant market in the United States. This work also fills gaps in addressing the reliability of pipelines, storage, and tube trailers for hydrogen. The project contributes to cost reduction in hydrogen compression, as it completes work that many other organizations, by themselves, most likely could not afford to do. This project lends itself to translation for broader audiences. The project contributes to strengthening the knowledge on the part of the hydrogen workforce, including the boots on the ground, planners, and policymakers.
- There is a broad approach to looking at different metals in hydrogen environments. While this can become cumbersome, the PI is doing a great job at advancing the knowledge for each of these areas. The team is encouraged to keep pushing. Novel work is being performed.
- The project has an experienced team, targeted objectives, and good experimental approaches, and the work has positive impacts in multiple areas of interest for hydrogen infrastructure.
- The project is excellent all around and will have impact.

Project weaknesses:

- The project could have been stronger had it, in parallel with the work, immediately transferred the results to hydrogen system planners, pipeline planners, and those who issue permits for hydrogen installations and expect them to work successfully. The H-Mat members could potentially strengthen this project through planners and implementers in their organizations. Although this may appear to be far from the original scope of work, it could be a logical spin-off of the work already completed and carried out expeditiously and effectively with people in the staff of the consortium members.
- The project(s) need more specific partners with more experience with certain materials and scientific fields to help guide the testing and research.
- The initiation work is weak.
- The project has no significant weakness.

Recommendations for additions/deletions to project scope:

- Hydrogen is hypothesized to decrease the cross-slip, thus reducing the obstacle spacing. It is not clear what the project team’s contention is. Regarding Al, no impact of hydrogen gas on fatigue is shown, and there was no cracking in high-pressure hydrogen with high levels of moisture. It would be helpful to know the loading rate on testing for the Al and whether there was a pre-charging step, particularly, the impact of the moist environment. The lack of dissociation also needs further explanation. It would be good to know whether the team is conducting any other work or simply checking to see whether charging was at all possible in the pressures of interest to determine whether moisture is even penetrating. Regarding new steels, the project team got pretty close on the strength and toughness, particularly with the low-carbon steel. Having looked at pressure and dependence, more information is needed on the spread in the low-carbon steel at lower pressures. There was a significant change with the low-carbon steels. More information on the microstructure and the status change of damage mode is needed, as well as how others can build on this information. Regarding austenitic stainless steels, the plot is the activation area (the area that dislocation sweeps under stress); the team is using plastic strain-controlled fatigue tests with strain rate jumps, and the resulting change in stress is correlated to the dislocation sweep. The plot shows air versus hydrogen (H is the higher group). There was a change in the dislocation organization at high and low strain amplitude conditions for testing in air.

- The project should consider crosscutting issues with the other H-Mat projects that address and evaluate the metals used with valves for systems used for gaseous hydrogen storage and tube trailer delivery, as these wear out and add to the system cost. The project should consider how many times they can be opened and closed, when they will need replacement after extended use, and what materials can be pre-selected for valves to optimize their life expectancy. The project should also consider adding various materials' impacts on system weight from the perspective of shipping costs. The project should consider adding an inventory project of existing natural gas pipelines and their materials. Although companies may have their internal reports, it is also possible that the public wants to know about the inventory, as would new market entrants and the investment community.
- The project should drop all the aluminum alloys, except for AA6XXX, and focus on 6082- and 6005-like alloys. If the project wants to keep the 7XXX alloys, the team should work on ways to elucidate the SCC mechanisms more clearly (hydrogen may not play much of a role). Corrosion, rather than hydrogen, is more likely the main driver.
- The project would benefit from additional experiments exploring the aluminum alloy behavior, particularly focused on near-Pa water vapor pressures and other alloy conditions.

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

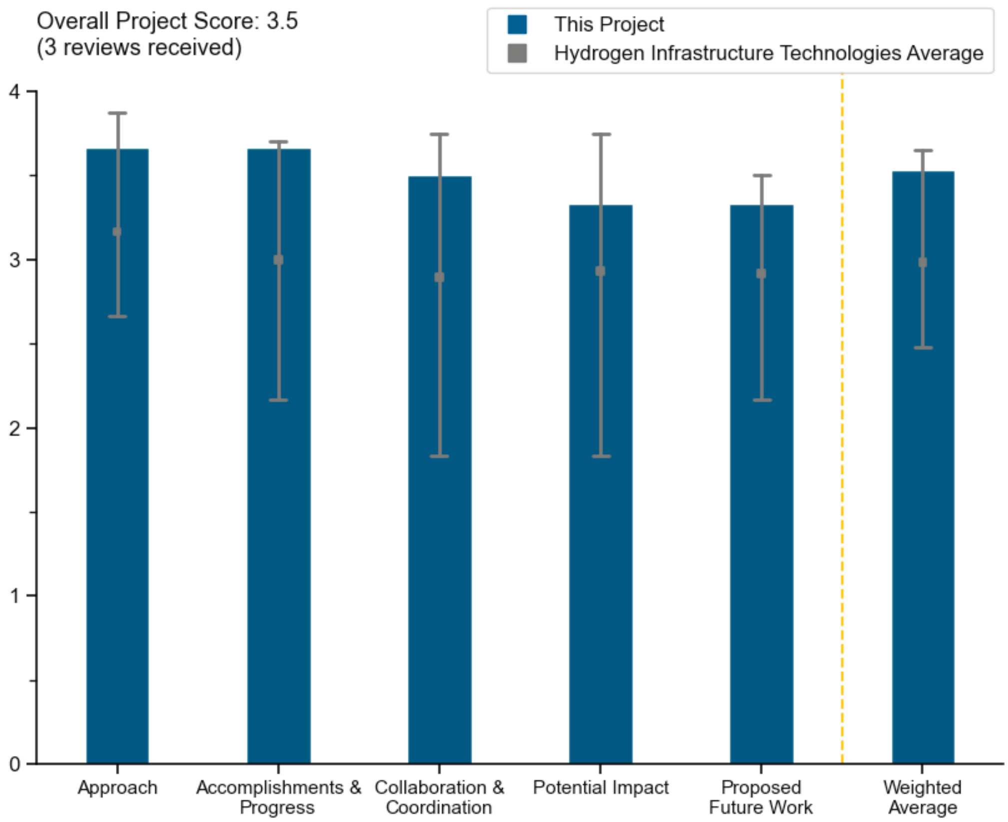
Kevin Simmons, Pacific Northwest National Laboratory

DOE Contract #	WBS 8.7.0.2
Start and End Dates	9/1/2018
Partners/Collaborators	Sandia National Laboratories, Argonne National Laboratory, Oak Ridge National Laboratory, Savannah River National Laboratory, Swagelok, Takaishi Industries, Burke Industries, ARLANXEO, Zeon Corporation, TSE, Chemours Company, Kyushu University (Hydrogenius), INVISTA, Ascend Performance Materials, Solvay, Saint-Gobain, Hummell, Dover Corporation, AMPO, Howden, Solar Turbines, Burckhardt, Green Tweed, Arkema, Kepner Products Company, Nel Hydrogen, Freudenberg Sealing Technologies, Evonik Industries
Barriers Addressed	Safety, codes, and standards • Safety data and information: limited access and availability • Insufficient technical data to revise standards • Limited participation of business in the code development process • No consistent codification plan and process for synchronization of research and development and code development Hydrogen delivery • 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 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.

- The project clearly states the focus on elastomers and the need to identify and model mechanisms of hydrogen-induced degradation in these polymers for the purpose of guiding materials selection and potentially improving performance. The considerable interest from industry illustrates the reality that selection and performance of polymers are critical barriers. The experimental and modeling tasks are well integrated and aligned toward accomplishing the project goals.
- The principal investigator's approach is simple and important, although it would have been good to see more materials investigated over wider temperature ranges.
- The project goal is to address hydrogen compatibility performance of materials to increase durability to provide more reliable and stable performance of systems in the hydrogen infrastructure.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- The project clearly states the goal of demonstrating an elastomer formulation with 50% less swelling compared to similar off-the-shelf materials, and the accomplishments indicate that this goal was achieved. Industry stakeholders' tacit endorsement of this project goal suggests that the accomplishments represent progress toward overcoming critical barriers.

- The project is demonstrating significant progress. The project's modeling and experimental results are clear and provide measurable indicators. However, there are still some barriers that the project leads may need to overcome, which is discussed in the project presentation.
- The project leads have met all performance milestones during a difficult period to do so and have many publications and workshops to disseminate the results. More cryogenic hydrogen work is needed.

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 presentation highlights contributions from Hydrogen Materials Compatibility Consortium (H-Mat) partners Sandia National Laboratories and Oak Ridge National Laboratory. The project is communicating information and results to industry stakeholders, but it is not readily apparent how input from industry stakeholders is helping to shape the project.
- The project held workshops to disseminate results, and a research agreement with Kyoshu University was signed. More could be done with round-robin testing to involve other universities and students. Many are still not aware of H-Mat, shockingly.
- The project shows collaboration with multiple national laboratories.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Since materials are an enabling aspect of hydrogen technology across the production, delivery, and storage spaces, the productive outcomes from this project contribute to progress toward Hydrogen Program goals and objectives.
- The project has great information on material compatibility, which is critical for nearly all working in this area. One project improvement would be to make measurements a function of temperature.
- The project goal is to address hydrogen compatibility performance of materials to increase durability to provide more reliable and stable performance of systems in the hydrogen infrastructure. However, the research does not show a clear path on how it aligns with the objective, as well as the scope of the Hydrogen Program.

Question 5: Proposed future work

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

- The future work is expected to have impact, particularly expanding on partnerships with industry and soliciting input from these stakeholders.
- It would have been useful to hear more about the cryogenics testing to learn where future work is needed, for instance, with three-dimensional (3D)-printed materials.
- The proposed future work is outlined. However, some tasks do not seem to tackle the most significant barriers discussed in the presentation.

Project strengths:

- The physics-informed finite element model appears to have the potential to enable the more efficient evaluation of elastomer performance in hydrogen.
- This is a challenging phenomenon to evaluate, and basic work is needed for the community. The project leads take a multipronged approach, with experimental measurements and modeling, that combines to leave us confident with the consistency of the results. The project held many publications and workshops to disseminate the results.
- Overall, there has been a significant amount of research to see how hydrogen works within different materials.

Project weaknesses:

- New polymer and polymer matrix composite formulations are rapidly being enabled by 3D printing. More information is needed on how the polymer classes were chosen for this study, as well as how much the amount of necessary testing will increase to characterize the new polymers. Slide 9 states that “higher coefficient of diffusion lowers risk of causing damage.” Assuming the spaghetti model of polymer chains, and assuming hydrogen is transported in through molecular motion, it is unclear that diffusion really lowers that risk. It might be higher polymer chain mobility allowing the material to recover, which is associated with higher diffusivity, as stated on slide 8. Similarly, slide 7 states that hydrogen’s inability to migrate with the decompression rate leads to early failure, which is likely highly temperature-dependent, but the graphs (a and b) do not specify the temperatures. Temperature should be a key parameter in the project studies.
- Regarding the project task on materials for cryogenic hydrogen service, it is not clear why cryo-compressed hydrogen storage onboard vehicles surfaced as such a high priority.
- The presentation did not show a clear route to how it aligns with the objective and Hydrogen Program goals.

Recommendations for additions/deletions to project scope:

- Use of 3D printed polymers is likely to increase, and the manufacturing imperfections could play an interesting extension of this work. A potential follow-up project could consider the presence of liquid hydrogen in 3D-printed cavities and the swelling to room temperature, which is ~2.5x larger an expansion than 700 bar to 1 bar.
- The project scope must be shaped by input from industry stakeholders.

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

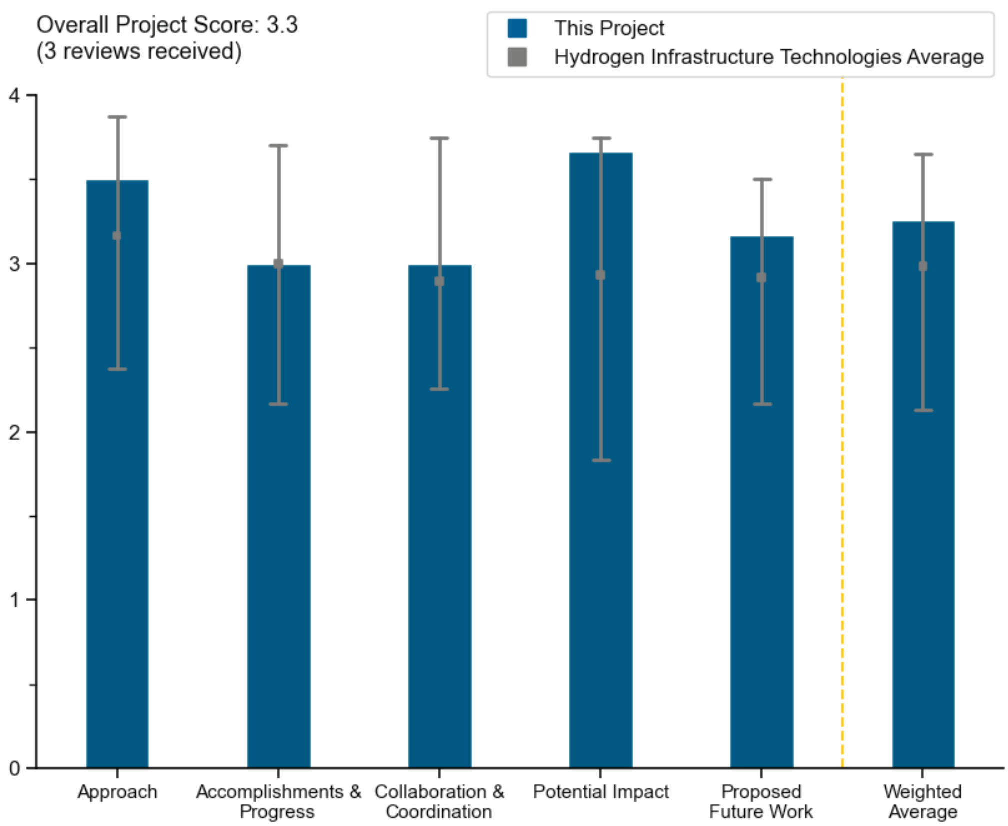
Jacob Leachman, Washington State University

DOE Contract #	DE-EE0008429
Start and End Dates	1/23/2019–9/30/2023
Partners/Collaborators	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 Washington State University's Heisenberg Vortex Tube cooling system can achieve the following improvements to cryogenic hydrogen storage 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 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.

- Using computational fluid dynamics (CFD) modeling of the effects of catalyst conversion provides an effective approach, provided it is validated with test data.
- The project has a great approach with an attractive solution.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- The experimental validation phase is an important aspect of this work. While the poster states that the conversion rates were confirmed experimentally, there is no data or results to back this up. This seems like an important omission from the progress to date.
- The project has many accomplishments in CFD and small-scale demonstration.

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 states collaboration with Plug Power Inc., but there is no information related to what the recommendations were. It is unclear whether the proprietary nature of the work or application prevents disclosure or presentation of the data. As a result, it is nearly impossible to determine the overall scope or impact relevant to the broader market. If the results are of such a proprietary nature that they cannot be disclosed, it is difficult to have a favorable review of the project and its impact, as it appears to be a DOE-funded project specific to a single player in the field and does not advance the broader market.
- The industry partner is definitely the best one to consider.

Question 4: Potential impact

This project was rated **3.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Addressing liquid tank boil-off is an increasingly important topic that needs to be addressed if LH2 is going to remain a viable market offering. Cost and efficiency are directly affected in this market, and there is significant likelihood that the environmental consequences of hydrogen boil-off will need to be addressed in some fashion. The use of a vortex tube cooling system provides a novel potential solution to address tank boil-off, and the work should be encouraged, provided detailed results can be presented for broader market adoption.
- The project is well aligned with DOE objectives, especially LH2.

Question 5: Proposed future work

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

- The project is planned to finish in June 2023 but has failed to provide lab result comparisons. The comparisons are an important step in the project, and it is encouraged that the project continue through this validation stage.
- It is unclear from the poster whether the project is implemented into a full-scale dedicated LH2 tank for field testing. If it is, then the future work gets “thumbs up.”

Project strengths:

- The project addresses a market need and works to solve a critical issue in the LH2 delivery model. The project is innovative, with the use of a vortex tube, and is a simple solution (no moving parts), even though it may suffer from some efficiency deficits.

- The project offers a simple, cost-effective solution for boil-off mitigation and has strong academic knowledge supported by strong industry.
- The persistence and work with Plug Power Inc. are project strengths.

Project weaknesses:

- The project's modeling work needs lab validation that either has not yet been completed or was not presented. It is unclear whether the detailed results were not presented because of proprietary information.

Recommendations for additions/deletions to project scope:

- The project is to be completed in June 2023, so completing the lab verification is an important next step.
- Industry should evaluate the usefulness of the project's technology.

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

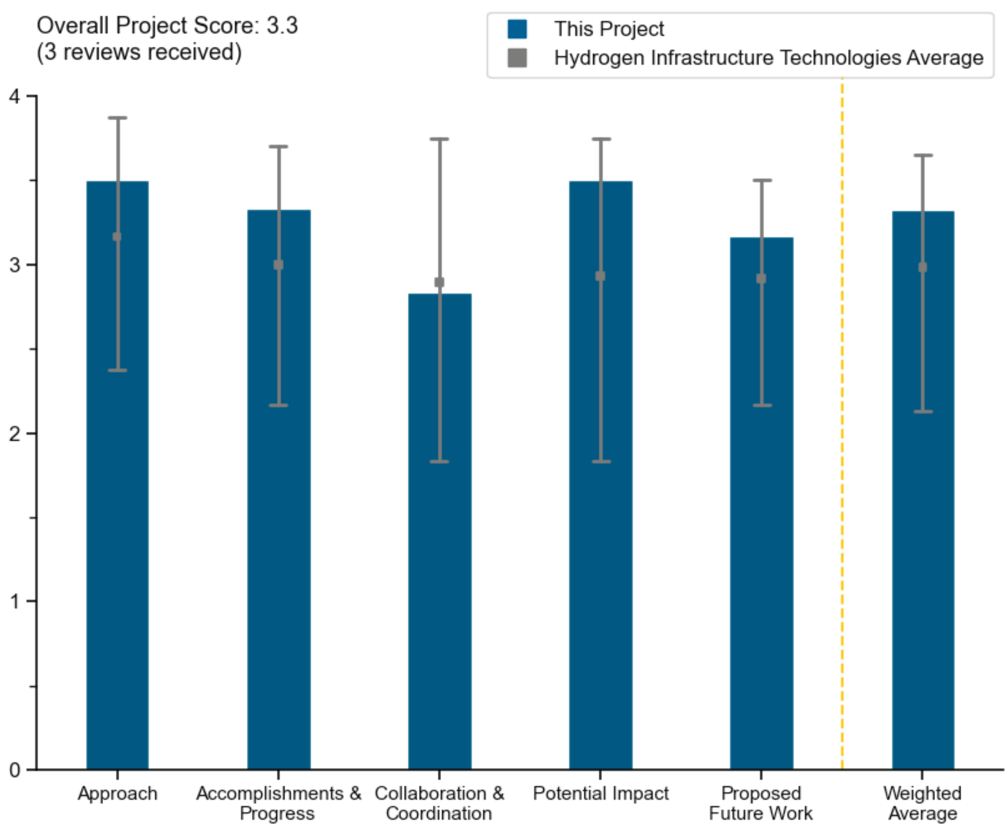
Devin Halliday, Gas Technology Institute

DOE Contract #	DE-EE0008431
Start and End Dates	1/1/2019–6/30/2023
Partners/Collaborators	University of Texas at Austin – Center for Electromechanics, Argonne National Laboratory
Barriers Addressed	• High fuel delivery costs • High fueling station costs • Limited consecutive fills

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 compressor 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 cell vehicle adoption.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure 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 objectives for achieving pre-cooling and energy generation are clear and reasonable. The potential impacts presented on slide 4 are helpful in understanding the financial objectives.
- The project has a great approach with basic calculations and proof of concept.
- Developing a new piece of hardware such as this is not a small challenge, and the project team has made admirable progress to advance it to this stage. However, there are numerous steps in front of them, with many of them not identified adequately. It is a good approach so far to get to this point, but the future approach needs significant work to look for and address many unidentified challenges. Some of these are enumerated in the Future Work section of this evaluation.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The project team has made good progress toward the project goals and, by extension, toward DOE goals for lower-cost hydrogen fuel by reducing capital cost and energy input for refrigeration.
- The project has made great progress, and the issues with leakages were well addressed.
- In considering the project goals of developing an efficient pre-cooling system and generation of electric energy, the project should have been split into two separate projects to accelerate the progress of the expansion technology. The demonstration of filling a target tank is interesting, but it was not clear whether the delivered gas was -40°C throughout the filling process. The work on improving the seal material is important. Presumably, the low-temperature condition was considered in the early stages of development. It would be interesting to know the expectation regarding the original seals.

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 project has a great mix of national lab, engineering, and academic collaboration.
- The project has collaboration with the University of Texas at Austin, Argonne National Laboratory, and Cook Compression, but it is not clear whether there were other collaborations. It seems that some of the challenges experienced could have been overcome through other collaborations. The development process is still in the early stages; nonetheless, it would have been helpful to see some projections regarding the price of a commercial system as compared to the 2015 information included on slide 4. As for the power generated by the linear motor, how it will be utilized in the overall fueling system is unclear.
- The project is lacking partners to manufacture/commercialize the unit and integrate the unit into a J2601 compliant dispensing process. Both have significant challenges, but the project should speed development so as not to lose time later, if and when those partners might provide helpful input to improve the designs.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- A functioning and reliable unit that meets this need could be a breakthrough for dispenser cooling. Resolving many of the barriers is high-risk, but addressing current high-cost and low-reliability refrigeration systems is high-reward.
- The project has outstanding impact on the industry.
- The project has advanced the concept but is a long way from proving commercial viability. Areas that require attention are conducting a technology demonstration using 900 bar gas, delivered at -40°C for 700 bar fueling; clearly defining how the power will be utilized in the system and determining any losses from generation to point of use; and estimating the cost and footprint of a viable system.

Question 5: Proposed future work

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

- The immediate proposed future work is appropriate and accurate. However, the remaining barriers and challenges leave out a few key items. The project should obtain a partner to help manufacture and commercialize, which is a critical next step for validating actual costs (for the business case) and understanding longevity of the unit, especially piston seals, since they are likely to be a design weak point. The project could verify that the unit can meet the J2601 fill temperature requirements (i.e., speed to temperature, and accuracy to stay within prescribed limits). The location of the unit likely needs to be close to the dispensing point. Co-location may be difficult because of footprint, noise, and safety considerations (i.e., high-pressure reciprocation near customers).
- The project was completed in June 2023, but the project team could talk to commercial organizations that are willing to invest in commercializing this concept.
- The reviewer is looking forward to the results.

Project strengths:

- Project strengths include the opportunity to achieve pre-cooling using expansion, the potential for power generation to serve the fueling installation or other adjacent requirements, a preliminary demonstration using 3,000 psi nitrogen, and identification of a cold-temperature material for sealing.
- The project directly targets one of the weakest links (for both reliability and cost) in a hydrogen fueling station, so it has high potential. Good progress has been made to demonstrate a working unit.
- The approach and technology are great.

Project weaknesses:

- Maybe the project had too many objectives to achieve in the timeframe (especially with the disruption of COVID). Perhaps not enough attention has been given to tracking economics in comparison to currently commercialized technology; it is not clear whether there is enough improvement to justify full development of the concept.
- Lack of a manufacturing partner that has experience commercializing a reciprocating high-pressure machine is a significant weakness, particularly with validation of a true “price” for a unit that includes design amortization, general and administrative costs, manufacturing overheads, profit, lifetime support, warranty, etc. The true “price” might be two to three times the target. Long-term testing to understand reliability and durability will be critical, as will the ability to function as an integral part of a fueling station (a partner is needed here, too).

Recommendations for additions/deletions to project scope:

- DOE and the Gas Technology Institute should seriously consider next steps to determine whether the project’s concept is truly viable and how to pursue commercialization.
- The project should seek partners, particularly in manufacturing and fuel station integration.

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

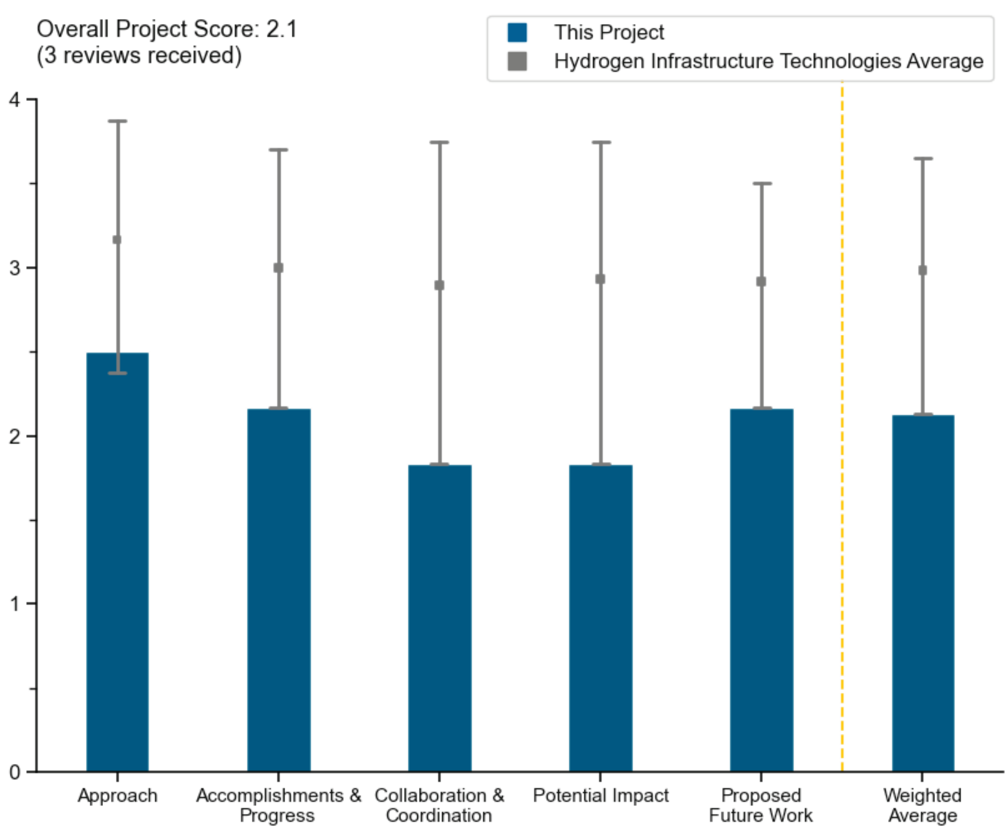
Kyle Gross, RotoFlow

DOE Contract #	DE-EE0008819
Start and End Dates	2/1/2020–5/1/2024
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 RotoFlow technologies 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



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

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.

- Air Products is taking a methodical approach to meeting the design targets for a large “liquid compressor” that would be used to fill compressed H_2 vehicle tanks on heavy-duty vehicles from a liquid supply. The project team tried an “outside-the-box” approach, found it had shortcomings, and pivoted to a more conventional design, which is commendable.
- The project could include more of the technology background, especially on the technical challenge, to help the audience understand how the approach will address the challenge. The project could provide an integrated overview of the tasks to help the audience understand the connections between the tasks, especially for the different parts of the pump system and test skid. The project could also include the cost analysis to estimate the capital expenditures (CAPEX) against the project target. The project goal mentions the upscaling of existing Rotoflow technologies to further advance high-capacity transportation fueling infrastructure. However, further information is needed on the project team’s existing technologies, as well as how the team plans to upscale the technology from the approach described in the slide.
- The objectives or challenges for the project are not clear. Simply stating “a pump exceeding DOE filling targets” is not enough, as the DOE targets do not consider uptime/lifetime and other important outcomes.

Question 2: Accomplishments and progress

This project was rated **2.2** for its accomplishments and progress toward overall project and DOE goals.

- The project has not completed any milestones yet, but Air Products is taking the right steps in developing a new product.
- Much of the progress made was erased because of maintenance and other issues that should have been avoided during a proper engineering design process. The project does not mention specific measurable metrics to determine whether progress was made.
- Further explanation is needed on how the expectation of 4,000 hours seems within reach. The project should include some test results to show progress made toward the target.

Question 3: Collaboration and coordination

This project was rated **1.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project has no collaboration specified in the proposal, and there is no clear opportunity for research dissemination to the public or taxpayer. When asked why the project had not collaborated with the Hydrogen Materials Consortium (H-Mat), the presenter responded, “What’s H-Mat?” The sole reason H-Mat has existed for the last four years is to directly address cryogenic polymer material problems like this in industry, and the project invested considerable time in selecting a new seal material without consulting H-Mat; given these facts, this project is wasting taxpayer dollars and not collaborating at the minimum level necessary to be an effective participant in the Hydrogen Program.
- Air Products is working individually with no external collaborators and has no intent to share findings outside of Air Products.
- The project should engage with more partners for the technology development and upcoming testing.

Question 4: Potential impact

This project was rated **1.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project will only benefit Air Products, if commercialized. There is no plan to make the technology, or the details behind critical learnings, known to the broader industry. Therefore, while this project, if successful, may result in somewhat lower costs for dispensed hydrogen at Air-Products-branded truck/bus refueling stations, it may be very difficult to know exactly what impact the project had (since there will be many other contributions to the dispensed cost). One opportunity for the project to benefit industry more broadly would be an analysis of the potential benefit of one large compressor (the objective of this project) over several smaller compressors, which may not be as challenging to design and manufacture, or other options to fill compressed H_2 tanks on heavy-duty vehicles from a liquid supply (e.g., cryopump plus re-gas).

- The presenter verified that there is no plan for liquid hydrogen testing of this liquid hydrogen pump as part of this project. Hence, there is no way for the project to verify improvement and a return on the taxpayer investment. When asked why the project does not fill a tube trailer to initially test pump performance, the presenter waffled that it was not reasonable to fit such a test into a tube trailer schedule. A tube trailer delivery is worth significantly less than the $2 million taxpayer investment for this project.
- The liquid hydrogen pump is an important piece for the liquid-hydrogen-based supply chain development. The project could add more potential impact by showing the significance of the research.

Question 5: Proposed future work

This project was rated **2.2** for effective and logical planning.

- The plan seems reasonable if the industry trusts that Air Products understands how to progress an internal project like this.
- The future work is not specified sufficiently to maintain accountability or ensure alignment or progress toward DOE objectives.
- The proposed future work includes only the planned activities to the go/no-go decision point in September 2023. The project could include the future work in 2024.

Project strengths:

- The project aims at the development of a cost-effective, reliable, high-flow, high-pressure reciprocating liquid hydrogen compressor system as first of its kind, with high potential impact and high novelty.
- Air Products know-how contributed to a high probability of success. A majority of the project is funded by DOE, yet the work will not be shared, which is a shame.
- The project addresses a much-needed area of the industry.

Project weaknesses:

- Slide 7 does not provide enough detail for us to know that research is being done or that technology is being advanced. It is possible to do this without divulging proprietary information (e.g., x number of tests were completed of y different configurations, Z% better performance than prior model, AA% more operational hours than prior). “Seems within reach” is insufficient; the project team needs to try harder. The project team should state the filing numbers or plans with specificity and not simply “under consideration.” When asked about this, the presenter was unable to produce a single metric that showed improvement was being made toward any kind of measurable objective. The Accomplishments on slides 8 and 9 are not specific enough to be considered measurable achievements. It is not clear whether fatigue tests will be done with liquid hydrogen, which is not covered within the ASME testing specification. Slide 10 says the innovative copper gasket, which was one of the original objectives, did not work and an alternative design is being pursued, which seems to negate the purpose of the project. It is unclear how anyone will know that performance will not be compromised. It is not clear whether any specific research information useful to the broader community will be made public from this project. Since the project is not being sold outside of Air Products, it is not clear how the benefit to the American taxpayer is quantified and how this project distinguishes itself from the non-taxpayer-funded technology improvement.
- The project has narrow benefits, even if it is successful. A giant company such as Air Products should develop in-house on its own dime.

Recommendations for additions/deletions to project scope:

- The project is not providing enough information to be a justifiable research expense to the American taxpayer. The company is simply correcting known issues to an existing machine on the taxpayer dime, with no intent to actually test with liquid hydrogen or provide any research results to benefit the public or community. The device will not be sold as a product outside of Air Products.

- The project could include the cost analysis to estimate the CAPEX against the project target. The project could also include liquid hydrogen testing in the scope.
- The project should add a formal technical target for pump lifetime.

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

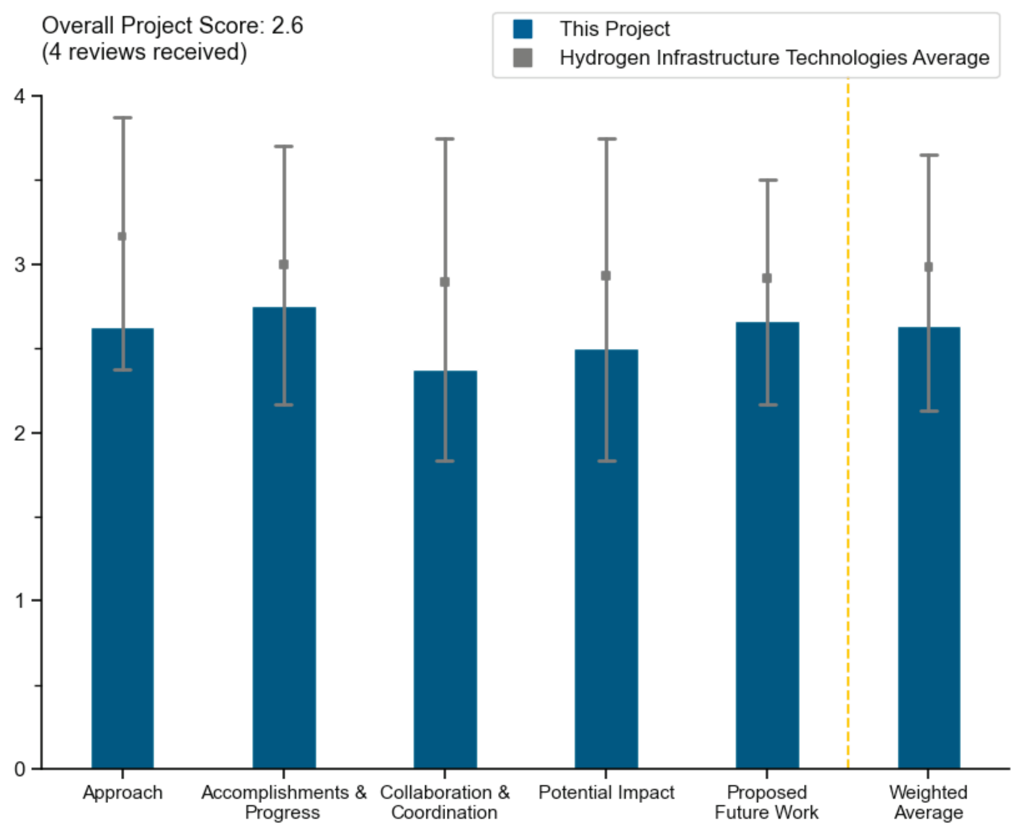
Marek Urban, Clemson University

DOE Contract #	DE-EE0008827
Start and End Dates	1/1/2020-4/30/2023
Partners/Collaborators	Savannah River National Laboratory, Sandia National Laboratories, Pacific Northwest National Laboratory
Barriers Addressed	• Fueling site/terminal operations • Reliability and cost of H_2 fuel pumping Target: develop inexpensive self-healable commodity copolymer fiber-reinforced composites as inner layers to extend the H_2 hose service life to over 25,000 cycles

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 Technologies 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 overall approach of the project appears to meet the criteria for developing a new self-healing polymer material for hydrogen hoses. The material was successfully synthesized and fabricated for testing in later phases of the project. Details remain somewhat unclear surrounding the metric for defining how self-healing properties are defined, as indicated in comments from previous Annual Merit Reviews. While the project's primary goal was to develop a novel material, the project should consider the functional aspects of translating this technology to a usable commercial product and hose assembly. Examples include the material's interaction with hose end fittings (a known industry failure point), bending, crimping, and crushing.
- The project has developed a self-healing commodity copolymer and added fiber reinforcement to it for use in a hydrogen dispenser hose. The project expectation is that the self-healing attribute will help extend the life of the hose and thus lower the overall cost of dispensing hydrogen. Integration of this material-focused work with a hose manufacturer, or at least participation of a hose manufacturer, early in the research process, would have been great to ensure that the output of this research was implementable in the industry.
- The approach does not seem to guarantee that the material can meet all the requirements for a hydrogen fueling hose or that it will be accepted by a manufacturer. It is also not clear that the testing, which is not well described, will actually result in a hose with at least 25,000 cycles. For example, many failed hoses clearly have had particles embedded with them, and it is unclear whether the particles will inhibit the self-healing. The responses to comments from the previous Annual Merit Review were helpful, but this year's presentation left many of the same types of questions unanswered. Last year's questions should have prompted a presentation with more detail about some of the salient issues this year.
- There are several weaknesses that could contribute to a final solution that does not address the mission. The industry failure mode this material is trying to resolve is not discussed. The initial approach did not seem to consider hose service conditions such as temperature, pressure, conductivity, and permeation/leakage requirements. It is not clear whether the material selected can withstand these conditions. How the damage-repair cycle was defined was also unclear, and a reference to hydrogen industry standards for hydrogen dispenser/fueling hoses was not included.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- The project has made good progress toward its goals. The team has figured out the process to make a self-healing copolymer, determined the required proportion of constituents needed for the healing action, and shown before-and-after mechanical property data to show the self-healing action. The team has also designed an inner layer with the project composite and run some finite element model simulations to determine stresses in the layers. Although the material is novel, progress toward DOE goals is a bit unclear, considering that there may be multiple failure/leak mechanisms in a real hose, which makes it difficult to estimate the contribution of a self-healing inner lining to the overall cost reduction.
- Overall, the project appears to have met the milestones set out for development, fabrication, and testing of the self-healing hose material. Testing appears to have met the metrics outlined in the milestone charts for number of cycles and pressure and temperature. The project now appears to be near the conclusion, at which point they are looking for commercial partners to advance the material to later stages of development. At this late stage in the project, it would be good to address the low-cost component of the original project criteria. This appeared to be missing from the presentation content.
- It is uncertain how the project can come to a successful conclusion. One question that was asked during the panel session involved the ability of the hose material to withstand crimping to attach the metal end fittings, and the answer was disappointing.
- The progress against the existing milestones shows progress, but it is not clear that those milestones indicate that DOE goals are being met. The DOE goals are met only if the work results in a completed hose that first passes certification testing and then survives actual service conditions.

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.

- While potential future partners have been listed, the existing partners are not in the business of manufacturing hoses and materials. In addition, there are no partners who use hoses and would serve as an opportunity to gain real-world exposure, acceptance, and ability to test. This is a significant weakness and affects the ability to make any further progress.
- The project utilizes expertise from various national laboratories, which seems appropriate for the development of the polymer material. The addition of an industry partner would have provided valuable feedback on how the material could be translated to a commercial product, as well as direct evaluation of the material for typical failure mechanisms seen in the field.
- The collaborators are all national laboratories, with no hint of industry, and although no offense is intended to the labs listed, the National Renewable Energy Laboratory should have been included by virtue of its hands-on high-pressure hydrogen testing capability, including a robotic arm that can simulate the rigors of the fueling process.
- This presentation was focused on budget period 3, and collaborative aspects between the principal investigator and the national laboratory partners were not obvious.

Question 4: Potential impact

This project was rated **2.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Hoses are a necessary part of a fueling station that, by extension, help meet DOE goals. However, existing hoses are currently meeting the need, albeit without the desired longevity. An existing, non-optimal hose is still more important to DOE goals than a preliminary material that marginally increases hose life, even if successful. The improvement would be welcome but will not have a significant impact on the overall rollout of fueling stations and is only successful if adopted by a third party, who still has to deploy. Also, existing hoses are improving in parallel to this effort.
- Overall, the project meets the baseline metrics for the development of a novel material for hydrogen hose applications. Some details are lacking on how the material could be integrated into a hose assembly, how the material meets the metric for low cost, and how it could increase durability over current products. The test plan could have included more relevant durability test for hose failures seen in the field.
- The project's goal to increase the life of a potential material for the hose aligns with the Hydrogen Program and DOE research and development objectives to reduce the overall cost of dispensed hydrogen. The project has started the initial steps toward finding an appropriate partner, funding sources, etc., to commercialize its material. The outcome of such efforts remains to be seen.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- The future work of engaging hose manufacturers is good and will validate whether the material has potential interest. That is when the real testing can begin. The plan could have further detail as to next steps, especially if there is lack of interest from the manufacturers without more testing. It is not clear how most of the organizations listed in the technology-to-market segment directly apply to developing new hoses.
- Future work was identified only as seeking future commercial partners and funding sources, but the impression was given that additional testing was being planned. It is unfortunate that simple leak and permeation testing of the hose was not planned.
- The project appears to have a plan for translating the material over to industry for the development of a hose assembly. There will need to be significant effort to build a hose prototype and evaluate the assembly.
- The project seems to be ending in Fiscal Year 2023.

Project strengths:

- Overall, the project appears to have met the milestones set out for development, fabrication, and testing of the self-healing hose material. Testing appears to have met the metrics outlined in the milestone charts for number of cycles and pressure and temperature. The project utilizes expertise from various national laboratories, which seems appropriate for the development of the polymer material.
- If this material meets hose manufacturers' process requirements and can demonstrate longer life, then it is a welcome improvement. The project is demonstrating that it can meet its milestones, but it needs more milestones to continue.
- The idea is sound, but the project execution suggests commercial benefactors might not see the value in the effort without closer attention to the product requirements.
- The project developed a self-healing polymer system that potentially has wide applications.

Project weaknesses:

- Several key weaknesses include a lack of definition of the failure modes that this solution is trying to solve and a lack of performance testing based on industry standard best practices. In the first case, there does not appear to be an attempt to assess in-service fueling hose failures that would allow the proper definition of the premature failures that could be "repaired" using this novel material. In the second case, it does not appear that the damage–repair cycles are based on any industry standard performance tests covered in documents such as CSA/ANSI HGV 4.2 (CSA Group/American National Standards Institute standard for hoses for dispensing compressed gaseous hydrogen) or ISO 19880-5 (International Organization for Standardization, Gaseous hydrogen – Fuelling stations – Part 5: Dispenser hoses and hose assemblies).
- The current lack of a partner to validate the ability to integrate this material into an actual hose is a major weakness. There are many aspects of hose design in addition to the self-healing ability that must also be demonstrated to obtain the required certification of the hose. The testing regimen is not well described, and it is not clear exactly what a self-healing cycle is nor whether that is pertinent to the overall life of a hose in real service.
- Some details are lacking on how the material could be integrated into a hose assembly, how the material meets the metric for low cost, and how it could increase durability over current products. The test plan could have included more relevant durability testing for hose failures seen in the field.
- The project team is missing a polymer manufacturer and a hose manufacturer; their involvement from the beginning would have ensured a higher chance of the self-healing polymer being adopted in a commercial product.

Recommendations for additions/deletions to project scope:

- The project is not really complete until a hose manufacturer accepts the material and demonstrates that it can safely meet the requirements of a hydrogen fueling hose by manufacturing and obtaining certification. This effort should be added to the project as final validation.
- The addition of an industry partner would have provided valuable feedback on how the material could be translated to a commercial product, as well as direct evaluation of the material for typical failure mechanisms seen in the field.
- It seems the project is nearing its conclusion, so it is unlikely there is room for additions to the project scope, but a good start would be to address the weaknesses identified.

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

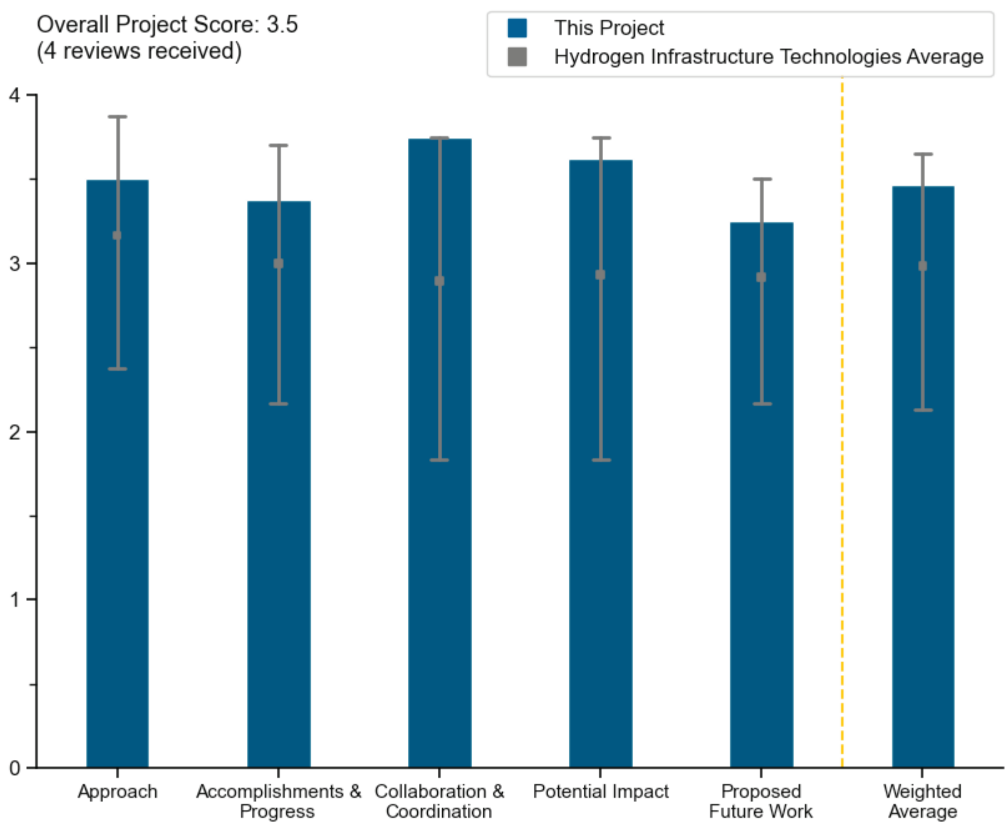
Kip Findley, Colorado School of Mines

DOE Contract #	DE-EE0008828
Start and End Dates	2/1/2020–5/31/2024
Partners/Collaborators	Los Alamos National Laboratory, National Renewable Energy Laboratory, Wire Tough, U.S. Steel, General Motors, Hydrogen Materials Consortium (H-MAT, Sandia National Laboratories), Chevron, POSCO
Barriers Addressed	• Hydrogen delivery infrastructure costs and reliability

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 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 identifies objectives related to alloy development that allow cost and performance targets to be established. For example, the project references two incumbent stainless steels, 316 and 255, as baseline materials, so that cost and performance targets for new alloys can be established relative to these baseline materials. The alloy development objective of reducing cost while maintaining performance in hydrogen addresses a critical barrier in the deployment of hydrogen technology. The tasks in this project related to tailoring alloy composition and material testing are well designed to meet the objectives.
- The proposed approach on developing high-Mn-Al duplex steels (ferrite/austenite microstructures) is based on stability of the austenitic phase, high stacking fault energy, and precipitate strengthening. At the same time, the approach aims to reduce expensive elements such as Ni and Mo in the composition. Cost reduction is an important metric for new alloy development, and the three metrics for hydrogen compatibility of the austenitic phase are sound and have been shown to have worked in a number of cases for several austenitic systems.
- The metallurgy discussion establishes the relevant knowledge gap and opportunities. The metallurgical approaches are sound and systematic. The testing approaches are not fully descriptive to capture the hydrogen degradation, which leads to potentially convoluted interpretation.
- The project objectives and barriers are clearly defined.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- First, the project assessed the uniaxial tension response of several austenitic steels (e.g., 316L, High Mn, and V-Micro-Alloyed High Mn) under various conditions (cold working, aged, hot-rolled) and concluded that high strength for cost reduction is an attainable target. Significantly, all microstructures were found to maintain their strength in the presence of hydrogen, and only the hot rolled V-Micro-Alloyed High Mn showed relatively substantial reduction. Then the project explored strengthening of High Mn Duplex steel compositions through cold working, aging, and V carbide precipitates. By measuring notch tensile ductility, the project concluded that the adopted approach of high-Mn composition and thermomechanical treatment yielded microstructures that do not lose their strength in hydrogen in comparison to baseline 255 Duplex stainless steel, which suffered an almost 50% reduction of its strength. In summary, with the use of tensile strength as a performance indicator, the project succeeded in presenting two duplex steel microstructures (High Mn, hot- or cold-rolled) that experience only a 15% tensile strength reduction in hydrogen. The neutron-scattering assessment of the two austenitic alloys, High Mn and High Mn Duplex, are not yet conclusive regarding the effect of hydrogen on deformation mechanisms.
- The project demonstrates progress toward its objectives, specifically through the results presented on the performance of new alloys relative to the baseline materials (e.g., slides 10 and 12) and the cost of new alloys relative to the baseline materials (slide 15). The results related to performance and cost targets represent progress in addressing critical barriers for materials in hydrogen systems.
- The approach and accomplishments were clearly explained. However, there were no milestones to identify the progress.
- Significant progress has been made on the metallurgy and characterization.

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 demonstrated effective engagement with partners such as Sandia National Laboratories, Los Alamos National Laboratory, and WireTough in the execution of tasks. The impact of the project has been enhanced by the involvement of industry stakeholders, particularly U.S. Steel and POSCO. The project has organized meetings with national laboratory and industry partners to communicate results and solicit feedback.

- The project has a large number of collaborating partners, including Sandia National Laboratories for testing in hydrogen, POSCO for developing alloy microstructures, and National Renewable Energy Laboratory and General Motors for market analysis. So far, the collaborations have been significant toward the project's development and accomplishments. The efforts to identify the nature of deformation mechanisms through neutron scattering are yet at an exploratory stage.
- The project has collaboration with national laboratories and industry.
- The project's work has involved relevant collaborators.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has explicit targets for new alloys related to cost and performance, and results from the presentation represent tangible progress relative to these targets. The cost and performance targets for new alloys align with Hydrogen Program goals, indicating the potential impact of the project for the deployment of hydrogen technology.
- The project's approach based on High Mn Duplex compositions yielded microstructures with significant strength in hydrogen at reasonable cost.
- 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 metallurgical insights establish a foundation for the future efforts for low-cost stainless steel. However, the impact is a bit skewed by the questionable hydrogen testing approaches.

Question 5: Proposed future work

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

- The proposed future work to identify the most promising alloy and process conditions based on strength, hydrogen embrittlement resistance, and cost represents a productive outcome for this project.
- Future work is set to tackle the challenges and barriers.
- The proposed work is reasonable and aligned with the goals of the study.
- Planned efforts to understand deformation mechanisms are important toward rational alloy design. The proposed further enhancement of hydrogen embrittlement performance in terms of tensile strength needs to rely on techno-economic analysis because it is not clear why further enhancement is needed. Also, it is not clear why the project plans to explore electrochemical hydrogen charging vis-à-vis gaseous hydrogen charging. Electrochemical charging is known to induce surface defects that affect uniaxial tension measurements. In addition, there is no fundamental theory underlying correlation of fracture toughness results from electrochemical and gaseous hydrogen charging. From the way the project was presented at the Annual Merit Review, it is not clear how market transformation analysis will impact the future research directions and outcomes.

Project strengths:

- The project provides a clear description of the metallurgical factors needing to be addressed, a logical plan for composition modification, and elegant and unique neutron-scattering work.
- This project has clear cost and performance targets for new alloys and effectively involves industry partners to enhance the potential for impact on hydrogen technology.
- The project has a strong approach with using duplex microstructures with high-Mn, low-cost austenitic microstructures (some of which happen to retain high tensile strength in hydrogen).
- The project provides a techno-economic analysis.

Project weaknesses:

- It is not clear how the task on fatigue crack growth modeling on slide 14 contributes to meeting the project objectives.

- It is not clear what the advantages of the project's results are in relation to the performance indicators of the already explored Mn-based microstructures, which can be found in the open literature (e.g., Koyama et al., *International Journal of Hydrogen Energy* 42: 12706–12723). In addition, it is well known that Mn reduces grain boundary cohesion, hence it is important that the project assess the fracture toughness of the various microstructures in hydrogen.
- The hydrogen testing is convoluted. The proposed fatigue modeling is rudimentary and not aligned with modern best practice approaches that consider the relevant damage physics and/or reflect the ability to handle the relevant engineering complexity. The different aspects of the project are not well integrated and seem disconnected.

Recommendations for additions/deletions to project scope:

- The project's future work was reasonable but seemed decoupled; better integration is needed. There are several questions:
  - What the design criteria are, other than strength, toughness, and hydrogen resistance, and whether any other is being sacrificed
  - Whether there are other factors that scale with stacking fault energy—the metallurgical features are controlling the stacking fault energy—and whether it is causal
  - Whether the project looked at how the solubility or diffusivity was modified with the metallurgy changes
  - Whether the project ensured there is a homogeneous hydrogen gradient
  - How fast the team loaded to allow for consistent hydrogen redistribution
  - Whether these are charged or just tested in environment
  - Whether the team is looking at notched tensile strength
  - What the details of the experiment are

  For the duplex, there can be modifications of the damage modes and where the hydrogen concentrates between them. It is unclear whether the team examined any of these details, or whether there are any insights to inform the project alloy design. It appears that the project planar slip occurs earlier in the engineering strain with hydrogen. Regarding the fatigue model, it is unclear whether it is empirical only because it is unclear that there is a direct link. It seems like it would be tough to link the R ratio to the crack tip hydrostatic stress.
- It is unclear how the neutron scattering information will help reveal the deformation mechanisms for the alloys under investigation. This reviewer does not know of any advancements made in the field of hydrogen embrittlement through neutron-scattering measurement. In addition, deformation mechanisms are sensitive to loading environment (e.g., uniaxial tension versus fracture toughness testing), and the project needs to account for this difference. Lastly it is not clear what the approach to fatigue modeling is (slide 14). Effort should be made in the approach to involve information on deformation mechanisms; otherwise, it will be another phenomenological approach based on ad hoc criteria, e.g., critical hydrogen concentration, that will be valid only for the load and environment conditions chosen for the present project.
- The fatigue crack growth modeling task could be deleted without compromising progress toward the project objectives. The resources supporting this task could then be redirected to activities that are more directly supporting the project objectives.

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

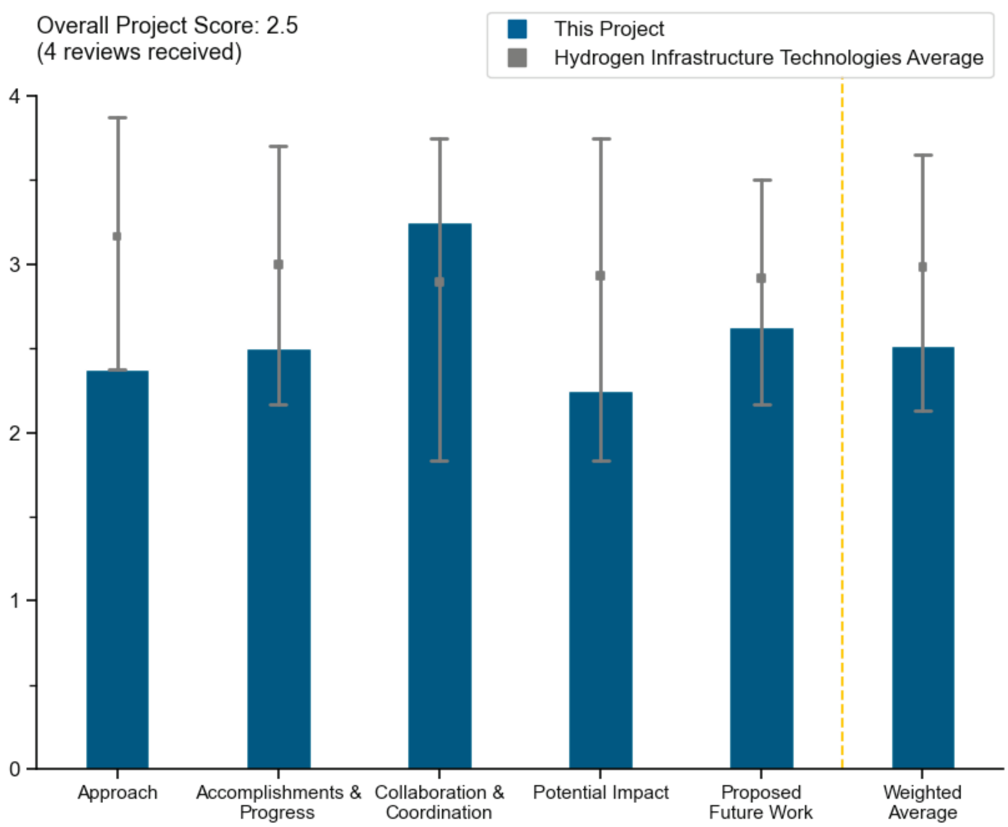
Gregory Thompson, The University of Alabama

DOE Contract #	DE-EE0008831
Start and End Dates	1/7/2020–9/30/2023
Partners/Collaborators	Colorado State University
Barriers Addressed	• Identification of the most suitable thermally stable transition metal carbides for hydrogen trapping • Uniform dispersion of tailored carbide traps within a matrix for optimal strength and ductility • Production of the most effective metal-rich carbide (hemicarbides) as traps

Project Goal and Brief Summary

This project is developing a new carbide-dispersed austenitic/ferritic steel (CDS) for hydrogen storage and dispensing applications. 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 Technologies projects.

Question 1: Approach to performing the work

This project was rated **2.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project goals and barriers are clearly defined, and the proposed solutions to barriers are identified.
- The fabrication and computational work are well-thought-out and well-executed, but there are opportunities for improvement in the project's approach. First, the team has not performed any validation of the trapping calculations via methods such as thermal desorption spectroscopy or permeation. This is a weakness of the project that could be addressed with limited additional efforts such as simple electrochemical permeation experiments that would provide a comparative diffusivity that would inform the trapping efficacy of the introduced carbides. Second, it would be more useful to benchmark hydrogen performance against 316 stainless steel rather than 304 stainless steel since 304 is known to be quite susceptible to hydrogen embrittlement. This sets the bar for performance lower than what can already be achieved with current materials (e.g., 316) that are widely used in hydrogen gas service. Third, it would be helpful to have direct comparisons of the alloy microstructure between the various conditions. For example, the improvement in static hydrogen embrittlement properties could be due to differences in other factors aside from the introduction of the carbides.
- The project vision on slide 2 indicates the intent is to develop a new type of steel with "higher hydrogen tolerance and higher strength." However, it is not clear what material serves as the baseline to establish a target of "higher hydrogen tolerance and higher strength." The absence of a baseline reference is particularly notable since the new steel is designated for specific applications, i.e., hydrogen storage and dispensing. In addition, the feasibility of improving "hydrogen tolerance" through manipulating hydrogen trap sites is in question, particularly for applications involving hydrogen storage. In these types of applications, it is expected that the pressure-boundary materials are continuously exposed to hydrogen, such that there is a continuous hydrogen flux in the material resulting in all trap sites filling to their equilibrium levels. In this case, trap sites with high binding energy are not preventing hydrogen from populating trap sites with lower binding energy.
- The project argues that hydrogen embrittlement can be mitigated by using transition metal nanocarbides to trap hydrogen, depriving the lattice of hydrogen that brings about embrittlement. The Annual Merit Review presentation referenced the oxide-dispersion-strengthened approach of creep resistance as a source of project inspiration. However, the two phenomena, creep and hydrogen embrittlement, are completely different, involving different degradation mechanisms; hence, any parallels are simply wrong. The project has investigated the trapping capabilities of a number of precipitates of groups IVB and VB metals through density functional theory (DFT) calculations. As such, the project can be considered to have met the objectives it set from the beginning. However, the project has not compared the calculated binding energies with experimental measurements through thermal desorption analysis, and the accuracy of the calculated binding energies has not been verified. The project says that the nanocarbide approach will provide higher embrittlement resistance than conventional steels, "particularly to limited exposure environment" (i.e., slide 4). The project does not present even a single example of an application where this "limited exposure environment" condition is prevalent. Unless the project provides such a technology basis, it fails to meet the DOE objectives for embrittlement mitigation.

Question 2: Accomplishments and progress

This project was rated **2.5** for its accomplishments and progress toward overall project and DOE goals.

- Excellent progress toward project objectives is demonstrated through clear and measurable performance indicators. The project's results suggest that one or more critical barriers will be overcome.
- The team has made steady and clear progress toward achieving the stated goals.
- On slide 12, it is said carbide concentrations less than 0.05 wt.% in 304L provide increased strength with compatible ductility. This claim is misleading because the ductility suffers a reduction from ~70% in the absence of hydrogen to ~32% in the presence of hydrogen. In addition, for any other precipitate concentration, the ductility loss is more severe. Hence, the project's results so far do not advocate that the transition metal carbide approach is a promising approach to mitigate embrittlement. On slides 10 and 11, the project presents calculations of the effective diffusion coefficients inside the precipitates through the

use of a phenomenological relationship by Oriani. It is unclear what the purpose of this calculation is in the quest of embrittlement mitigation. It is based on a percolation theory with unknown boundary conditions at the precipitate–matrix interface and fictitious assumptions (e.g., only one extraordinary trap per carbide particle). In fact, on slide 10, it is listed that the referenced calculation on this slide relies on traps being only on the surface of carbides. This assumption is wrong, as we know trapping at the interface is only through misfit dislocations, and the project's calculations do account for this important underlying mechanism. On slide 13, the project's experimental measurements show once again why the nanocarbide approach does not mitigate embrittlement. For instance, even for the ZrC precipitates that the project's publication considers as a most promising class of precipitates (*Physical Review of Materials* 5 103603, 2021), hydrogen reduces the failure strain and reduction in area by as much as 50% in 304L. In summary, the project's approach and results do not provide a pathway to meeting critical goals of DOE.

- This project does not specify performance indicators but states the general goal of developing a new type of steel with "higher hydrogen tolerance and higher strength." For this reason, progress toward project objectives cannot be readily evaluated. There are results on slide 12 and slide 13 that compare mechanical properties of CDS alloy 304L to those for conventional 304L following hydrogen exposure, but it is not clear that conventional 304L is the baseline material in hydrogen storage and dispensing applications. Presuming that conventional 304L can serve as a baseline, the data does not show an improvement in "hydrogen tolerance" for the CDS alloy compared to the conventional one, so that even the general goal of "higher hydrogen tolerance" is not achieved with the CDS approach.

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 appeared to engage effectively with Hydrogen Materials Consortium (H-MAT) partner Sandia National Laboratories to perform tests on hydrogen-exposed tensile specimens from CDS 304L and conventional 304L. The project needs to collaborate with industry stakeholders in hydrogen technology so that goals and performance indicators are defined and have impact.
- The team is working closely with collaborators at Sandia National Laboratories, NASA, and Ames Laboratory. These engagements are positively impacting and accelerating the project.
- The project's results involve collaborations with Colorado State University (DFT calculations), Sandia National Laboratories (hydrogen testing), and Ames Laboratory (powder metallurgy). However, the collaborations are just serving the nanoprecipitate approach of the project, which, as has been elaborated in this review, is not serving DOE goals.
- The project is collaborating with another academic institution, national laboratories, and NASA.

Question 4: Potential impact

This project was rated **2.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- If results can demonstrate that tailored CDS is suitable for hydrogen storage, then it will be critical to the Hydrogen Program and has potential to significantly advance progress toward DOE goals and objectives.
- The potential impact of the project is minimal since no specific performance targets were established relative to a baseline, technology-relevant material. Although materials are an enabling aspect of hydrogen technology, it is not clear that outcomes from this project will advance progress toward Hydrogen Program goals and objectives. For example, results from this project do not demonstrate cost savings or improved "hydrogen tolerance" relative to incumbent materials in hydrogen technology.
- Unless the project defines its quantitative relevance to the "limited exposure environment" condition (see slide 4), it cannot be considered as meeting DOE goals and objectives. In an open system, carbides saturate, and hence they are rendered irrelevant to mitigation, as hydrogen will always be available in the lattice to initiate embrittlement. So far, the tensile results in hydrogen show that the nanocarbide approach cannot mitigate loss of tensile ductility, even in the classic 304L system. The project so far has not demonstrated any promise toward advancing DOE goals and objectives.

- The project is studying an interesting topic, but concerns remain that the potential impact of the project is limited by the reliance on trapping-based approaches to mitigate hydrogen embrittlement for an open system exposure condition. The team has tried to address this concern in the presentation, but more consideration of specific applications in hydrogen infrastructure where this approach would provide measurable improvements in performance is recommended. Second, the required approach to introduce the carbides appears quite intricate; however, it is not clear this approach is readily scalable to a level necessary to support hydrogen infrastructure applications. Additionally, it is unclear what components are being targeted. It is not clear how difficult it will be to implement this material into existing manufacturing pathways for these components. It is unclear whether challenges with broad implementation limit the potential impact.

Question 5: Proposed future work

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

- Proposed future work will contribute to overcoming most barriers.
- The proposed future work will augment the team's past progress and is reasonable, given the stated goals. However, the proposed pathway should be augmented by (1) detailed microstructure characterization to provide insights into the role of other known contributing variables, (2) specific studies of hydrogen trapping parameters to validate computational studies, and (3) comparisons of results to incumbent materials already known to exhibit high hydrogen embrittlement resistance (e.g., 316L).
- The future work is summarized on slide 19. The proposed tasks are a continuation of the project's present approach, in particular to the case of ZrCx carbides. Hence, there are no alternate pathways to mitigate the project's failure in meeting DOE goals and objectives.
- The proposed future work is essentially an extension of the current approach, so the project impact is not expected to improve.

Project strengths:

- The project has complementary experimental–computational expertise of primary team members, novel ideas and fabrication approaches, excellent collaborations that are providing clear benefits, and continuous scale-up in outputs.
- The modeling performed in this project is solid and likely has scientific value.
- The project demonstrates potential to be effective and aligns with Hydrogen Program and DOE goals and objectives.
- The strengths of the project are its experimental powder metallurgy component and the development of carbide-rich microstructures that are well characterized relative to particle shape, size, and distribution. An interesting aspect of the project could be the use of atom probe tomography (APT) to verify the project's DFT results related to vacancies within the precipitates or even the nature and composition of matrix–precipitate interfaces. Unfortunately, the project has shown no progress in this direction, as can be seen from slide 15.

Project weaknesses:

- The project's approach and results cannot be used for hydrogen embrittlement mitigation in open systems because eventually carbides saturate and cease to deplete the lattice of its interstitial hydrogen. For closed systems, the approach depends on the hydrogen pressure and the time of exposure. The project has not addressed such conditions in relation to real-world applications. In summary, trapping of hydrogen and its effect of hydrogen embrittlement is well known since decades ago. This project neither identifies any gaps nor advances a mitigation strategy.
- The diffusion model presented on slides 10 and 11 may not be applicable to the CDS alloys in the project. This model is formulated based on several assumptions, including equilibrium between hydrogen in lattice sites and trap sites, as well as a low fraction of traps populated with hydrogen. These assumptions may not apply to the CDS alloys, so the model formulation on slides 10 and 11 is not appropriate.

- The project needs experimental validation of computational work and should compare results to alloys that set standards for performance (rather than more susceptible materials), where these materials will fit into hydrogen infrastructure. The team should also perform detailed microstructure characterization to ensure that other factors are not driving observed differences in hydrogen embrittlement performance.

Recommendations for additions/deletions to project scope:

- The project's results on binding energies need to be verified experimentally. DFT calculations need to be shown to yield reliable predictions for the systems under investigation. Activation barriers for trapping in precipitate vacancies have not been calculated. Perhaps this can be an important future outcome of the project, given that its promise as a mitigation strategy is not credible. As has been argued, the project's proposition is anchored entirely on "limited exposure environment." This condition needs to be addressed and quantified in relation to real-world applications.
- It is possible that modification of trap sites in stainless steels can reduce effective hydrogen diffusivity and, in turn, lower hydrogen-assisted fatigue crack growth rates. Given this prospect, such fatigue crack growth testing on CDS alloys in hydrogen gas needs to be included in future work.
- The team should perform thermal desorption spectroscopy experiments (or elevated temperature electro-permeation experiments) and microstructure characterization of specimens to confirm the efficacy of introduced traps and other factors that are not responsible for the improved performance.

Project #IN-025: Hydrogen Delivery Technologies Analysis

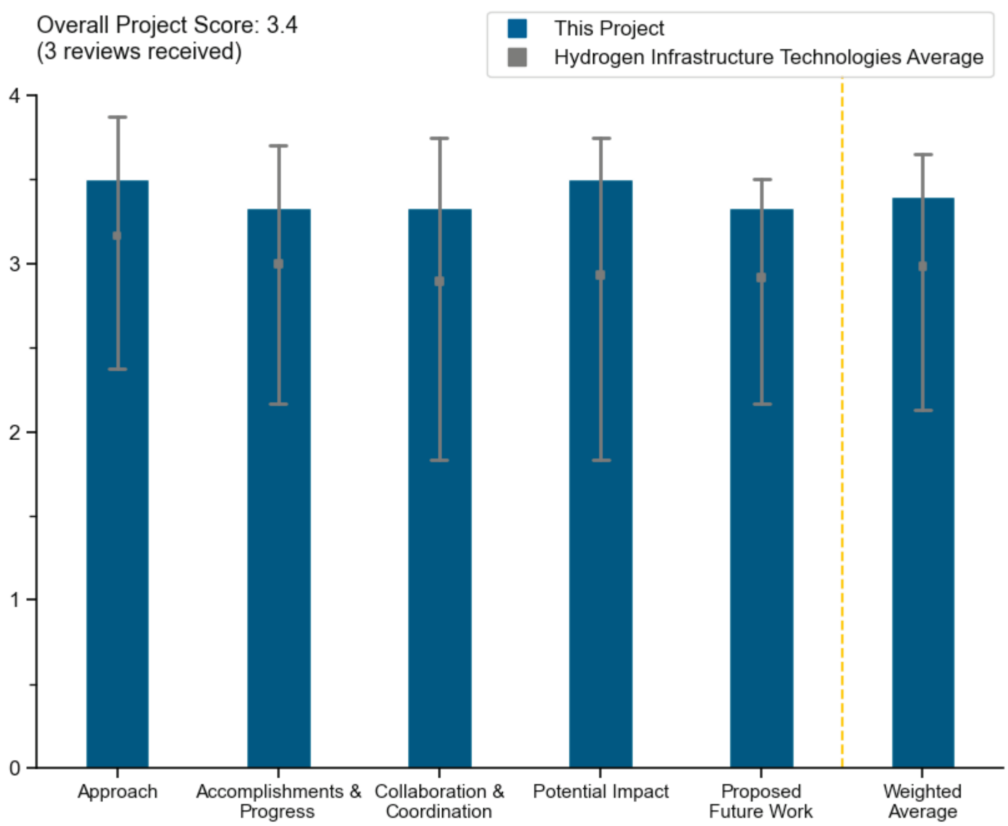
Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	WBS 3.4.0.1
Start and End Dates	10/1/2005
Partners/Collaborators	Energy Technology Analysis
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools • Stovepiped/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 and ammonia delivery technologies. Researchers will analyze various hydrogen and ammonia technologies throughout their life cycles 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 and other industry partners on this project.

Project Scoring



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

- Hydrogen delivery for fuel cell vehicles and stationary applications is a promising opportunity to create sustainable hydrogen infrastructure. ANL's approach is quite comprehensive and responsive to DOE needs. Comparing liquid hydrogen (LH2) and ammonia (NH_3) is a very useful strategy.
- The project provides a needed tool/analysis for future expansion of the hydrogen/ammonia markets, building on the successful modeling work done by the ANL team.
- The project objectives and barriers are clearly identified, with some being addressed. The project demonstrates feasibility, especially if the project team can overcome barriers.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The modeling approach and results are quite promising and useful to industry. The Hydrogen Delivery Scenario Analysis Model (HDSAM) updates are quite relevant. The project should include the heavy-duty fueling infrastructure with pipeline, tube trailer, LH2 tanker truck delivery, and other cost components. The project also includes regional cost variations, which is very important for deployment and compressor costs. The project addresses pipeline costs for ammonia versus hydrogen, which is quite important.
- The project uses case study examples of potential pipelines, which is a good approach to demonstrate the model usefulness. Such cases should consider that pipelines are generally built in many stages across many years. The staged process generally starts with a core line and then builds out to individual and regional new users over time. The project should show a build-out over time, as this would probably have a significant impact on the line sizing, as the core line would likely be significantly oversized (regarding the initial pipeline usage) to enable future growth. On slide 6 of the presentation, there is a good deal of variation in the relative costs of pipelines in the United States. In general, this is probably attributed to permitting costs and land acquisition more so than materials or labor. It would be helpful for the project to provide clarification on the costs across regions and include some detail on the subcategories, as this would demonstrate regional variation. To improve the impact of the studies, the project should have a standardized delivery cost across all models for improved impact of studies. It is difficult to compare \$/ton for NH_3 vs. \$/kg for H_2. Perhaps this can be normalized, for example, to an energy basis or a utility basis, such as per-mile when used as a transportation fuel.
- The project objectives and progress have been demonstrated and clearly measured. However, in the Approach/Accomplishment section, it states that the delivery cost is optimized for the combined pipeline network and compression stations. Clarification is needed on how they were optimized, or the information used for optimization should be 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.

- ANL industry partners have provided good guidance on cost drivers and contributed to the delivered hydrogen cost. Partnerships with hydrogen industry leaders are important for producing high-value analysis results. Collaboration with the ammonia distribution network is critical to strengthening the alternate pathways for lower-cost delivery.
- Collaboration and validation with industry are critical aspects of the deliverables of the project's modeling work. The weaknesses of such modeling work are typically limited access to data for validation and continued collaboration with the industry representatives who own/operate/design/build pipelines.
- The project has a few collaborators.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Effective cost modeling of pipeline systems remains one of the most challenging aspects of regional H_2 development. The huge uncertainty associated with cost-per-mile, along with the associated timeline for developing projects, is a limiting factor in being able to make roadmap projections for market expansion and timing.
- Hydrogen delivery cost is a major challenge for successful transition to a zero-emission economy. The cost analysis is quite comprehensive and inclusive of relevant cost contributors, which should enhance the usefulness of the results to decision makers in the delivery aspects of hydrogen infrastructure. The potential impact is quite positive in the transition strategy for hydrogen infrastructure.
- The project aligns well with the Hydrogen Program and DOE mission and goals.

Question 5: Proposed future work

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

- The future work is clearly defined. Ideally, the team will have the capability to access the cost data for ammonia delivery because it would help provide a more accurate financial analysis and comparable data to the delivery of H_2O.
- Future work includes an ammonia pathway, which is a useful new opportunity compared to LH2 and green hydrogen modes of transportation. The Ammonia Energy Association would benefit from expanding the ammonia delivery model to include loading terminals for rail and tanker trucks. The project would also benefit from releasing a standalone model for evaluating ammonia delivery cost.
- The remaining effort on the project and the project closeout timeline are uncertain. The project is listed as 70% complete, but no date is listed on slide 2.

Project strengths:

- The ANL team is supported by a skilled consultant and industry partner and is well positioned to do the HDSAM modeling work. Inclusion of NH_3 as hydrogen carrier is consistent with international efforts to transport hydrogen worldwide. The focus on delivered hydrogen cost is very timely and appropriate.
- The project encompasses a topic relevant to industry and regional planners. The project has a strong modeling team with a history of delivering models relevant to the market.
- The project is clearly outlined and demonstrates feasibility in the industry.

Project weaknesses:

- Incorporating risk management and its cost in delivery is important. For example, insurance industry underwriters have national conferences that look at this as an opportunity for investment and also a risk in terms of insurance policies and claims. Comparing onsite production with LH2 pipeline delivery may be helpful in a very large-scale futuristic scenario. The comparison will be very productive for hydrogen industry participation, while contributing to better industry engagement.
- The project's next steps are not clearly defined.

Recommendations for additions/deletions to project scope:

- The project future work is valuable as proposed. Adding pipeline safety and insurance cost may increase investor community confidence in the analysis results and value proposition.
- It would be good to see comparable data for the delivery of NH_3 and H_2O and costs to separate H_2 from both.

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

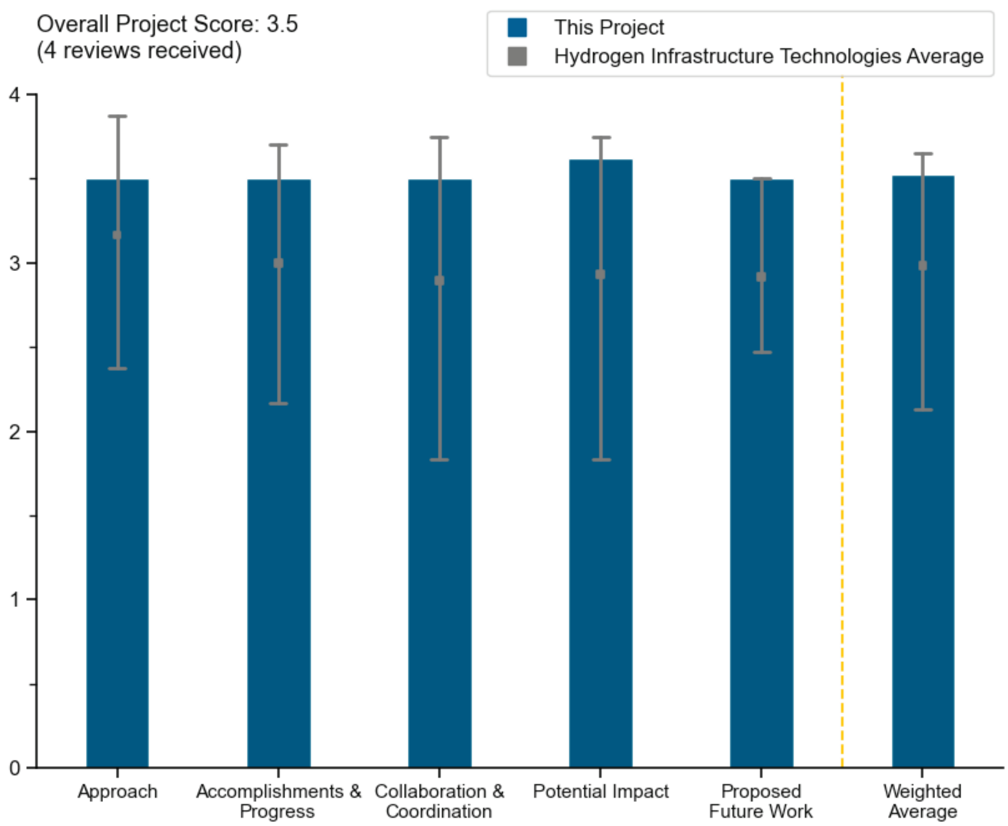
Petros Sofronis, University of Illinois Urbana-Champaign

DOE Contract #	DE-EE0008832
Start and End Dates	10/1/2019–9/30/2023
Partners/Collaborators	Swagelok, Linde plc, Arcelor-Mittal, 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. 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 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 basic premise of the project and its approach are reasonable, with a clear alignment toward breaking through key barriers. Regarding the approach, the team developed the various alloys to isolate the contribution of short-range order (SRO), but it is not clear how this effect will be decoupled from the substantial changes in alloy chemistry (and any associated effects). For example, the team should be confident that any observed differences in behavior can be ascribed to specific effects of SRO.
- The project objectives were clearly identified. The barriers were identified, and the project team understands what is needed to overcome them.
- The project is interesting but seems to be segmented between understanding the SRO and designing low-cost stainless alloys for hydrogen service.
- The characterization work is world-class in identifying SRO. However, the approach to linking to hydrogen damage was not clear.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The team has made tangible progress toward identified milestones, including a clever implementation of scanning transmission electron microscopy (STEM) to image regions with SRO and the down-selection to the final candidate alloys that will be studied in more detail.
- The milestones were defined, and the project has completed approximately 50% of its milestones.
- Significant progress was made on the project; however, the remaining lack of clear correlation between the efforts to establish SROs and the hydrogen compatibility will limit the material development goals.
- The project appears to be tracking well.

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 a well-balanced group of collaborators from industry, academia, and national laboratories. The team seems to be weighing industrial input in the appropriate context.
- The project has dedicated significant efforts to collaborate broadly, particularly with industry stakeholders, with clear evidence of tangible and coordinated engagement (involvement with down-selection of alloys, for example).
- The project team collaborated with multiple national laboratories, an international university, and private industry.
- There is good collaboration within the project.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project aligns well with Hydrogen Program objectives and has the potential for larger impacts. Several of the candidate alloys exhibit interesting behavior, but additional work is needed to confirm alloy fatigue and fracture performance.
- The alloy development work is critical and should be pushed forward as fast as possible, especially considering the good performance of alloys 2 and 3.
- The project is critical to the Hydrogen Program and has the potential to significantly advance progress toward DOE goals and objectives.

- This category is difficult to judge, given the intermediate stage of work. If there are strong SRO impacts that can be logically tuned to impact the behavior, then the project will be impactful. However, if not, then the project will not impact the development of new stainless steel. However, the methodology will impact the science community.

Question 5: Proposed future work

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

- The project should be segmented into understanding the nucleation of SRO in these alloys (i.e., what the elements contribute to the ordering, whether they influence strength, and whether they influence mechanical properties in hydrogen). In parallel, the team should consider focusing on alloy development based on the current set of tests. Regarding the next phase of alloy development, the project should consider modifying the down-selected chemical compositions based on which elements appear to be playing significant roles in the behavior (e.g., alloys 2 and 3 exhibited good resistance to hydrogen embrittlement, which might be partially due to the copper addition). Nitrogen provides strength, but the project likely needs at least 4–5 wt.% Ni. The project should consider something like 15% Cr, 4% Ni, 12% Mn, 0.3% N, 0.15% C, and 3% Cu.
- The project's next steps are very logical and well planned.
- The steps to complete the uncompleted milestones were defined.
- The project proposes reasonable next steps.

Project strengths:

- The assembled team is highly qualified and has partnered with key industry stakeholders who are actively engaged in the project. The general approach is logical, and the team has project goals that are well aligned with the Hydrogen Program objectives. A synergistic combination of mechanical experiments and characterization, including the development of a novel STEM technique, will have broader impacts on the metallurgy community outside of this specific project or area.
- The project is very straightforward and is explained concisely. This project will be beneficial for the Hydrogen Program.
- The project's novel new characterization capability is a strength.
- The project has an excellent team composition.

Project weaknesses:

- While the title of the project is focused on leveraging SRO for alloy design, there seems to be limited attempts to establish connections between alloy performance and SRO. This hinders the potential impact and utility of the theoretical aspects of the project, which are the key to the material design elements that the team hopes to develop.
- There is a lack of clear correlation with the SRO behavior and the hydrogen compatibility. Also, there is uncertainty in knowing the factors that control and the extent of tunability of the SRO.
- The project places too much emphasis on SRO.
- The project has no apparent weaknesses.

Recommendations for additions/deletions to project scope:

- The project should make it a priority to establish the correlation between the SRO and hydrogen behavior. The short-range ordering is just in the presence of hydrogen. When considering the damage mode, it is not clear how this also occurs in high-strain conditions. Nickel content actually has an important role, where less nickel content causes more hydrogen embrittlement. Only slow strain rate tests (SSRTs) are done, and such tests can be misleading for true hydrogen cracking compatibility. Authors suggested a role of local chemical heterogeneities (SRO, either a change in local order with or without deviation from the chemistry). The statistical distribution of the SRO must be determined, as it is relevant to the propensity to impact the dislocation behavior. In the end, there is a need for a potential shift on the global nature of the dislocation behavior to impact hydrogen compatibility. As the project builds up in scale, the team looks at individual impacts, but results will depend also on the spatial distribution. If the team cannot look at that, it is not clear how the project will handle this as the technology scales up. It is not clear whether the hydrogen impact is the nature of the SRO or whether it impacts the distribution. Different behavior is seen in different alloys. It would be helpful to know whether the team sees differences in the SRO between the alloys of interest, and whether the team has any reason to believe that the SRO should change. It would be nice to build more incontrovertible evidence of a correlation between the hydrogen embrittlement behavior and the SRO.

- The tensile data are difficult to interpret without knowing the hydrogen concentrations of each material, so gathering this information should be a high priority (acknowledging that it was stated in the talk that this was in the work). Additionally, the team should further elaborate on why SRO will dominate hydrogen behavior over other potential changes induced by the significant variations in alloy composition. As of now, it appears that SRO has been assumed to dominate, but clear linkages between SRO and hydrogen performance have not been established.
- The project should broaden the alloy development work to include slightly more compositions.
- There are no recommendations at this time.

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

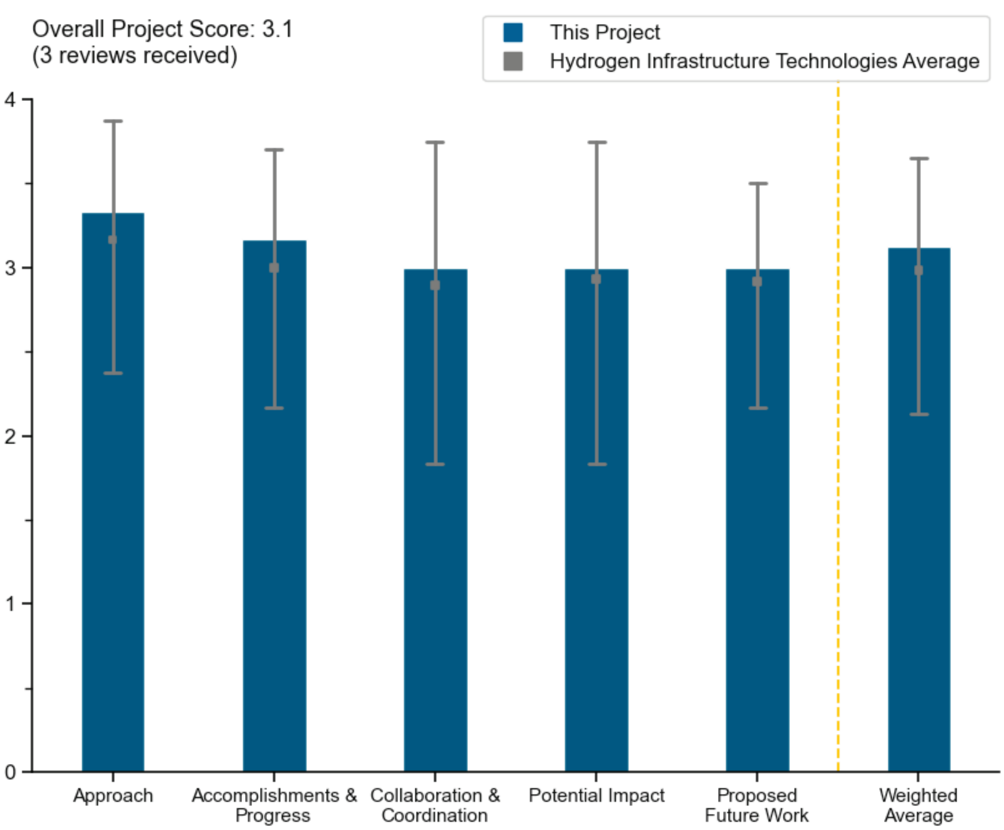
Kevin Nibur, Hy-Performance Materials Testing, LLC

DOE Contract #	DE-EE0008829
Start and End Dates	3/24/2020–10/31/2023
Partners/Collaborators	Somerday Consulting, LLC, Sandia National Laboratories
Barriers Addressed	• Safety, codes and standards: permitting

Project Goal and Brief Summary

Hy-Performance Materials Testing, LLC, Somerday Consulting, LLC, and Sandia National Laboratories (via 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 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.

- This is an important project whose goal is to reduce the time and cost of FCGR measurement in hydrogen environments through a new testing approach. American Society for Testing and Materials (ASTM) standards require that FCGR measurements be conducted at low frequencies, close to 0.1 Hz, to account for the hydrogen effect. As a consequence, tests of fatigue crack growth per loading cycle (da/dN) versus the cyclic stress at the crack tip (ΔK) may take an enormous amount of time, which is measured in months and years if multiple load ratios (R), pressures, material compositions, etc. need to be ascertained. The project has developed an experimentally verified and tested approach that can markedly reduce the measurement time of threshold stress intensity factors (e.g., from 55 million cycles to 8 million cycles, as shown on slide 15; or by 80%, as shown on slide 13) for the cases of 4130X and SA-372 Grade J steels. As such, the project is well designed, has clear objectives, and, most importantly, serves the acceleration of FCGR testing processes that are essential to real-world technology applications and hence to the scaling up of the hydrogen economy.
- The overall approach to using lower-pressure testing to correlate material performance is admirable, and impacting codes/standards requirements will be useful. This will be especially true for applications outside of high-pressure applications.
- Defining the steepness of the K transition is a good way to accelerate fatigue testing.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments of the project can be clearly seen on slide 9, in which the shedding of the maximum stress intensity factor is shown as a function of fatigue crack advance. The ASTM E647 standard requires that the load shedding be done at a given value of the normalized K-gradient rate parameter C=(1/K)dK/da that controls the shedding of the maximum stress intensity factor (load) upon crack growth, which, as has been introduced, is independent of the material yield strength. To accelerate the testing time, the project advanced the application of multiple C values (e.g., three values) for load shedding as the applied stress intensity factor decreases with crack advance. This multiple C-value approach advanced by the project is particularly better than the ASTM fixed K-gradient rate that can yield load shedding rates that are too slow for stronger materials. Most importantly, this year, the project came up with a continuous reduction of the K-gradient rate parameter C in a way that elegantly accounts for the yield strength of the material. This has been accomplished by the introduction of a single parameter Cnorm from which the K-gradient rate parameter C is calculated as Kmax/Kmax,i =sqrt(1–2Cnorm*Da/(Kmax,i/σ_{sy})^2))—the definitions of the parameters in this equation can be found in the slides of the Annual Merit Review presentation. To put it another way, the project incorporated the material yield strength into the shedding rate, which effectively ensures that the loading history (active plastic zone and near-crack-tip residual stresses) do not influence the crack growth. This new FCGR acceleration Cnorm approach that yields a continuously reducing C for load shedding has been experimentally verified—by comparing its results to those of the so-called baseline approach that does not involve load shedding—as shown by the graphs of slide 10 for the cases of SA-372 Grade J and 4130X steels. The associated reductions of testing time and run time costs relative to those of the baseline are 66%. Based on the new testing approach, the project also investigated the effect of water vapor in the hydrogen gas. The results of slide 14 show that below a certain value, ΔK excursion, of the stress intensity factor range ΔK, the FCGR is controlled by water vapor and not by hydrogen. The value of ΔK excursion increases with increasing water vapor concentration, that is, the water-vapor-controlled regime spans a larger range of stress intensity factor ranges with increasing water vapor content. This is an intriguing result that is opposite to the well-known fact that oxide presence in the crack wake results in higher threshold stress intensity factor ranges.
- The project has good accomplishments and progress to date. The data generation is the easiest part, with ultimate ASME and ASTM buy-in being the most difficult. Initial feedback from the various committees on whether this could be accepted would have been appreciated.
- The project has met all its milestones and deliverables.

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.

- Collaboration and coordination with Sandia National Laboratories for experiments at high hydrogen pressures, the ASTM Task Group on load history effects, and ASME are most ideal. ASTM and ASME can coordinate the adoption of the Cnorm approach to the practice standards.
- The principal investigator's (PI's) past connection to Sandia National Laboratories' materials program is great, but the degree of external interaction and feedback is not clear. The PI is involved with the codes and standards committees.
- The project has good outreach to standards organizations.

Question 4: Potential impact

This project was rated **3.0** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project is tremendously impactful. Reducing FCGR times and costs by 66% (for the systems that have been tested in this project) is a significant advancement of the current state of the art as described by the ASTM protocol. The project serves the DOE goals and objectives in the space of safety assessment and codes and standards development for the hydrogen infrastructure.
- The project has a high potential impact, but the degree of impact will not be understood for some time.
- It seems that some testing capacity is being underutilized. Other approaches to increasing testing efficiency, such as the National Institute of Standards and Technology "daisy chain" method, could be compared to the approach in this project.

Question 5: Proposed future work

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

- The project's identification of remaining challenges for the adoption of the Cnorm approach to the standardization method (such as ASME KD-10) is the right pathway during the completion stage of the project. Coordination with Sandia National Laboratories for further validation of the approach at higher pressures is most appropriate. Additional efforts on validating the capability of the Cnorm approach to the measurement of the stress intensity factor are warranted.
- The project winds up in October 2023, and there is not much future work left to do.
- The project is closing, and future work was not significantly highlighted.

Project strengths:

- Strengths include (1) the elegant accounting of the material yield strength in the normalized K-gradient rate parameter C through the introduction of the new Cnorm parameter, (2) the departure from the ASTM standard for a fixed C value during load shedding is a strength, and (3) the project's continuously varying C results in dramatic testing time and cost reductions.
- The project has strong involvement with codes and standards bodies.

Project weaknesses:

- A weakness is the study/knowledge of the load history effects and how they can be avoided/controlled in the measurement of the FCGR upon load shedding, but this can be the subject of project continuation through additional funding.
- The project's presentation of results was weak.

Recommendations for additions/deletions to project scope:

- As the project advances to completion, nothing can be deleted from the project's scope. Upon completion, the capabilities and approach developed by this project can be further advanced and explored in the identification of regime in the multi-dimensional space of pressure, frequency, load ratios, etc. over which Cnorm yields C values that are independent of load history and crack tip residual stresses. This may lead to choices of Cnorm parameters that are better informed by the relevant application conditions, and, as such, they can yield further testing time and cost reductions. The underlying fundamentals in the moisture-induced acceleration of FCGRs can also be further explored.

- No additions are recommended, as the project is ending.

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

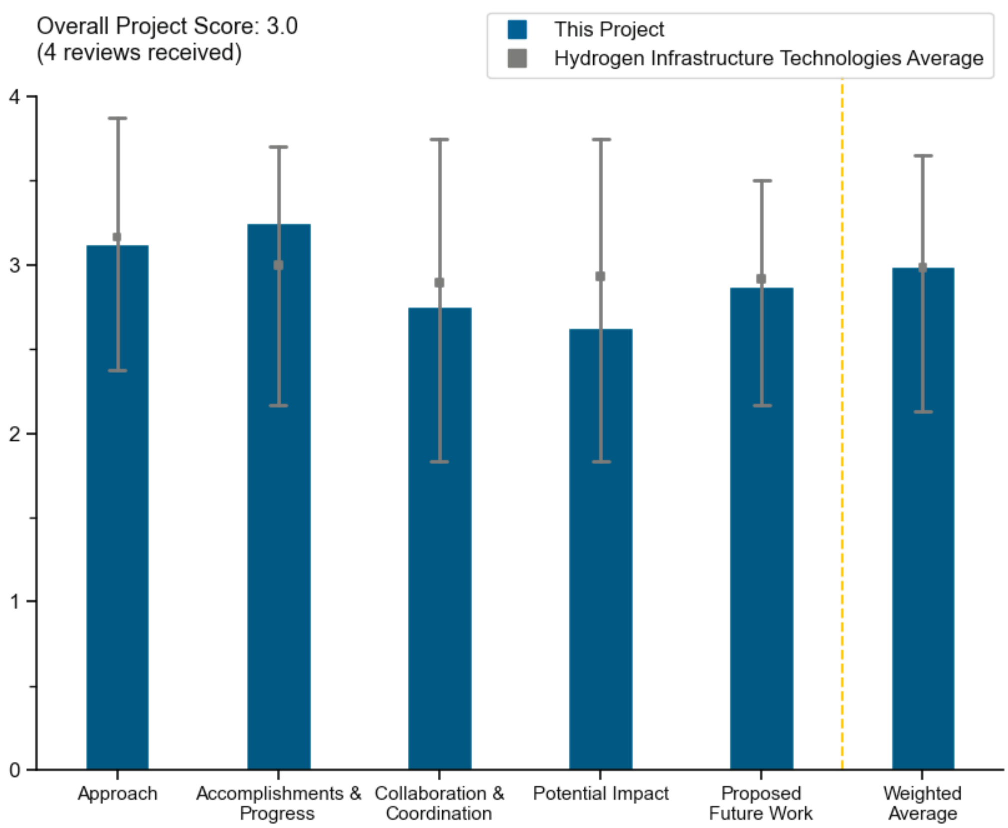
C. Cem Tasan, Massachusetts Institute of Technology

DOE Contract #	DE-EE0008830
Start and End Dates	4/1/2020–5/31/2023
Partners/Collaborators	Harvard University, ATI
Barriers Addressed	• Hydrogen delivery: gaseous hydrogen storage and tube trailer delivery costs • Hydrogen storage: 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 resistance. The research will focus on using metastability to enhance resistance. 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 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 concept of this project is sound: applying micromechanical screening, bulk alloy design and screening, and computations to identify materials with particular mechanical properties. However, the goal of applying these methods to develop new alloys with superior hydrogen embrittlement resistance is too general for a technology-oriented project. The project needs to identify incumbent, technologically relevant materials to serve as a baseline so that a target for “superior hydrogen embrittlement resistance” can be established.
- The project’s screening concept was a novel approach. It is interesting to consider high-entropy alloys for hydrogen embrittlement.
- The project goals were clearly identified and have been met.
- This is a questionable approach to attain the goal, given the lack of scalability.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The project has a good alloy development approach. Understanding the phase stability is important for predicting performance of stainless steels and similar alloys in hydrogen environments.
- The project has completed its milestones and succeeded in its technical accomplishments.
- The project has done significant work.
- Since the project does not identify baseline materials, progress toward a performance target cannot be evaluated. In reference to the general goal of developing new alloys with superior hydrogen embrittlement resistance, the project presents results relevant to this goal on slide 15. However, these results are not particularly compelling, since the test specimens for evaluating hydrogen embrittlement resistance were not exposed to hydrogen sufficiently. Since the alloys featured in the project contain 5% cobalt, the project will likely not contribute to resolving the critical barrier of reducing material costs.

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 project has coordinated with partners at Harvard, but there does not appear to be any engagement with Hydrogen Materials Consortium (H-Mat) partner Sandia National Laboratories. The project needs to partner with industry stakeholders that are developing hydrogen technology so that baseline materials and associated cost and performance targets can be identified. The industry partner, ATI, may contribute to alloy production, but other partners are needed that are immersed in hydrogen technology development.
- The project has good collaboration within the group but has a lack of relevant external collaboration toward the main goal.
- The project has collaborated with academic institutions.
- The project has limited collaboration and coordination.

Question 4: Potential impact

This project was rated **2.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project aligns well with the Hydrogen Program and DOE objectives and, with more research, has the potential to advance progress toward DOE goals and objectives.
- Further understanding the role of phase transformations is important.
- The project’s approach shows promise for improving the properties or lowering the cost of materials, but since no baseline materials or associated cost and performance targets are identified, it is not clear that the project advances progress toward Hydrogen Program goals and objectives.

- The project is doing interesting scientific work that will impact the field, but the output of this will be irrelevant for materials replacement in the foreseeable future.

Question 5: Proposed future work

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

- The proposed future work of investigating alloys with specified stacking fault energy but different compositions is reasonable, but such work must be performed in reference to a technologically relevant baseline material (e.g., 316 stainless steel).
- The proposed work is reasonable for the framework.
- The approach seems reasonable.
- Though the project shows completion, possible future work is outlined.

Project strengths:

- The project has identified compositions of interest for complex concentrated alloys and demonstrated the potential for superior hydrogen embrittlement resistance in alloys with metastable austenite and hexagonal close-packed martensite.
- The approach of this project is promising, involving micromechanical screening, bulk alloy design and screening, and computations to identify materials with particular mechanical properties.
- The project employs novel testing methods and explores new materials.
- The project has a strong team and unique approach.

Project weaknesses:

- The project must identify technologically relevant baseline materials so that cost and performance targets for new alloys can be established.
- The approach will not result in achievement of the primary goal.
- The test results were not clearly communicated.

Recommendations for additions/deletions to project scope:

- Testing to evaluate hydrogen embrittlement must be performed either on specimens in hydrogen gas or on specimens that have uniform hydrogen concentration.
- The conceptualization of the project to reach the stated goal is not feasible, and there is no time to modify.
- The project’s progress on alloy development is limited.

Project #IN-034: HyBlend: Pipeline Cooperative Research and Development Agreement (CRADA) Cost and Emissions Analysis

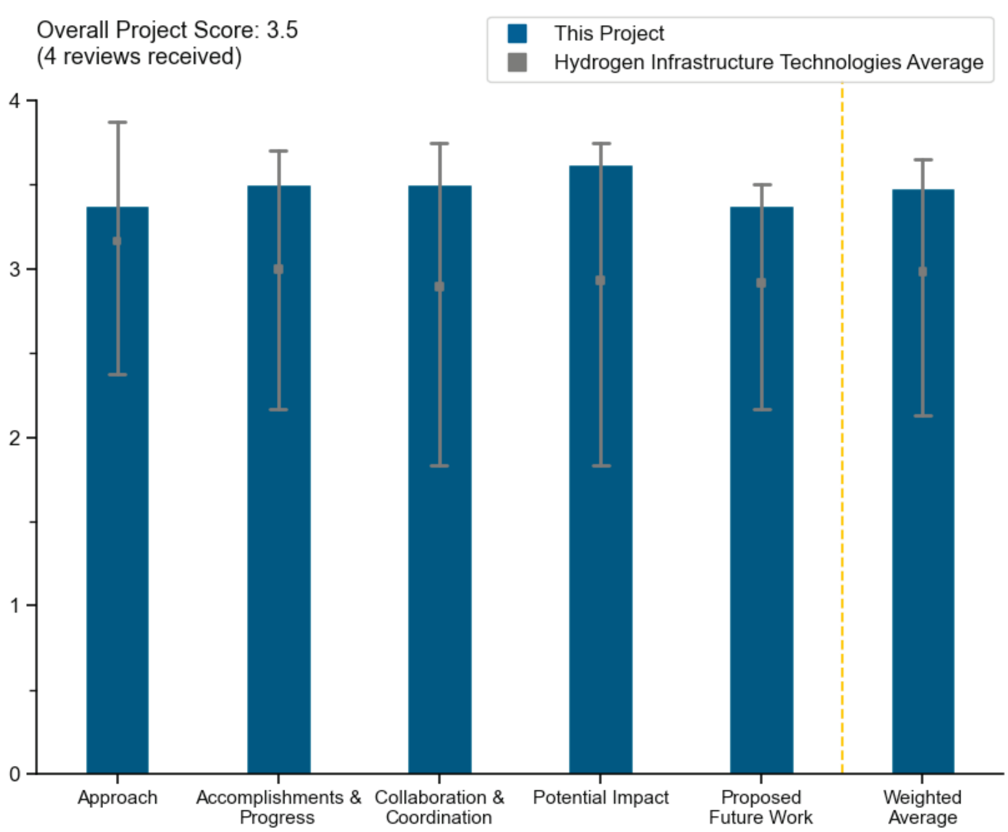
Mark Chung, National Renewable Energy Laboratory

DOE Contract #	WBS 8.6.2.1
Start and End Dates	10/1/2021–9/30/2023
Partners/Collaborators	Argonne National Laboratory, Sandia National Laboratories, Pacific Northwest National Laboratory, Air Liquide, Chevron Corporation, DNV, Enbridge Inc., Electric Power Research Institute, ExxonMobil, GTI Energy, Hawaii Gas, Hydril Company, National Grid, New Jersey Natural Gas, ONE Gas, Inc., Pipeline Research Council International, Sacramento Municipal Utility District, Southern Company, Stony Brook University, Southwest Research Institute
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools

Project Goal and Brief Summary

This project will develop tools to quantify the economic and environmental impacts of blending hydrogen into U.S. natural gas pipelines. Existing national laboratory tools (e.g., the Hydrogen Analysis [H2A] model) will be leveraged to estimate and quantify the value proposition with the goal of accelerating early-market hydrogen technology adoption and short-term emissions reduction. Scenarios will be designed to evaluate the application of hydrogen blending across different sections of the U.S. natural gas pipeline system, helping to provide pipeline operators with a pathway to converting existing assets into clean infrastructure.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure 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 project strives to analyze the techno-economic analysis, life cycle analysis, and greenhouse gas (GHG) emissions from adding hydrogen to a natural gas pipeline. The thoroughness, completeness, and conclusions of the analyses are excellent. This project highlights the overall cost and benefits of adding hydrogen to the natural gas grid.
- HyBlend is a timely tool to transport and distribute hydrogen in natural gas pipelines and assess its value proposition. The parametric analysis and contribution of different factors is very important to the natural gas industry and consumers. Engagement of critical stakeholders from industry, safety, and home appliance manufacturers is critical. This is partially being addressed.
- The approach is based on existing modeling methods that have been used for similar models in other areas and appear sound. Publishing as open-source increases the tool value and credibility of the project.
- The project objectives and critical barriers are clearly defined. The critical barriers seem a little difficult to overcome because there seem to be insufficient models and tools and inconsistent data.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- Excellent progress and accomplishments toward the DOE goals have been achieved in this project to date.
- The Python model parameters are quite comprehensive. The project should identify the GHG emissions associated with each stage across the full supply chain of hydrogen–natural-gas blend, e.g., natural gas recovery and transport, hydrogen production and injection, compression and transmission, and final application of the hydrogen–natural-gas blend. The only missing numbers are for extraction of higher-purity hydrogen for transportation and stationary fuel cell use.
- The development of the modeling and assessment tool has progressed well. Application to a specific case study provides an important real example for evaluation and comparison (as compared to a completely hypothetical case). It is not clear how the synthetic natural gas (SNG) evaluation fits into the project, as it does not appear to be included in the originally stated goals, nor is it clear how it factors into the blending cost modeling.
- Accomplishments and progress were understandable. The project provides the status of its milestones. The team has completed 64% of the project. The analysis depicts different methods of modifying the pipelines. However, it does not provide a cost analysis for each of these mods.

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 collaboration with other labs whose expertise is in analysis (Argonne National Laboratory [ANL] and National Renewable Energy Laboratory [NREL]) is excellent. Also, to pull in Sandia National Laboratory's materials group (Chris San Marchi) is very appropriate and excellent. This makes a powerful team to investigate the benefits and/or costs for hydrogen addition into the natural gas distribution system.
- Collaborations with external industry and institutions are quite impressive: Air Liquide, Chevron, DNV, Enbridge, Electric Power Research Institute, ExxonMobil, GTI, Hawaii Gas, Hydril, National Grid, New Jersey Natural Gas, ONE Gas, Pipeline Research Council International, Sacramento Municipal Utility District, Southern Company, Stony Brook University, and Southwest Research Institute. It was unclear whether there is a project review meeting workshop planned for all the collaborators and partners.
- Credibility of the modeling work is predicated upon having industry buy-in and validation with real-world data. This project has a strong set of industrial supporters, provided sufficient market information from the participants can be validated with project data.
- There is collaboration among national laboratories.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The potential impact of HyBlend is huge. The NREL and ANL team identified this very well in a qualitative fashion:
  - The use of existing infrastructure before developing new infrastructure is a transition strategy with lower risk and cost, etc.
  - Engaging critical stakeholders is very important; this is done well.
  - Quantifying the impact will be helpful. It would be helpful to know how many million tons of hydrogen can be stored in the high-pressure transmission pipelines at the 10% level. This will help in communicating the true impact potential.
- The potential impact can be huge. To make use of the natural gas distribution system as a transition strategy or permanently can greatly reduce the distribution costs.
- The project aligns well with the Hydrogen Program and has the potential to have significant impact once the analysis is complete.
- The value and impact of the blending pipeline models is clear, but it is not obvious how the SNG component adds value to this assessment. Similarly, the planned tasks, including the direct air capture activities, are not clearly linked to the modeling. It is suggested that the project stay focused on the development of the blending models.

Question 5: Proposed future work

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

- The proposed future work is well aligned to complete this task in Fiscal Year (FY) 2023 and to improve its public availability and use for FY 2024 and beyond. This is excellent.
- Proposed future work is clearly defined based on the project goals. It is understandable that insufficient tools and inaccurate data would make it difficult to overcome barriers.
- The proposed next steps should emphasize model use and validation using existing projects and/or planned projects by industrial partners. This validation would be an important step in building model/tool credibility. Expanding the model to develop power grid capacity expansion will be an important deliverable, especially in light of the recent U.S. Environmental Protection Agency (EPA) rulings related to H_2 blending in the natural-gas-fired power sector. The project may consider deemphasizing the SNG and direct air capture (DAC) work, as this seems disconnected from the model and blending focus of this development.
- The future work, as proposed, seems to be pretty good.

Project strengths:

- This project is well positioned to continue to perform analysis (case studies), to elucidate the benefits of blending, and to make available to the public the tools that perform these analyses.
- The project has excellent partners and a team with proven history of credible model development. Value to market and planners, especially in light of the EPA power sector rulings, is also a strength.
- The project team collaboration partners list is very impressive and comprehensive. It could be made stronger by having a workshop to share the results to engage all stakeholders. The methodology and results are consistent.
- The analysis would be beneficial for the Hydrogen Program.

Project weaknesses:

- Incorporating public utility company (PUC) comments and engaging the PUCs are very important. They approve what can be done with pipelines in all 50 states. This is done to protect public safety and ensure highly reliable natural gas, at an affordable price, that is suitable for home appliance use and industrial boilers. Adding hydrogen alters the British thermal unit (Btu) value and appliance performance; Hawaii

Gas—the only company that has had 10%–12% hydrogen in its SNG pipeline for over 50 years—has to balance the Btu value approved by the PUC. This is done by adding higher hydrocarbons to lift the Btu value at about 1,000 Btu/ft^3. The emission numbers will change as the higher hydrocarbons increase associated CO2 emissions. There are additional emissions to extract the hydrogen in the pipeline that the project needs to address.

- This is a "what if" analysis project. It analyzes the benefits and costs associated with adding hydrogen to the natural gas supply. The changes in the compression load are clearly shown to be instrumental to the increased cost and to the increased GHG emissions. It seems that to also model the movement of the national grid (or local for case studies) to a zero-emission system needs to be considered. The project does include wind machines, but not a systematic move away from the current mix to one that is more GHG-sensitive.
- The connection to SNG and DAC work was uncertain.

Recommendations for additions/deletions to project scope:

- The scope of work looks good. One suggestion for scope addition is to clarify whether the PUC feedback on Btu reduction is due to hydrogen. This is potentially a significant challenge. Also, the Wobbe Index of the blended gas for natural gas appliances must be maintained in the approved range. Also, estimation of hydrogen storage potential in transmission pipelines at 5%, 10%, and 15% levels can justify the investment by public and private partnerships. It will also be helpful to have these estimates by regions, as pipelines are by regions and follow different rules.
- This project is strongly advised to embrace the changes seen/expected in the power mix associated with the grid power. Presumably in the not-too-distant future, part to all of this grid will be zero-emission. Inclusion of this change in power mix will directly affect the compressor performance with respect to GHG emissions.

Project #IN-035: HyBlend: Pipeline Cooperative Research and Development Agreement (CRADA) Materials Research and Development

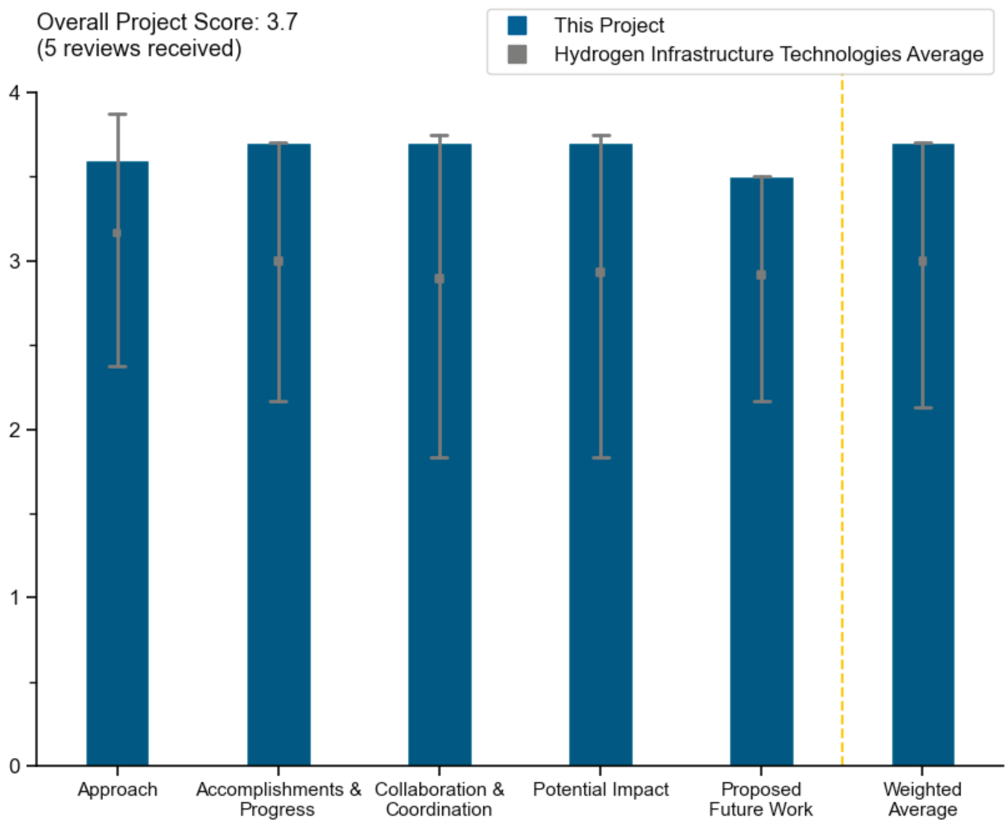
Chris San Marchi, Sandia National Laboratories

DOE Contract #	WBS 8.6.4.2
Start and End Dates	10/1/2021–9/30/2023
Partners/Collaborators	Argonne National Laboratory, National Renewable Energy Laboratory, Pacific Northwest National Laboratory, Air Liquide, Chevron Corporation, DNV, Enbridge Inc., Electric Power Research Institute, ExxonMobil, GTI Energy, Hawaii Gas, Hydril Company, National Grid, New Jersey Natural Gas, ONE Gas, Inc., Pipeline Research Council International, Sacramento Municipal Utility District, Southern Company, Stony Brook University, Southwest Research Institute
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools

Project Goal and Brief Summary

This project aims to provide a scientific basis for the assertion of pipeline safety for hydrogen service. More specifically, the project aims to develop a scientific understanding of variables and mechanisms that contribute to hydrogen-induced degradation of piping and pipeline materials. National lab capabilities will be leveraged to examine materials performance in hydrogen environments, and the project will design probabilistic analysis tools to quantify the structural integrity of pipeline networks for hydrogen service. Converting networks for hydrogen blending within the natural gas pipeline system may offer a low-cost pathway to distribute clean hydrogen, and the data gathered for this project will help ensure the safety of decarbonized energy infrastructure for both transitional and long-term strategies of hydrogen conveyance.

Project Scoring



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

- The project clearly identifies progress in overcoming some of the barriers to the acceptance and popularity of hydrogen. These barriers can stem from the need for information about the structural integrity of both polymer and steel pipeline used for hydrogen distribution. Sometimes these are repurposed from natural gas applications. The project's approach is to characterize some of the properties of changes due to hydrogen exposure, for plastics and metals. The approach includes life-prediction models for materials. The imagery used for polymer and metal pipes shows some of the visible changes in the microstructures (i.e., "an enlarged fracture surface") due to hydrogen interactions. For metals, a blend of 20% hydrogen and 80% methane was used for the testing, as included in the original scope of work for this project. Information was presented that is typically missing to those not directly involved in this research. As a result, the safety of piping and pipelines for hydrogen "service" can be understood. This project developed tools for determining the probability of fractures (and the mechanics) occurring in metals. It also includes a testbed for high pressures to simulate stresses and enable the manufacture of surrogate defects. The surrogate defects can be used to evaluate variables in laboratory fatigue and fracture testing of pipeline steels in gaseous hydrogen environments. The work looks at fatigue crack growth and fracture resistance of pipeline steels, including welds, in gaseous hydrogen.
- The performed approaches to date are relevant and well designed. The development of in situ capabilities to assess the polymer behavior and subscale pipeline testing will be particularly interesting once implemented.
- The brief nature of the review precluded detailed description of all aspects of the approach; however, the aspects communicated in the review were logical and aligned with best practices.

- The project goals and barriers are clearly defined. Unfortunately, the barriers outlined in the beginning of the presentation might not be overcome unless there are accurate data, sufficient models, and tools. However, the remaining challenges and barriers can be overcome with future work toward the project goals.
- Overall, there is direct correlation from the developed scientific basis for the metals work, but the polymer work is too fundamental and does not correlate well to the application.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- The project evaluated variables that induce degradation of pipeline materials for hydrogen distribution. Under this project, tools were designed to quantify the structural integrity of pipeline materials. This progress can help natural gas pipeline operators when they review the potential to convert existing pipelines used for natural gas to hydrogen. The project can also help with the design and implementations of the design for new hydrogen pipelines to reach emission reduction goals. The development of a significant database containing the properties of hydrogen-assisted fatigue is another accomplishment; this work appears to consistently represent the fatigue. Additionally, relationships between pipeline microstructures, composition, hardness, and hydrogen-assisted fatigue are emerging from this work.
- The team is making consistent progress toward the established goals, which are consistent and informed by broader DOE hydrogen objectives.
- All indications are that the project is progressing toward the stated objectives.
- Progress made in this work is good, but any additional work should be better aligned with other activities on materials. Ultimately, the blending activities will move from low-concentration hydrogen in natural gas to 100% hydrogen, which has been a focus for the Hydrogen and Fuel Cell Technologies Office for years.
- The project demonstrates excellent progress toward the objectives. The testing and results of the polymers are clearly measured. However, the graph “MDPE [medium-density polyethylene] Modern” on slide 9 has results and a legend that do not correlate, making the results somewhat unclear.

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 HyBlend Pipeline cooperative research and development agreement (CRADA) encompasses the perspectives of a significant number of industry stakeholders who are participating in this project. These include DOE national laboratories (engineers and economists), utilities, and researchers. Multiple CRADA partners supplied the materials for this project. As a result, the project connects to industrial needs. This CRADA supports coordination on the part of numerous research and commercial natural gas organizations. It also fulfills an advisory role on the U.S. Department of Transportation’s Pipeline and Hazardous Materials Safety Administration projects and those at the National Institute of Standards and Technology and the ASME B31.12 standards committee. This research in hydrogen blending provides significant input with those organizations that need the results for their directions and standards for hydrogen.
- Collaboration and coordination are project strengths. How this information gets disseminated is important, both to the broader community and to any codes/standards organizations making critical decisions with blended materials.
- The project augments expertise through interactions with Oak Ridge National Laboratory, Southwest Research Institute, Electric Power Research Institute, and DNV; works with relevant stakeholders; and coordinates with other ongoing projects abroad.
- There is collaboration with national laboratories and industry stakeholders.
- The project demonstrates clear evidence of collaboration.

Question 4: Potential impact

This project was rated **3.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has significant potential and positive impacts. The work helps to debunk some of the preconceived assumptions that the natural gas pipeline infrastructure is inappropriate for hydrogen: "It is too old." While many are planning hydrogen projects, the results of the CRADA research will inform those projects and support public policy. The research results will provide consistent data to support the use of hydrogen and contribute to near-term emission reductions. These data are needed for hydrogen as a replacement in hard-to-decarbonize sectors and for ammonia production. The research will also help with hydrogen adoption in heavy-duty transportation applications by providing the hydrogen supply chain with data about the impacts of using the existing natural gas infrastructure (pipeline) and planning to buy new pipelines for hydrogen.
- The release of a probabilistic fracture mechanics code for hydrogen infrastructure and the dedicated engagement with standardization stakeholders (American Petroleum Institute, ASME, etc.) will ensure the performed work has broad impact. New insights into polymer performance will address known areas of need. The outcome of the microstructure–fatigue correlation work on the pipeline steels is impactful, as will be the developed hardness–fracture relationships.
- The Hydrogen Extremely Low Probability of Rupture (HELPR) tool will be effective for aiding prognosis for pipelines. The pressure cycling bed fills a needed gap in the space for efficient testing.
- The project is critical to the DOE Hydrogen Program and has potential to significantly advance progress toward DOE goals and objectives.
- The potential impact remains to be seen, and the project is starting to wind up.

Question 5: Proposed future work

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

- This CRADA ends in September 2023. As of April 7, 2023, the work is 60% complete. Not only is the Hydrogen Extremely Low Probability of Rupture (HELPR) tool (a probabilistic tool) needed, it is due to be released in September 2023. Also needed are two long-term hydrogen in situ creep experiments, which are in progress. A need exists to develop recommendations under this project to assess the impacts of hydrogen on pipe steels and to minimize the burdens of future testing. Others will benefit from this work; they will not have to find and manage the expertise to carry it out. A basic system is constructed for metals research and development, and testing is to start before the end of the third quarter of 2023. More work is also ongoing on the hardness–fracture relationship, and this is needed.
- Proposed future work is well aligned with project goals and maximizing the impact of research performed to date. The subscale pipe testing results will be particularly interesting to see in the future.
- The future work is aligned with the stated objectives and is reasonable based on the results.
- The future work will assist with overcoming the remaining challenges and barriers.

Project strengths:

- One of the strengths of this project is the development of the HELPR tool, a probabilistic toolkit for fracture analysis, which is due to be released in 2023. HELPR is highly needed. Work stayed within the original scope: a 20% hydrogen and 80% methane blend. A strength of this project is that it addressed 30- to 50-year-old pipelines. These are legacy metals. Additionally, this project informs and provides input to the ASME B31.12 standard. The work covers 2-inch diameter pipe and also pressures for larger sizes of pipes.
- The project is well conceived, with a solid approach, and will provide useful outputs. The foundational exploratory work for the structural modeling and the testing capability for metals will be very impactful. The motivation for the project is to establish a scientific basis for a design tool, looking for a generalized structural integrity framework. There are inconsistent data and insufficient models. The project is looking to use the natural gas pipeline (three million miles of pipe, 50% of which is polymer). For the future, the project should look at both blended and pure hydrogen. The transmission system is high-pressure and

mostly metallic, but the distribution systems (low-pressure) are more polymers (with some legacy metals). Regarding polymers, the goals are to define environments and evaluate the impact of hydrogen. More information is needed on the failure modes in polymers without the hydrogen. There is an important time sensitivity: there are effects that are seen in situ (in hydrogen), but these effects are not seen if testing is conducted after the hydrogen is removed. The level of crystallinity impact changes after exposure. This is semi-crystalline, and the hydrogen has impacts on the polymer morphology and also on the fracture toughness. In high-density polyethylene (HDPE), there is a strong and persistent impact of hydrogen, while in medium-density polyethylene (MDPE), there is recovery. In fracture in single-edge-notch-beam (SENB), there is a higher decrease in fracture in blended hydrogen when compared to pure hydrogen. The project should look at SENB slow crack growth and tensile creep. The polymer details are sensitive, even in HDPE (one improves, and one decreases). Regarding metals, the transmission pipe has higher pressure and stresses. The project should take a three-pronged approach: probabilistic tools for engineering critical assessment, a platform for sub-scale pipe testing (with 2-inch instead of 36-inch diameters) via higher stress levels, and fatigue fracture data collection in situ and correlated to the microstructure. The project is looking to compare predictions and coupon-level tests. There are good models for the crack growth, but clarification is needed on the models used for initiation. For the surrogate defects, clarification is needed as to whether the project is testing to failure and by which metric it is measured. The project shows a lower fracture resistance, with the lower bound decreasing with strength. It is not clear if there is sufficient data to have the model be sensitive to the different environments. The project mentions an upper bound, but it is not clear whether it has the flexibility to evaluate excursions to different blends and to establish the sensitivities. It is not clear whether the probabilistic model will have the opportunity to evolve as the data and understanding increases and whether a damage accumulation mode is in use. The project has a fatigue model that allows for scaling with pressure cycle stress ratio and the hydrogen pressure. During the review, it was asked if the project was accounting for impurities, and the response was that, currently, the project was accounting only for the equivalent hydrogen fugacity.

- The targeted areas of focus, experienced team, development of novel testing approaches, and creation of technologically useful datasets and correlations for material compatibility are all project strengths.
- Project objectives and barriers are clearly defined. The project is beneficial for the Hydrogen Program and DOE goals and objectives.
- Metal activities are valuable, along with the many CRADA partners.

Project weaknesses:

- Further development is needed to evaluate the inventory of existing assets and the metals in existing pipelines using non-destructive evaluation (NDE) tools, which will be a massive effort. The project would have been stronger had it evaluated and reported on the level of certainty about the materials testing. Additionally, some of the results are needed in the near-term by the designers, planners, and permitting agencies for the regional hydrogen hubs. The scale-up of this work in large-scale polymer and metal pipelines, in situ, is important, and this is a challenge. Accelerated testing for polymers is still needed, so it is only a weakness since some of the work is not done. It was noted that there is a lack of available scientific data, and sometimes this lack leads to acceptance of anecdotal information, and this is only a weakness due to the timing of the release of results from this project. The Emerging Fuels Institute, a stakeholder, has identified critical defects that still require some testing and simulation. For metals, more guidance to explain pressure, hardness, and other characteristics is still needed.
- There are no major weaknesses. However, the ability to come to a conclusive answer on the polymer work is untenable. The project could focus more on enabling solutions to a single subset instead of having a broad focus.
- Applicability of the polymer work is a project weakness. Also, the existing hydrogen materials work could have been leveraged more than establishing a separate effort with a large funding effort. It is also not clear how this effort fits into the larger support of H2@Scale.

Recommendations for additions/deletions to project scope:

- The project should consider a “soft launch” for HELPR so the tool can be used right away. The project team should consider adding “reusing natural gas pipelines” and new, hydrogen-only pipelines that reflect the planned regional hydrogen hubs to the project scope, as practicable. Additionally, the project team should consider transferring these research results for use by hydrogen pipeline planners and investors. The project team should consider developing an approach for use in the industry that creates an inventory of the age and quality of the polymer and steel pipelines to help plan regional hydrogen hubs.

- It will be important to ensure that the HELPR model has sufficient flexibility to add modules as further understanding and data become available.
- Better alignment with other office activities is highly suggested.
- The planned activities for next year are sufficient.
- Updated graphs are needed.

Project #IN-036: Cost-Effective Pre-Cooling for High-Flow Hydrogen Fueling

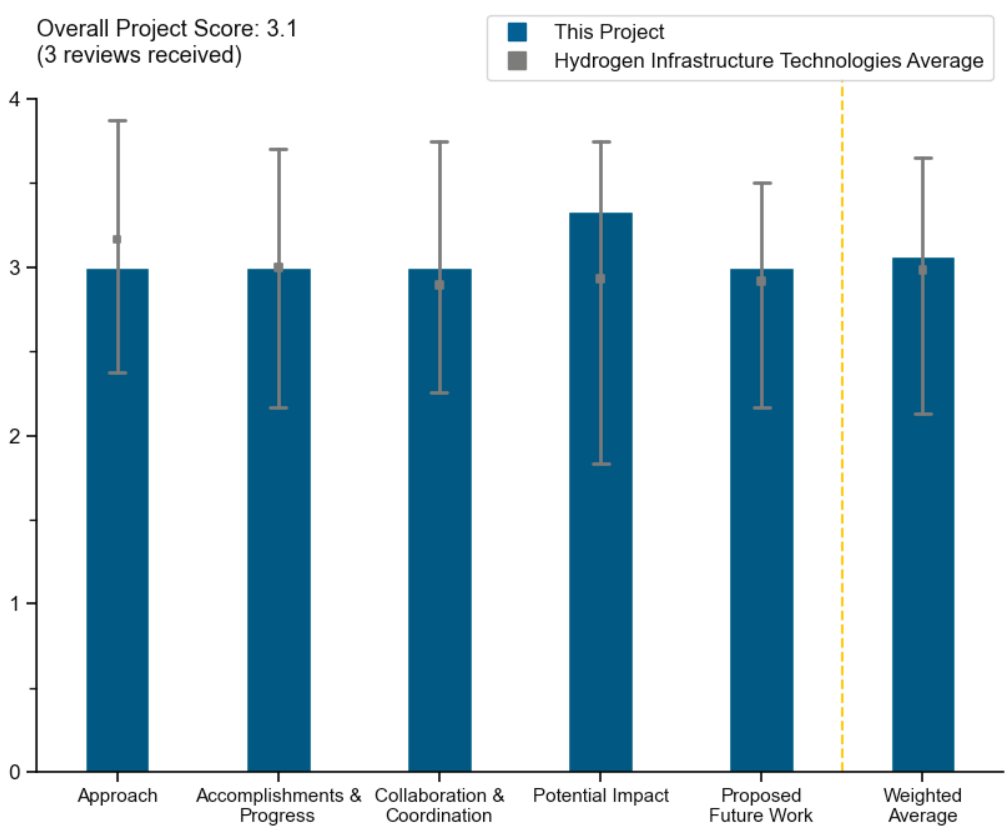
Devin Halliday, GTI Energy

DOE Contract #	DE-EE0009625
Start and End Dates	8/1/2022–7/31/2025
Partners/Collaborators	Creative Thermal Solutions, Argonne National Laboratory
Barriers Addressed	• Lack of commercial pre-cooling technology Targets: • <200 kW peak load • <$500,000 capital cost

Project Goal and Brief Summary

This project aims to deliver a validated high-flow chiller design for heavy-duty (HD) hydrogen fueling stations. The product will be designed to withstand evolving regulations. Researchers will begin by developing a detailed understanding of requirements and use the findings to identify the optimal configuration. A pilot-scale chiller will be constructed for testing, and results will be used to update the design. The final stage is technology transfer activities to ensure market adoption.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure 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 demonstrates an excellent effort with a sound approach, but a quick reassessment of the target design might be necessary. For example, with the target design being associated with heavy trucks, likely operating at 70 MPa nominal working pressure (NWP), it is worth taking a step back to fine-tune the opportunity. For example, most agree that heavy trucks will need to fuel at stations with over one ton of hydrogen or more onsite. This requires a liquid hydrogen supply chain, which in turn may not require pre-cooling at the station. It is worth stress-testing this concept to determine whether more focus should be placed on medium-duty applications and possibly at lower NWPs (e.g., 35 MPa). Perhaps liquid-hydrogen-supplied 70 MPa stations would still require pre-cooling if the design concept utilizes some amount of high-pressure storage buffers, but it is not believed to be the case.
- The project appears to be in the early preliminary design phases, with a plan for moving into subsequent phases. The poster and the presenter were not present at the Annual Merit Review poster session, so it is difficult to assess the project based on presentation content alone. The poster did not convey details on the target chiller design, other than refrigerant down-selection. It would be good to include more details on current project progress and comments regarding system design relevant to HD fast-flow fueling.
- The approach models high-flow rate refueling. The model represents one-fifth the capacity of an actual HD refueling station. Two duty profiles are selected: maximum cooling duty and minimum chiller power. The goal is to deliver and validate a high-flow chiller design that can be manufactured and installed for use in an HD refueling station. Another stated goal is to optimize the system to meet the demand for HD refueling. Refrigerant regulations are addressed. The project addresses some of the cost barriers to HD hydrogen refueling. The project stands to reduce the greenhouse gas emissions caused by diesel trucks, with the uptake of hydrogen fuel cell trucks. At the end of this project, there is an interest in transferring the work to private-sector ownership of the chiller design so it can become commercialized.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- Transportation emissions reduction is one of the DOE goals that this project addresses. Decreased costs for hydrogen used in transportation is a stated DOE goal to which the planned optimized chiller design contributes significantly. The planned contribution is specifically in the total cost of ownership, which encompasses more than the capital cost of the equipment. The modeling of the heat exchanger performance in this project is delayed since the lead time was five months. Additionally, there were long lead times for other minor components in the project. Testing in the first nine months of the project is incomplete. Down-selection to two to three refrigerant systems is complete. The project is on track for the preliminary design due July 31, 2023.
- Progress is slow in the first year, but presumably some catch-up will occur. The project supports DOE goals. The project has a very good tank system model that covers the sweet spot for heavy trucks operating at 70 MPa, and the ensuing model demonstrating the need to target only -30°C pre-cooling is consistent with industry thinking. In fact, T20 (-26°C to -17.5°C) is more than adequate in 90%–95% of the fueling cases.
- The project appears to be in the early phases, with less than a year of work completed. There was some discussion on the down-selection of refrigerant but not much other content regarding progress made on the greater system design or heat exchanger technology. The poster references modeling results, but none appeared to be presented. Slide 10 states "modeling determined -30°C pre-cooling likely necessary," which is not in line with current industry requirements for HD hydrogen pre-cooling. Current protocols are targeting down to -40°C as a baseline, with warmer pre-cooling gas temperatures potentially being considered as more research is completed and protocols are evaluated.

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 seems to be well coordinated, with a good mix of institutions and a commercial manufacturer and with no issues noted.
- Project partners include DOE, Argonne National Laboratory (ANL), and industry. In the future, HD truck original equipment manufacturers could be considered as partners, along with private-sector truck drivers who will plan to make a business by using fuel cell trucks. Ultimately, these drivers will have to use the refueling station and incorporate the station reliability levels into their business plans. The work can inform and lead that of the SAE International standards committee on fueling protocols. The standards committee work will require collaboration and coordination. Likewise, the work can inform refrigerant regulations that will require collaboration and coordination with external regulatory bodies.
- The partners appear to be appropriate for the project scope. However, it is unclear how the project will evaluate heat exchanger performance for fast-flow fueling, beyond modeling.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The potential positive impact on commercial pre-cooling technology will help to inform the standardization of HD refueling. The project will have positive impact on the industry, as there is a plan to select an optimal configuration for a chiller that provides the best total cost of ownership. Additionally, the chiller will comply, as practicable, with future refrigerant regulations, making it easier to use. If the experts in this project remain informed and become very involved with those regulations, as practicable, they can lead the regulatory process, yielding quicker regulations and supporting faster use of the commercial pre-cooling technology under development in this project.
- The potential impact of low-cost, reliable pre-cooling is critical to the success of HD fuel cell electric vehicles. Perhaps DOE should take a step back to determine whether the HD market is truly the right one to target, given the fact that the vast majority of these fueling stations will entertain liquid hydrogen supplies.
- The project aligns with the Hydrogen Program goals for developing a cost-effective hydrogen pre-cooling system for HD fast-flow fueling.

Question 5: Proposed future work

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

- Future work is well identified and coincides with the progress to date. Significant emphasis should be placed on understanding the direction of HD fueling protocols, so a review of the protocol for heavy-duty hydrogen refuelling (PRHYDE) project, funded by the European Union, might be worthwhile. The PRHYDE project offers several fueling protocols that will be adopted into the International Organization for Standardization's Technical Committee for Hydrogen Technologies, Working Group 24 (ISO/TC 197 WG 24) standards. Participation in the SAE J2601-5 Technical Committee (High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles) is also useful, as participants would be aware of the interim protocols being developed in that group.
- This project is 20% complete. It appears that testing and refining the model for effectiveness in replacing full-scale testing of an HD hydrogen refueling station will be needed. Testing heat exchanger performance (milestone M1.2.1) and other components with long lead times will occur in the future, slightly behind the original plan. An increase in participation in the refueling standards committees and refrigerant regulatory discussions may become necessary to make sure the design of the chiller is compliant with both activities. Likewise, the standard and regulatory activities should be informed about this work.
- Because the project started recently, there is a significant amount of work to be done. The poster slides demonstrated a high-level overview of future work to be accomplished. However, details on future work were somewhat lacking.

Project strengths:

- The project capably modeled standards, regardless of the lack of public, open, de jure HD refueling standards. The team modeled fueling 60 kg of hydrogen in six minutes (this is an average of 10 kg/min) at 20°C at an average pressure ramp rate (APRR) of 13 MPa/min. The project manager provided this information during the Annual Merit Review during the poster session. He explained that this APRR is near the light-duty SAE International J2601 requirement tables for the largest tanks at -30°C pre-cooling. The team also modeled 40°C and APRR at 7 MPa/min, again following the J2601 light-duty standard. The project determined that these two ambient temperatures are the most important for the design because an ambient temperature of 20°C is about where the maximum flow rate is achieved in J2601 and 40°C is where the chiller will be most challenged to hit the cooling targets. Depending on the equipment being specified, inputs from either or both profiles may be required. The project may use more profiles as it progresses to its full design, and the project manager explained that the team has this capability.
- The project is well organized, with defined and achievable goals. The modeling assumptions related to the size of an HD vehicle are perfect, and the ensuing output showing T30 (-33°C to -26°C) pre-cooling is consistent with industry. The refrigerant chemistry and system down-selection are well done.
- The project is still in the preliminary design phases, making some progress within the first budget period. There was content shown regarding refrigerant down-selection.

Project weaknesses:

- The delayed heat exchanger testing challenges the proposed schedule and may occur at the end of 2023. The project could be strengthened with reconsideration and reprioritization of participation in the SAE International J2601 standards committee to represent the refueling protocol used in this project and to transfer learnings to the broader standards effort. Although the poster mentioned staying up to date with the HD standard protocol, the project could be strengthened by actually leading the SAE International standards effort. This standards participation could consume budget. The same is true for regulations for refrigerants; participation in regulatory discussions may strengthen this project. Additionally, there may be a need to connect the reported lowest total cost of ownership with the configuration costs and benefits in this project.
- Details on the project were lacking within the poster to assess project progress. Modeling results should be shown for the simulations run by ANL. The system requirements did not seem to align with current industry hydrogen precooling standards being developed for HD fast-flow fueling.
- It would be helpful to indicate the type of heat exchanger that is being pursued in this project. Recognizing that the manufacturer may not want to reveal details, at least the general style, etc., should be identified.

Recommendations for additions/deletions to project scope:

- The project should show more details regarding work performed, as well as potential system design, so others can better understand how pre-cooling requirements will be met. More details on the heat exchanger technology are required to assess project progress and viability. It is unclear how the project will evaluate heat exchanger performance for fast-flow fueling, beyond modeling. Modeling results performed by ANL should be shown, along with variable inputs. The project should ensure that system requirements align with hydrogen pre-cooling requirements being developed under new HD fueling protocols.
- The project should consider emphasizing the transfer of learnings from this project to the SAE International J2601 standard (J2601-5 for HD vehicles) and to regulatory bodies for future refrigerant regulations, as practicable, so others can benefit. This may or may not involve committee participation and representation in public discussions, which may or may not be included in the plans and budget.
- Determining whether the target market is accurate, or whether some tweaking to the deliverable is required, might be useful. If it is established that HD truck fueling infrastructure will be sourcing high-output pre-coolers, then the project should stay the course.

Project #IN-037: Autonomous Fueling System for Heavy-Duty Fuel Cell Electric Trucks

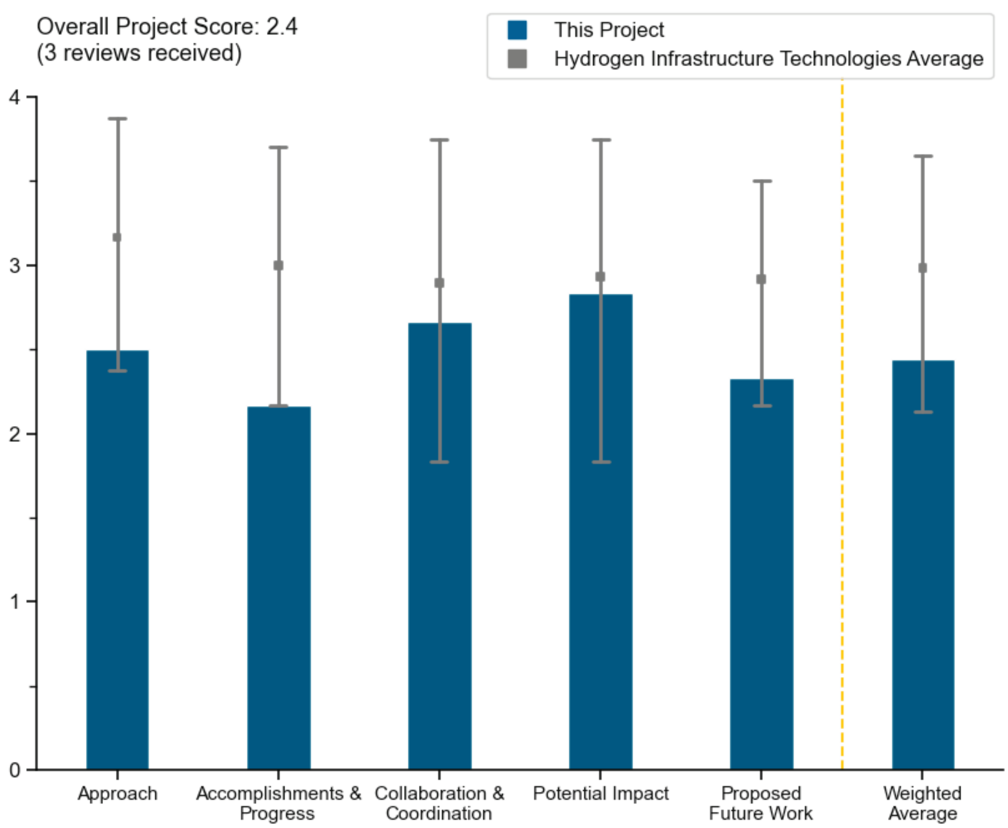
Renju Zacharia, Nikola Motor Company

DOE Contract #	DE-EE0009627
Start and End Dates	6/1/2022–10/31/2025
Partners/Collaborators	National Renewable Energy Laboratory, Hydrogen Heavy Duty Vehicle Industry Group (Air Liquide, Hyundai, Nel Hydrogen, Nikola Corporation, Shell, and Toyota)
Barriers Addressed	• Rapid fueling of a heavy-duty hydrogen truck • Technology limitations requiring larger and heavier fueling hardware

Project Goal and Brief Summary

The project aims to develop an autonomous fueling system for heavy-duty fuel cell electric trucks, including testing the integrated system under operational conditions in the continental United States. The project aims to offer better user ergonomics, potential for user-less refueling, longer component lifetimes, and the implementation of a de-icing system to reduce or eliminate “freeze-lock” behavior. The project has made progress in defining system use cases, establishing system requirements, and assessing the system concept, with future work involving technology development, vendor selection, and work toward a technology readiness level (TRL) of 6 or higher.

Project Scoring



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

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.

- The barriers to be addressed in this project are those that slow down rapid fueling solutions for heavy-duty fuel cell trucks because of technology limitations that require larger and heavier refueling hardware. More information is needed about the metrics used to evaluate the effectiveness of tests and evaluations. While the project may be an excellent choice and contain excellent technology plans, more information is needed on the approach for this project.
- At a high level, the overall approach makes sense, but if purchase orders for long-lead items are placed in mid- to late 2024, it creates significant uncertainty with the ability to keep to the proposed timeline. The presentation approach is light on details.
- This project started June 2022 and recently experienced a change of leadership. Effectively, that caused a restart. Of all the milestones for this project, the team has just now completed the Milestone 1.1 System Requirements specifications. The project is off to a rocky start and has a long way to go.

Question 2: Accomplishments and progress

This project was rated **2.2** for its accomplishments and progress toward overall project and DOE goals.

- System use cases and system requirements (interface, environmental, regulatory, and safety) are accomplished and complete. The system concept assessment is in progress. More information, details, and explanation about the use cases, system requirements, and system concept are needed.
- The change of principal investigator and reorganization of the project team will significantly affect the proposed timeline. The area where changes will occur in the statement of project objectives (SOPO) is unclear. To achieve even budget period 1 targets, the whole timeline appears to have been shifted by close to a year.
- The project has just experienced a change in leadership and hence a restart. Only the first milestone (Milestone 1.1) has been completed to date.

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 project is a collaboration between Nikola Motor Company (Nikola) and National Renewable Energy Laboratory (NREL), with the Heavy-Duty Hydrogen Fueling Industry Group providing feedback and the voice of industry. The collaboration is satisfactory at this stage of this project.
- The partners include the organization of the project lead and a DOE national laboratory. Discussions are ongoing with NREL about the system interface design. The Heavy-Duty Hydrogen Fueling Industry Group is included in the industry collaboration for technical feedback and serves as the “voice of industry” for this project. Discussions are ongoing with the industry group on the goals for this project, and technical feedback is being obtained from the industry group about the methodology used in this project. More information is needed about whether the industry group will help with the technology selection that is included in the go/no-go decision point in the fourth quarter (Q4) of 2023. More information is needed about building consensus with the industry group to best represent and integrate their input to this project. More information is needed about the details of the collaboration. More information is needed about whether this is the commonly referred to Hydrogen Heavy Duty Vehicle Industry Group.
- What, where, and how input of the Heavy-Duty Hydrogen Fueling Industry Group will occur is unclear.

Question 4: Potential impact

This project was rated **2.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The potential impact of this project stands to be significant, owing to the need for technology to support heavy-duty refueling. The project can inform the SAE International J2601 (Fueling Protocols for Light

Duty Gaseous Hydrogen Surface Vehicles) standards committee. More information is needed about the positive ergonomic impacts of this project and how they will accelerate the acceptance of heavy-duty refueling. More information is also needed about the potential to be realized through user-less fueling. More information is needed about how this user-less fueling system would work technologically, perhaps with applications of sensors, cameras, and biometrics. A definition and technological scope of user-less refueling would help to determine the potential impact of this project.

- The potential impact can be large. The heavy-duty fueling hardware is large, heavy, and awkward to handle. This will be a challenge for manual fueling, resulting in increased wear and tear; however, an automated system will solve the problem.
- There is no apparent involvement of truck users/fleets/operators. It is unclear whether there is a targeted reduction in equipment cost or reduction in fueling time, nor is it clear how such factors will be assessed in benefiting the industry overall.

Question 5: Proposed future work

This project was rated **2.3** for effective and logical planning.

- The poster explains that the SOPO is being amended and the project team is being reorganized to better align with the SOPO. More information is needed about how and why the SOPO is being amended and the impact of the changed SOPO on the project. Potentially, the placement of the two go/no-go decisions could be reconsidered (1) after the technology development plan is complete and the vendors are selected and (2) after long-lead, high-dollar items are received. Potentially, the second go/no-go could be prior to the identification (and cost assessment) of the long-lead, high-dollar items.
- The project is in early development and needs to include a preliminary assessment of anticipated lead times for long-lead items (i.e., whether a final decision has been made on technical specifications). The project appears to consider early technology development components that are identifiable. The project should include identification if the concept pursued will also be applicable to components other than 70 MPa technology (the referenced industry group currently has a narrow focus on 70 MPa technology).
- This project has already experienced a change in leadership, resulting in a rocky restart. The reviewer hopes the new team can keep a focus on the target at hand and produce.

Project strengths:

- Strengths include the potential of solving challenges related to the fueling interface and the driver's ability to handle the fueling interface for fueling. Another strength is the potential for improved equipment life through a predictable connection process (i.e., computer-guided equipment). Automated fueling would allow for autonomous truck fueling, which is also a strength.
- The project addresses how autonomous fueling can offer ergonomic benefits and may support increased lifetime for refueling station components. Potentially, reductions in freeze-lock will be achieved through this project. Original equipment manufacturers, fuel providers, and industrial gas companies are participating in this project, contributing to its strength. A go/no-go decision point in Q4 of 2023 includes the technology selection to result in a TRL of 6.
- The project team members, Nikola and NREL, are clearly qualified to accomplish the project tasks.

Project weaknesses:

- More information is needed on the substance of the deliverables for System Use Cases, System Requirements, and System Performance Attributes (although the poster shows these items as completed). Information is also needed for the system concept assessment and the related deliverables that are in progress. The validation of indoor, hot, and cold operation should be done sooner in the project to allow time for any needed course correction (which is presently planned for the last year of the project). Although the project started mid-2022, most milestones are in the later part of 2023 (the first budget period) and the last two budget periods, possibly putting project completion by 2025 at risk.
- More progress would be expected were it not for the project restart. The next Annual Merit Review should provide more insight.

- The project is in early development and has suffered delays due to project team reorganization. The narrow focus on 70 MPa technology is limiting to the project's potential. Long-lead items may be severely delayed at this point because of hardware component market characteristics.

Recommendations for additions/deletions to project scope:

- The project should consider a new timeline to "catch up" the schedule, as progress has been slow as a result of the change in principal investigators. The project should consider adding the metrics to be used in this project (1) to evaluate the results of tests and evaluations that to measure the effectiveness of user ergonomics, (2) to articulate the degree to which the potential for user-less refueling is met through the deliverables in this project, (3) to confirm how autonomous refueling equipment enables longer component lifetimes, and (4) to determine the effectiveness of a de-icing system that can be implemented to reduce or eliminate "freeze-lock" behavior as a result of this project. The project should consider adding metrics that will be used to prove that barriers are reduced to rapid refueling of a heavy-duty fuel cell truck. The project should also consider adding standards compliance testing for fueling protocols and participation in de jure standards committees (i.e., SAE International J2601 for heavy-duty fueling protocols).
- De-icing equipment should be eliminated as a project focus (the team should first figure out how this could work). The project should add a cost analysis of the impact of implementing the proposed concept on fuel cost and fueling equipment availability.
- The project monitor should closely watch the project's progress.

Project #IN-039: Analytic Framework for Optimal Sizing of Hydrogen Fueling Stations for Heavy-Duty Vehicles at Ports

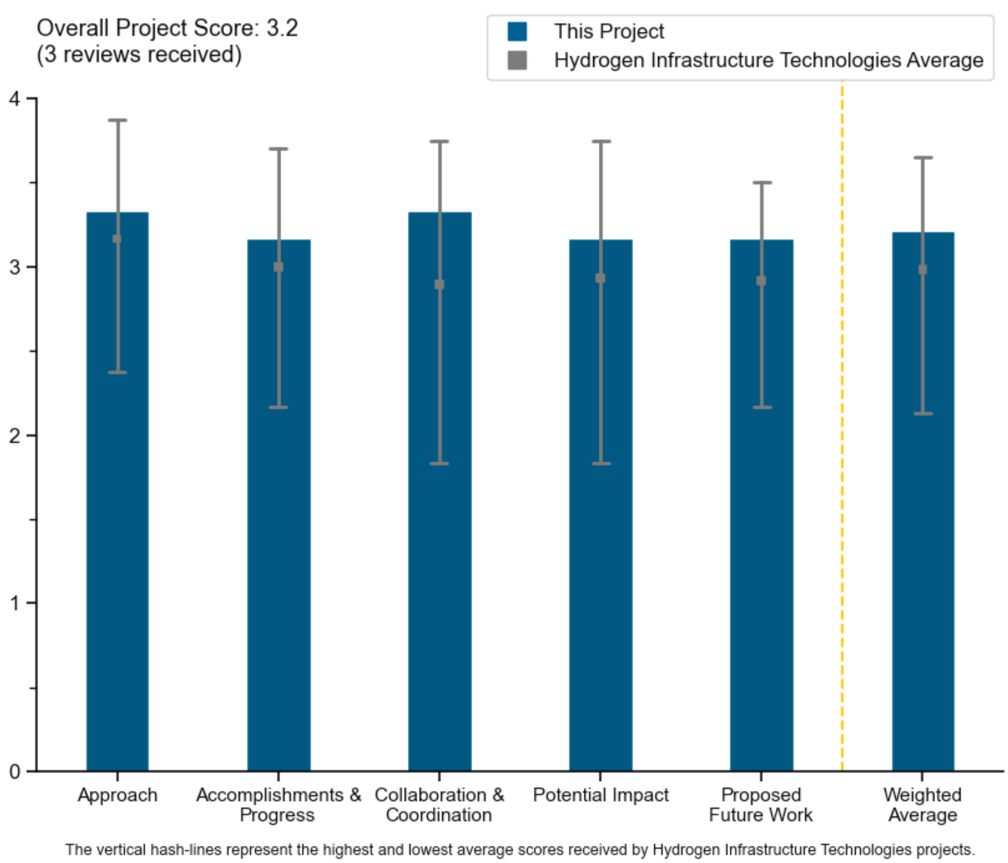
Todd Wall, Pacific Northwest National Laboratory

DOE Contract #	WBS 8.6.5.1
Start and End Dates	3/31/2021
Partners/Collaborators	Sandia National Laboratories, Seattle City Light, Port of Seattle
Barriers Addressed	• Initiate transition to clean hydrogen for ports and identify potential scale-up opportunities • Demonstrate grid impacts of hydrogen production and the extent to which hydrogen can provide grid services • Elucidate the dynamic nature and impact of water electrolysis at large scale on the power grid

Project Goal and Brief Summary

The project aims to develop a framework and guide for sizing and siting industrial hydrogen nodes at U.S. ports. The work involves designing modular and commercial-scale hydrogen nodes using proton exchange membrane electrolysis, compressed gaseous storage, refueling for fuel cell vehicles, and fuel cell power generation. The project seeks to provide guidance to stakeholders and potential market participants on designing commercial hydrogen nodes, estimating the potential for cost savings and emission reduction, and advancing private-sector participation in clean hydrogen infrastructure.

Project Scoring



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 addresses critical barriers to using hydrogen at seaports and heavy-duty fuel cell truck adoption. The project provides guidance for optimizing the size of hydrogen refueling stations at U.S. seaports through a framework and guide for station sizing and siting. The approach includes specifying the designs for modular and commercial-scale equipment, including hydrogen storage; accommodating the vehicles; and planning for resilience in fueling and power generation for ancillary grid services. Another goal in the project approach is to determine the power grid impacts of commercial-scale hydrogen nodes. DOE national laboratories, an electric utility, and a seaport are participating.
- The project is a study of a real-world, at-scale, integrated hydrogen–electricity system and is identifying bottlenecks. The project team's "modular design" approach to modeling the system should be useful beyond this project. It would be good to explicitly show how this would be the case.
- The approach to performing the work is unclear from the visualization on slide 5. A written explanation, beyond the diagram, is needed.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The project advances DOE goals for hydrogen installation, providing auxiliary savings and fuels to utilities and port operators while decreasing the cost per kilogram of hydrogen, lowering greenhouse gas emissions in port operations, providing requirements for qualitative assessments for siting and constructing hydrogen infrastructure, and increasing private-sector participation while educating about the design parameters to help the public understand and appreciate the project goals. The process designs for modular and commercial-scale hydrogen "nodes" that include electrolysis, hydrogen gaseous storage, fuel cells for generating power, and heavy-duty vehicles are accomplished and complete. The electrical loads are modeled. A virtual hydrogen summit (public- and private-sector) was held. The resilience goals are in process, along with the design of a resilience plant for cranes, yard trucks, forklifts, containers, and electric vehicle charging. The resilience scenario is for 10 days of backup power for container movement at the port. The project has completed the daily resilience for the electrical load profile that enables the sizing of components and analysis of their capital costs. The development of the layout of bulk storage (10,000 kg for 10 days of backup power) is accomplished and complete.
- A key contribution is identifying bottlenecks and proposing solutions. The project is doing a good job on proposing solutions, but to maximize impact, the project also needs to address identifying bottlenecks.
- The Port of Seattle's perspective is needed on the use of such a large swath of land for hydrogen storage.

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 between DOE national labs, Seattle City Light, the Port of Seattle, and industry advisors who assist with planning is integral to the project. The analyses and conversions of the power system to which the hydrogen system will be connected were accomplished and completed through collaboration by these parties. The results, accomplished in collaboration with Seattle City Light, include (1) the potential stability (through dynamic representations and simulations) for a hydrogen system connected to the electric grid over a simulated timeframe and (2) the grid's response to the hydrogen plant's loads and the export of power from the hydrogen node.
- The Port of Seattle's and the local power company's involvement with the project is outstanding. The project is encouraged to have discussions with technology providers as well, in particular, electrolyzer, storage, and engineering, procurement, and construction firms. The project should also talk to the DOE Hydrogen and Fuel Cell Technologies Office (HFTO) Safety Codes & Standards group, if that has not already happened (it was not obvious from the slides).

- The project appears to have a reasonable inclusion and range of main stakeholders in and outside the Port of Seattle for the outlined modeling effort/exercise.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Other seaports, fuel cell applications, and heavy-duty fuel cell electric vehicle and electric vehicle charging applications will benefit from the results of the project. For example, information about the "Resilience Plant's" size, components, and land use that meets the Port of Seattle's resilience goals will assist other ports and original equipment manufacturers with their planning and calculus. The positive potential project impacts include providing information about hydrogen installations, vehicle providers, and utilities with an approach to storing hydrogen for grid-connected cargo-handling equipment (e.g., cranes), refueling for medium-duty fuel cell trucks (e.g., drayage trucks), refrigerated containers, and electric vehicle battery recharging. With planned input from representatives of Seattle City Light about the critical loads, the project will come closer to scoping the utility's actual needs for resilient generating capacity and the design of the commercial-scale hydrogen plant to meet the load. The project should make these analyses available to others to increase the number, effectiveness, and optimization of other hydrogen nodes at other seaports.
- Impact on DOE research, development, and demonstration goals will come from identifying bottlenecks for hydrogen systems like this and, more importantly, solutions. If implemented, a successful demonstration of a system like this will be very impactful for others. A challenge not identified is the potential for the analysis methodology to be so complex (e.g., because of specialized software tools) that others cannot take advantage of it. The project should consider how to make it easy for others to repeat the process for new ports.
- More information is required as to whether the project's outcomes can transfer/apply to other major U.S. ports.

Question 5: Proposed future work

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

- The future work includes further clarifying the port's critical operations and critical loads for future electrical grid connections. Additionally, the concept of resilience for the commercial scale of the plant will be further developed for ancillary services and grid impacts. Load schedules, operationality schedules for the hydrogen plant, and assessments of impacts to the electrical grid to accommodate the commercial-scale hydrogen plant are proposed for future work.
- Outcomes should contribute to value added for project partners and understanding of the subject matter as applied to the port setting in the context of the regional electric grid.
- The project fails to address the completely unrealistic hydrogen storage plan, which was missing from the proposed future work.

Project strengths:

- The accomplishments from this project in understanding how to integrate hydrogen at a seaport will help other seaports. The explanation of the optimized final hydrogen plant design, along with the sizing and siting requirements, will help other installations. As a result of this project, industry will be better equipped to make decisions about selecting equipment, siting (including pathways for people and vehicles), ensuring safety, and integrating hydrogen plants with the electrical grid at seaports. The optimization of connecting electrolyzers with the grid will help other installations that plan to do so.
- The project takes an integrated systems approach, which is a strength, as is working with the port and power company.
- The area of application (i.e., the port and utility setting) is a project strength.

Project weaknesses:

- The project plans to address footpaths for people to walk safely at the seaport to complete their work processes; equipment set-back distances, i.e., the National Fire Protection Association's Hydrogen Technologies Code (NFPA-2) for the system components; needs of first responders; needs for piping and instrumentation diagrams (P&ID); plans for sea level rise; space for aboveground electrical conduits; and vehicular access and egress once the node is ready to reach commercial size. A rough estimate early in the project for these items would be beneficial. This would allow for course correction. More information is needed to support the footprint of refueling equipment with actual equipment being built today. More information and documentation are needed about the 10-day ride-through period, its justification, and how this figure was derived, as practicable, to help others with similar needs for resilience. More information is needed about how the hydrogen will be practically accessed and managed in terms of space requirements and safety for the 30 bar storage for the fuel cell used for power grid resilience and the cascaded storage (high-pressure) for the vehicle refueling. More information is needed about safety for stacking equipment to reduce the footprint.
- The project is narrowly land-focused, with limited consideration of the gas utility as part of the solution.
- A project weakness is the hydrogen storage plan.

Recommendations for additions/deletions to project scope

- The project should consider including underground storage and barge-mounted storage as options (for hydrogen storage options on slide 10), because these options may allow for broader and flexible use of stored hydrogen and continued use of aboveground (and potentially very expensive) real estate in a port property. The project should consider higher storage pressures for part or all of the hydrogen storage if hydrogen is partially used for truck fueling and reducing the footprint on available real estate.
- The project should consider adding pathways for safe foot traffic (for work operations) and safe entrance and exit for the vehicular traffic (for operations) early in the project to adequately address safety concerns. Adding pathways for first responders early in the process could also be considered. The project should also consider adding accommodations for sea level rise early in the project.
- The project should consult with the DOE HFTO Safety Codes & Standards program on overall design and with the Storage & Delivery program on realistic storage options.

Project #IN-040: The HyRIGHT Project: 700 bar Hydrogen Refueling Interface for Gaseous Heavy-Duty Trucks

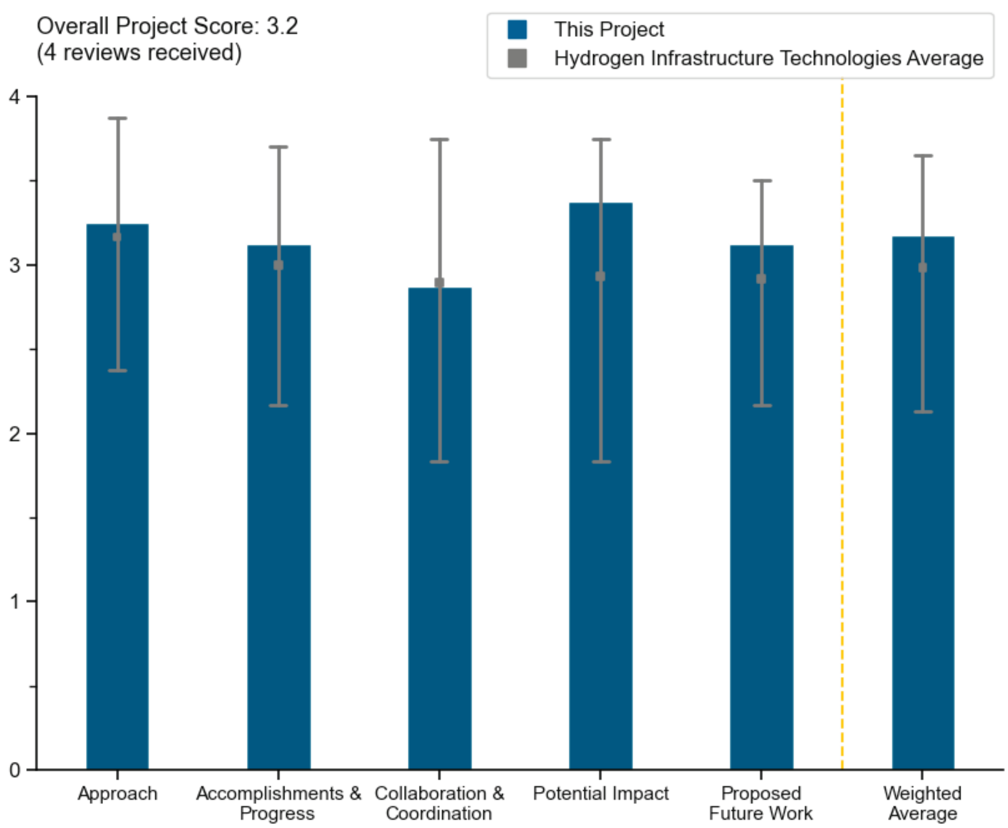
Will James, Savannah River National Laboratory

DOE Contract #	WBS 8.6.3.304
Start and End Dates	10/1/2021–9/30/2023
Partners/Collaborators	Argonne National Laboratory, Sandia National Laboratories, Nikola Motors
Barriers Addressed	• Lack of understanding between precooling performance and cost for high-flow fueling (both station and vehicle impacts) • Potential communications cyber vulnerabilities • Risks associated with high-flow fueling

Project Goal and Brief Summary

The project aims to support the development of 700 bar hydrogen refueling processes for gaseous heavy-duty (HD) trucks, with a focus on optimizing precooling strategies, creating a cyber vulnerability assessment, and disseminating the results to relevant standards development organizations. By utilizing a dynamic model, the project seeks to develop an optimized precooling strategy based on real-time communications and initial precooling status. The outcome of this project will contribute to the development of fueling protocols for HD trucks, enhancing efficiency and safety in hydrogen refueling processes.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure 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 includes an excellent analysis breakdown of hose and pipe, tank conditions, and pre-cooling strategies. The project has good analysis on baseline refrigeration methods and a nice presentation of cyber vulnerability analysis.
- The modeling and techno-economic assessment of HD refueling options are critical steps in developing the infrastructure for this important sector and build on similar work done in developing the light-duty vehicle markets in previous years. Precooling continues to be a primary contributor to the cost and complexity of stations and can have a dramatic impact on station reliability. Optimizing design around this, considering both batch and continuous operational modes and designs, is an important consideration. Among the most important considerations for the optimization is the potential for <15-minute refueling, but this needs to be better characterized. Information on the best-case scenario or optimum time for refueling is required. Insight is needed regarding how realistic these <<15-minute fills are. System reliability is among the most critical design considerations that is not included in this project but should be considered for future work. Simultaneously optimizing for cost, refill time, and system reliability is important to the final design and protocol recommendations. The cybersecurity topics seem to be very independent of the modeling work, and a clear tie-in between the two does not seem to exist.
- The project is developing a model to guide technology development for high-flow hydrogen precooling at HD fueling stations, which is good since a robust precooling solution is an important barrier for HD stations. The project is also developing cybersecurity and risk assessments, which addresses critical issues. It is not clear why they were joined into one project, and the case is not really made.
- The approach to the work seems well-thought-out, although there does not seem to be an obvious synergy between refrigeration and cybersecurity. It is not clear why these divergent topics were chosen as part of the same project.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- Overall, there is good progress on developing the model and in evaluating case studies, especially regarding the precooling systems.
- The project appears to have set up a fair amount of work in Year 1 for a big payoff in Year 2. Accomplishing all the deliverables will require a good deal of effort.
- The summary information on each breakdown is clear and easy to follow. The “quantitative risk assessment of refueling of HD vehicles” topic appears less developed.
- There are many aspects to the work that are useful, but there do not appear to be specific targets or well-defined goals. For example, more information is needed on the specific cost per kilogram that is being targeted for the cooling systems.

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 good variety of collaborators. However, the limitation of only one original equipment manufacturer (OEM) and no dispenser equipment provider is a bit troubling. The presence of groupthink is a concern.
- Nikola Motor’s involvement with the project is appreciated. It would be good to know more about how the company is contributing.
- Inputs from additional HD OEMs is important. While Nikola Motors is a good partner, a single OEM is less likely to represent all technologies and refueling challenges that will be seen on the market.
- There is a good cross-section of participants. The project would benefit from additional industry partners to get a better cross-section of opinion as to the value of the work and the applicability of the results.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- It is unfortunate, but cooling systems will be critical to the HD fueling market. Optimizing the design and operation will be key to 70 MPa HD fueling, so the impact of the project could be important.
- The project addresses a critical topic for HD market development. Optimization and modeling are needed to ensure that the fueling protocols and station designs can meet the market needs. The project's impact would be greatly expanded if it included an assessment of station reliability as well as cost and performance.
- The project provides vital characterization for HD fueling. It is concerning that the project will be terminated prior to making meaningful progress that can be implemented in real-life scenarios.
- The project's results will be useful to station developers and to other DOE projects, for example, H2-041. (There should be some coordination between the projects.)

Question 5: Proposed future work

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

- The proposed work looks reasonable. The project should develop a stronger tie-in between the modeling work and the cybersecurity protocols. Expanding the project scope to include reliability as a critical assessment would be valuable.
- The proposed future work appears reasonable. However, there is concern that funding and project deadlines will pass before objectives are completely achieved.
- The future work seems to be equally split between three tasks: precooling system hardware assessment, cybersecurity assessment, and risk assessment. There is much to do, and the latter two should be done well.
- A comparison of the anticipated reliability, operating costs, and maintenance cost is one area that seems to be missing regarding the cooling system design. These factors might be more important than the capital cost of the refrigeration and heat exchange equipment over the life cycle. An estimated all-in cost per kilogram of the hydrogen cooling systems to compare to the cost of the hydrogen itself would be helpful. Understanding the potential impact of allowing temperatures higher than 85°C would also be useful. There has not been enough evaluation to see the relative impact/cost of building a tank that might be capable of 95°C or 100°C instead of 85°C. How much it might affect the cooling system cost and state of charge (SOC) is a variable that should be better understood.

Project strengths:

- Characterization of the various aspects of the onboard fuel system and analysis of the precooling system under different conditions is a project strength, as is the analysis performed to date.
- The modeling team is strong, with a proven history of developing credible tools.
- The project's fundamental approach in the modeling effort is a strength.
- The project contains useful work to enable HD fueling.

Project weaknesses:

- Always assuming requirements of 100% SOC and 85°C maximum temperature potentially hamstrings other options that could result in lower cost. Understanding the impact of cooling on overall cost per kilogram and reliability of the fuel station may show that it can be worthwhile to consider alternative approaches via tank design changes and/or adjusted expectations on SOC (perhaps it does not always need to be 100% full). In other words, the scope could be broadened to look for cost reduction in hydrogen fueling overall, rather than just the cooling system itself. The lowest cost is eliminating or reducing the need. The project needs to consider the operating and maintenance costs of the cooling systems as part of the overall economics. The combination of evaluating cooling needs and technologies with cybersecurity is not obvious; this seems to be two separate projects.

- The precooling model development seems unconnected to the cybersecurity/risk assessments, like two separate projects.
- The uncertain tie between cybersecurity and modeling work is a weakness. Additionally, the project has limited OEM involvement and should expand to get input from others.
- The communication (cybersecurity work) for the project seems unnecessary and like it was tacked on to attract attention. The economic analysis was very unclear.

Recommendations for additions/deletions to project scope:

- The project should consider splitting into two (refrigeration and cybersecurity), but it is probably too late for that. The H2SCOPE (Hydrogen Station Cost Optimization and Performance Evaluation) model could be used at higher temperatures to see whether there are significant benefits of tank design changes that allow higher operating temperatures.
- The project should scale back the precooling system assessment. This is something industry can take forward. The project should add station reliability assessment, in parallel to station risk assessment, to avoid safety approaches that significantly deteriorate reliability.
- The project should expand collaboration with OEMs, dispenser suppliers, and fueling systems. The economic analysis should be expanded.
- Funding for this work should continue for another 18 months.

Project #TA-049: High-Pressure, High-Flow-Rate Dispenser and Nozzle Assembly for Heavy-Duty Vehicles

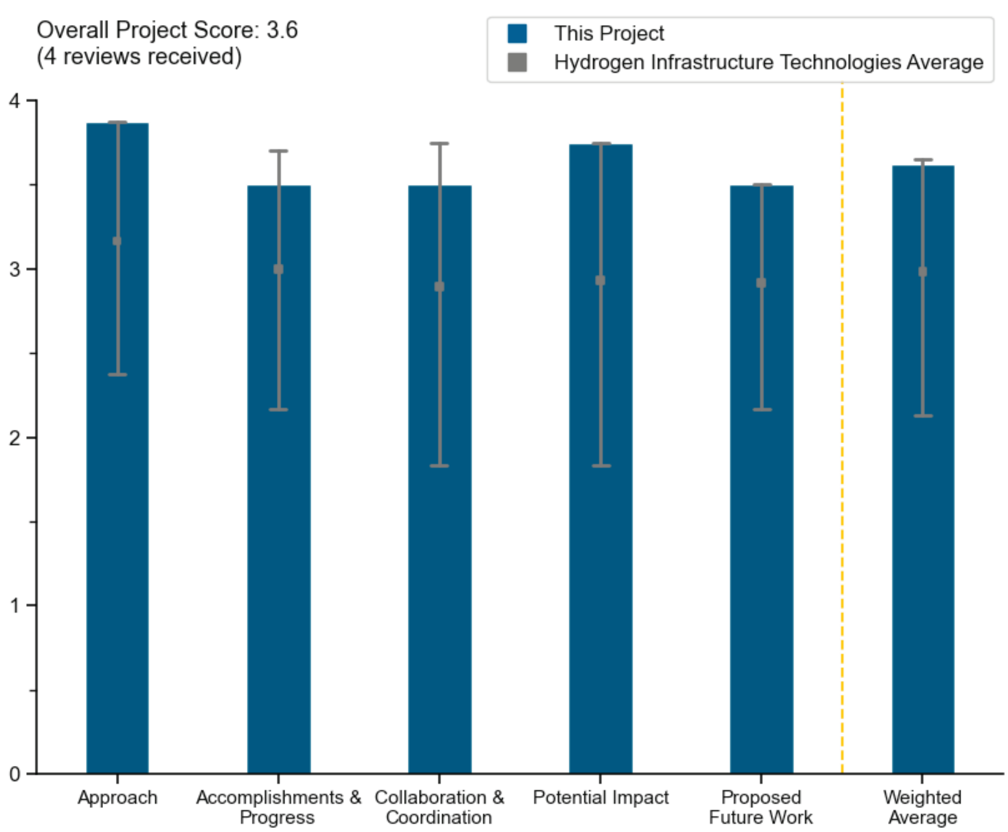
Spencer Quong, Electricore Inc.

DOE Contract #	DE-EE0008817
Start and End Dates	10/1/2019–7/31/2023
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 Hydrogen Infrastructure Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.9** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project objectives and barriers were clearly defined and are being addressed. The project is developing a dispenser and nozzle assembly for HD hydrogen vehicles not commercially available. The project has designed and fabricated the dispenser and nozzle system based on stakeholder feedback and existing standards with testing under way at the National Renewable Energy Laboratory (NREL).
- The project has done a good job of developing a plan to execute successfully, as well as identify potential barriers. The presentation laid out the overall approach well and explained how barriers were overcome. In particular, the outreach to many parties via a survey was a good idea and one that other projects should emulate. One piece that was lacking was identification of the challenges in developing easy-to-use hardware for the dispenser operator, given the required pressure rating and cold temperature operation. As a result, it is not clear how or whether these have been overcome.
- The project is encouraged to continue its progress. Some of the "Approach" slides (slides 7–15) may have been mislabeled and perhaps should be titled "Accomplishments and Progress."
- The project goals and barriers are clearly identified, and the goals are set to overcome the outlined barriers.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The project team has advanced the project to the point of functioning hardware and should be proud of the efforts to get this far. This hardware is critical to the success of upcoming stations needed for HD markets.
- The project has achieved solid progress. The major impact of the slow reaction time of the control valve (possibly compounded by a combination bank switching in a back-to-back fueling configuration) on the fueling process and protocol is a main lesson learned. It is not clear what the anticipated difference in impact is between relying on banks of gaseous supply for fueling and a system based on a more continuous supply of high-pressure hydrogen (such as a cryopump compression system).
- The project has been progressing systematically and has designed and fabricated a dispenser and nozzle for HD hydrogen vehicles; this accomplishment is commendable. While the two manufacturers on the team have gained experience in design and manufacturing through this project for HD vehicle applications, it is not clear what the project is doing (or whether the project can provide suggestions of what could be done) to help overcome the barrier of absence of a "manufacturing base." "Base" alludes to multiple suppliers and manufacturers for a robust domestic supply chain. No estimates have been made for the dispenser and nozzle costs, and therefore, it is not clear to what extent the project will enable reaching the hydrogen delivery cost target of <$4/gge listed on the Overview slide.
- The presentation does not explicitly list milestones. However, the project team has identified several approaches to accomplishing the project goals through manufacturing, testing, and demonstration.

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.

- While the tasks were well delineated among team members (e.g., dispenser, nozzle, testing) and the hardware/controls designed to specific standards, the scope of collaboration and coordination among the team members was not immediately apparent from the presentation and could be better clarified. For example, decisions at different stages of fabrication or selection of design would likely have involved collaboration among the team members but was not immediately apparent in the presentation.
- The appropriate partners are in place to design, build, install, and test the entire dispensing system as a cohesive product. The collaboration slide highlights numerous companies and organizations but does not highlight who these are, which would help with understanding whether they bring real-world experience. Similarly, it is not clear whether the design of the hardware is ready or has widespread support for standardization in the relevant codes and standards.

- While the project team includes competent hardware suppliers and feedback from industry, because of the broad value of this project through its publicly funded nature, it would be instructive to learn how other component suppliers align with the project findings. More specific feedback or issues identified with the hose component supplied by an external party to partners would provide additional value.
- The project shows collaboration with industry and a national laboratory.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The lack of hardware to enable dispensing into HD vehicles at up to 10 kg/min has been an impediment to scoping, proposing, and testing HD stations. If the hardware (particularly the hose, nozzle, and breakaway) is successful, then this will be a large step forward for the industry.
- There are excellent lessons learned based on progress achieved toward targets for this project. Preliminary comparative cost information that covers only the cost of materials, such as amounts of materials before processing into parts and assembly (stainless steel and composites without inclusion of common parts such as infrared data association and wiring), may provide at least a preliminary indication of how cost compares to light-duty 70 MPa nozzles.
- The team has designed, has built, and is testing a dispenser and nozzle system for HD vehicles at 10 kg/min and 70 MPa, which aligns well with the Hydrogen Program and DOE research, development, and demonstration objectives.
- The project is significant to the Hydrogen Program and has the potential to advance toward DOE goals and objectives.

Question 5: Proposed future work

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

- The team has shown progress based on past work and is sharply focused on critical barriers to project goals, and future work depicts this.
- Based on the scope and timing of the project, the future work for this year is fairly straightforward and logical. It would be helpful to add a feedback step from potential user–operators that could use the installation at NREL as an opportunity to handle the hardware and assess its practicality based on weight, size, and ability to handle. While it is likely past the scope of this project, there is a need to develop and implement a long-term test to identify operating problems.
- The proposed future work is logical and comprises commissioning of the nozzle assembly and a couple of additional tests. It would be great if the project team could include working with the standards groups and disseminating the results of the work as specific action items in the list of remaining activities.
- For future Annual Merit Reviews, the project should include the latest fueling protocol reference.

Project strengths:

- The project is developing technology in uncharted territory. The project provides initial indications of HD high-flow H70 interface capabilities. The project is also sharing the findings with the public to provide a reference for an HD high-flow H70 option.
- The project is well organized and has made significant progress toward the development of operating hardware. This development is critical to meeting the upcoming needs of the HD market.
- The project team has the right expertise to design, fabricate, and test a hydrogen system for HD vehicles. The project is ironing out the engineering and codes and standards details to build such a system.
- The project shows a clear outline to barriers and project goals. Future work displays the plan of action on overcoming the barriers to complete the project.

Project weaknesses:

- The team has not presented any cost estimates of the HD nozzle and dispenser system, so it is not clear how the team's efforts or this project enables reduction of "...the cost of manufacturing components and systems to produce and deliver hydrogen at <$4/gge (2007 dollars)." Plans to disseminate the results of this work were not presented.
- The lack of understanding of costs is a major weakness. The cost information provided for light-duty vehicles was vague and dated and, more importantly, not applicable to the hardware developed. The vendors should be able to provide an estimated market price for the hardware, especially with much of the development cost having been developed with this project. The operation of hardware at very high cost will not succeed.
- The project should be better prepared to test and gain specific operating experience that can demonstrate long-term success, which is needed to understand whether the development has been successful.
- NREL HD high-flow H70 station equipment has limitations.

Recommendations for additions/deletions to project scope:

- The project should explore options/alternatives for an HD high-flow H70 fueling protocol modification to deal with slow reaction speeds of the control valve. The project should also look at the impact of required National Fire Protection Agency (NFPA) leak checks on the path to 100% state of charge for HD H70. Both are within current limitations, and it would be helpful to look at, for example, what would happen if fewer leak checks were required by the NFPA.
- The project should provide cost estimates for the HD nozzle and dispenser system. Various types of reports are listed on slide 6 as deliverables. The project should provide references to these reports. Publication and presentation of the project's work in conference proceedings or journal articles will be great.
- It is late in the project, but the project team should include a completed cost estimate for the hardware. Real-world feedback regarding the ergonomics of the hose/nozzle should be obtained from actual users.

Project #ST-127: Hydrogen Materials Advanced Research Consortium (HyMARC) Overview

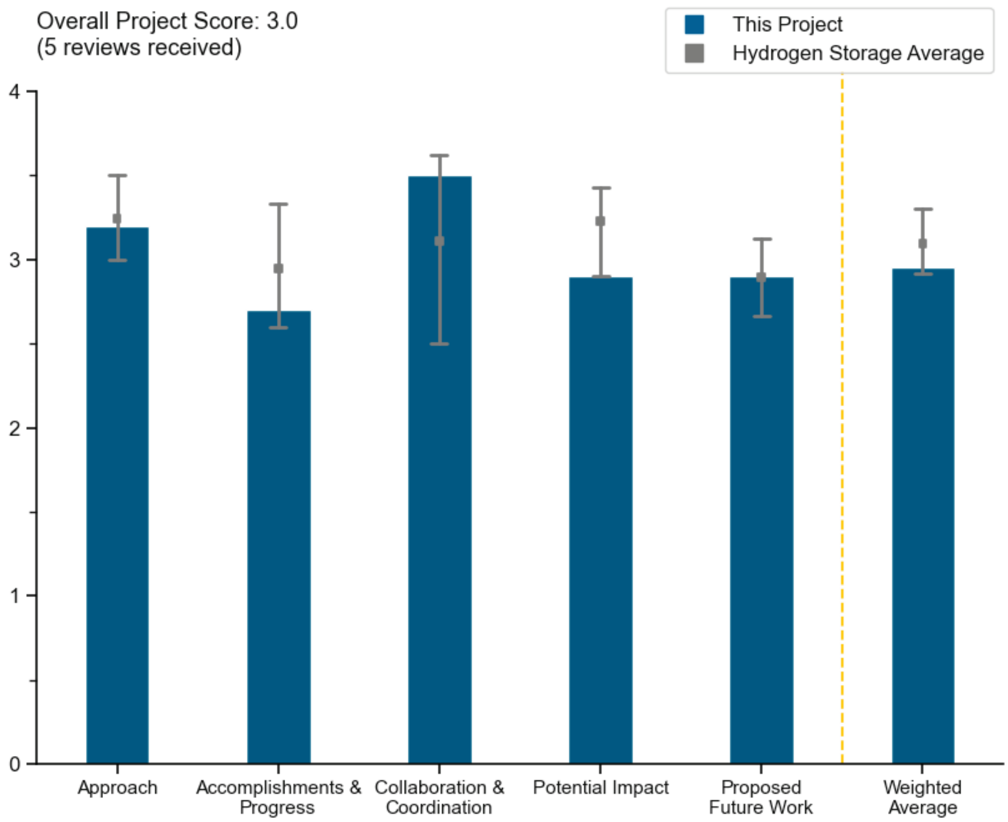
Mark Allendorf, Sandia National Laboratories

DOE Contract #	WBS 4.1.0.805 (SNL); 4.1.0.501 (NREL)
Start and End Dates	10/1/2015
Partners/Collaborators	National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Pacific Northwest National Laboratory, National Institute of Standards and Technology, SLAC National Accelerator Laboratory, Immaterial Inc., GKN, Southern California Gas Company, OCOchem, Honeywell, Stoke Space Technologies, Airbus, Microsoft, Colorado School of Mines, University of California, Berkeley, SyZyGy Plasmonics, NuScale Power
Barriers Addressed	• Cost • Weight and volume • Efficiency • Refueling time • 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 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.

- This year, the Hydrogen Materials Advanced Research Consortium (HyMARC) team has addressed many of the systemic approach issues reviewers have perennially complained about in the earlier years of the project that felt ad hoc in end-point goals. The new approach is analysis-based on end-user needs, rather than basic science discovery and mechanism elucidation of materials that were never going to meet targets. This change in direction is much more in line with the continuation of the predecessor Engineering Center of Excellence (CoE) that focused on all material parameters required to deliver an overall system superior to incumbent 700 bar and liquid technology. Hanna Breunig deserves credit for marshalling the center's vast resources toward a clear and common vision. Expanding the scope beyond automotive now also makes sense where applications for hydrogen in grid and energy infrastructure are increasingly finding use. Developing the levelized cost equation to compare all projects is also an outstanding metric and keeps them focused on the real-world constraints and needs of end users. This approach should be benchmarked for all CoEs, as it truly reveals where a material's strengths and weakness are. One drawback is that emphasized materials discovery remains focused on 15–25 kJ/mol materials for room temperature. While room-temperature materials should be the target, a "net" material enthalpy target near to thermoneutral is what is needed, particularly for any application where fast fueling/defueling is required. Otherwise, the heating/cooling requirements of a system become onerous quickly with fast fueling/defueling. Ideally, a slightly exothermic (on defueling) material is what is needed—just exothermic enough to offset the cooling effect of gas expansion (hydrogen tanks today quickly hit lower temperature limits during heavy loads from heavy-duty applications) but not so exothermic as to potentially enable a runaway thermal event. There was evidence of this approach in the poster sessions with the flexible metal–organic framework (MOF) approach, in which the MOF morphology change during hydrogenation did create a heat sink of about 30% of the heat generation of the 15 kJ/mol binding to the metal site. The project is encouraged to pursue these approaches further and perhaps use the flexible MOFs (and potentially others) as a heat sink in addition to a storage material support, etc.

- In general, the recent shift in emphasis to higher-level system analyses that connect promising hydrogen storage material candidates with specific applications that have benefits over batteries and physical storage is compelling. It is a rational strategy that facilitates the evolution of the HyMARC activity into an application space that is meaningful to the Office of Energy Efficiency and Renewable Energy. Likewise, the incorporation of a task on material co-design, scale-up, and integration provides a solid pathway to extending the aspects of materials discovery, synthesis, characterization, and modeling/simulation to meaningful performance regimes. Again, it is a good approach for extending what has been learned and developed previously in the project to application areas consistent with overall DOE goals. The strong focus on new materials and catalytic processes for liquid carriers also seems reasonable. In addition to successfully addressing the overall challenge of hydrogen storage, the development of liquid hydrogen carriers capable of efficiently storing and efficiently transporting hydrogen is a critical component of DOE planning and process execution. The approaches adopted by the HyMARC team have considerable promise and are showing good progress toward achieving DOE goals. Overall, it seems that there is a conscious effort to push the project further up the "technology readiness level (TRL) chain." Although this seems reasonable at this stage of the HyMARC effort, there is some concern that this is a major departure from the "foundational" research that was the hallmark of the initial HyMARC mission. (It was disappointing that important basic studies of reaction dynamics and structural changes during hydrogen sorption in candidate systems were scarcely mentioned in the review.) Realizing that this project cannot continue to dwell solely in a regime of fundamental science, there are some approaches that should not be abandoned or overlooked. Most notably, the collaboration with the Advanced Light Source (ALS) on use of sophisticated in situ/in operando characterization tools to probe hydrogen sorption reaction processes and dynamics in a well-controlled reaction environment could pay big dividends and support a deeper understanding of critical hydrogen storage processes that could be vital for guiding future work in the consortium. It was mentioned in the question-and-answer portion of the review that the ALS collaboration has been renewed. It is strongly recommended that the HyMARC team build on that renewal to conduct a focused effort on that important topic.
- The addition of the techno-economic analysis function (Breunig/Lawrence Berkeley National Laboratory) to the HyMARC approach, while not completely integrated within the project yet, is clearly going to help re-focus material design efforts within the center. The approach to focusing on use-case scenarios to help in preliminary analyses of whether certain material development strategies have value in certain hydrogen storage applications is useful. With these developing tools, it may be possible to do more "reverse engineering" of materials to meet specific use cases and focus the research and development (R&D) effort.
- The project is aimed at seven major barriers officially. The project could add more effort to align work with end-user requirements, meaning the work will be directed toward more useful avenues at an earlier point in the R&D stream. The project continues to use a theory-guided experiment method that is growing ever more efficient. The broad scope of activities increases the odds of impact.
- Moving away from material discovery into application of the discovered materials is a good idea.

Question 2: Accomplishments and progress

This project was rated **2.7** for its accomplishments and progress toward overall project and DOE goals.

- Solid progress has been achieved in the systems analyses task ("Driven Efforts for Use-Case Scenarios"). It is providing an efficient and clear pathway to meeting performance targets. Especially noteworthy progress has been achieved on development and application of screening approaches capable of identifying material and system conditions that can achieve performance superior to incumbent technologies. The results achieved on improved hydrogen carriers and catalysts, ternary amide-based storage materials, and novel frameworks for multiple hydrogen binding are also significant. Specifically, exploring ternary amide-based materials in specific use cases provides information that directly supports the effective introduction of these novel materials in important hydrogen storage applications. The overall impact and importance of the work on polymer-coated framework materials, MXenes, and plasmonic materials for liquid organic hydrogen carrier (LOHC) dehydrogenation remain questionable. Apart from some general comments about potential advantages, compelling data were not provided to adequately support a case for continued work in those areas. For example, polymer-coated framework materials currently have a capacity of ~1.5% w/w. A well-defined pathway to achieving a capacity competitive with 350 bar compressed hydrogen (~2.5% w/w) was not provided. Likewise, it is not evident how photocatalytic dehydrogenation of LOHCs in plasmonic material matrices can achieve efficiencies that would make that process competitive with conventional thermal approaches. Additional justification and quantitative performance projections are needed. The isosteric heat inter-laboratory comparison effort is a natural and effective extension of prior National Renewable Energy Laboratory (NREL)/HyMARC work on understanding inconsistencies in experimental results obtained by different researchers on similar materials. This continuing effort will be important for establishing best practice protocols for conducting accurate isosteric heat measurements. The number and scope of the recent HyMARC publications and presentations are impressive. In addition to creating scientific impact, the publications and presentations serve as a useful way to document progress by the consortium and provide outreach to the science and technology community.

- It appears that not much progress in the materials arena has occurred in the last few years except for the work at the University of California, Berkeley, on improving storage on absorbents and new materials, the MXenes. The work on plasmonic catalysis for release of hydrogen from formic acid does not seem to be progressing or have the potential to outperform conventional catalysis. The rates/conversion shown in the presentation are not inspiring. The simulation of drive cycles for heavy-duty trucks using the LiMg amides is intriguing; this modeling awaits experimental verification that did not appear to be in the list of proposed future work. The work of Parilla et al. in providing the sorption community with the tools and techniques to improve sorption measurements is, as always, laudable—but also crucial to bring a uniform approach to sorption measurements across the community. The work at Pacific Northwest National Laboratory (PNNL) on formate/bicarbonate (and others) as a hydrogen carrier system is excellent and is well regarded within the scientific community. This work has taken the techno-economic analysis (TEA)/life cycle analysis (LCA) approach to heart to focus the research and down-select promising candidate systems. The center has done a nice job of working with seedling projects. The work with McGuirk at the Colorado School of Mines on characterizing sorption and structural aspects in the class of flexible frameworks is very nice.
- The project should develop engineering models to better know where a material might be useful and what is needed to make it useful. The project could electrochemically make carriers to use stranded or curtailed power to make carriers. The project identified the advantages and hurdles in an ultrasafe bicarbonate-to-formate system. LiMg amide can match compressed gas density and provide a ~500-mile range. There is interesting work to "dial in" the backbonding of metal centers to linkers in MOFs and tuning the delta H to the best area of about 20 kJ/mol. A poster showed ~3% (mass) deliverable excess hydrogen at room temperature and <100 bar. There has been nice progress in several seedlings, for example, the MOFs that made and analyzed by theory that approach what may be the limit of storage.
- Accomplishments are strong, but progress toward goals is still in process. The consolidation of projects to focus on the levelized cost equation is a tremendous change in direction and reshuffling of the entire center. The approach alone revealed ideal placement for some existing materials that had previously fallen short of the transportation-focused goals. For example, the project showed MOFs can outperform 350 bar compressed and liquid in backup power situations but should be looking at systems that look for low carbon. A 90T system and slow charging rates are needed. The project should move away from using hydrogen to generate heat (thermodynamically) and use an electrocatalytic process with waste energy from renewables/nuclear to lower the number of steps of energy loss. How the new direction drives novel material discovery will be interesting. The pursuit of thermoneutral materials or composite material systems is strongly advised.
- The calculations show some applications where the materials are competitive versus pressure vessels. However, the assumptions used in the modeling are not clearly indicated and seem extremely optimistic, based on the little that could be figured out from responses given to questions during the presentation.

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.

- Both external and internal collaborations have greatly increased the "reach" of HyMARC, and they continue to be strong aspects of the project. Significant academic and national laboratory collaborations have been augmented by a large number of new industrial collaborators. As the project evolves to support higher-TRL activities, those collaborations will undoubtedly be important for enabling more efficient technology transfer and overall project impact. The collaboration with Metro State University (Denver) to support ongoing diversity, equity, and inclusion initiatives has the potential to achieve a "win–win" for both NREL/HyMARC and Metro State.
- The project added a number of corporate partners to provide better input on what the materials must do and the conditions under which they must operate. The project has International Energy Agency collaboration on isosteric heat calculation harmonization. There seems to be more cross-pollination between projects inside HyMARC. Of course, this is not the collaboration this topic aims at elucidating, but it is important and points to a greater chance of success, just as external collaboration does.
- A highlight of HyMARC has been the consortium's interest in reaching out to other researchers for collaboration that often leverages their own capabilities, as well as helps to promote scientific progress in general. The project's collaboration helps provide insights into what the international community is doing to address specific regional or national needs. The project offers an invaluable window on the world to DOE R&D efforts.
- The project has a good team, with high-quality science being conducted.
- The center has all the relevant partners. The project has always covered a wide variety of institutions. The project lacked direction but was never short on horsepower.

Question 4: Potential impact

This project was rated **2.9** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The addition of the "reverse engineering" aspects, including the TEA/LCA/levelized cost assessments, has brought focus to some of the HyMARC project areas and has accelerated progress in those areas. Other areas are not up to speed in this regard. The future impact of this new analysis-based focus will depend on whether the HyMARC leadership can be hard-nosed enough about its implementation to discard materials approaches that are unlikely to bear fruit and refocus those efforts on more promising areas that have improved opportunities for potential deployment against specified use cases. The new Hydrogen Roadmap calls out hydrogen carriers explicitly as a key technology for widespread adoption of hydrogen for various uses. HyMARC's impact can be amplified if the researchers really focus on translating foundational R&D to practical carriers and on toward deployment.
- HyMARC remains a critical element of the DOE Hydrogen and Fuel Cells Program portfolio. It is assumed that the recent shift in project focus and emphasis is being driven by the need for greater near-term relevance and impact of HyMARC in the overall DOE Hydrogen Program. Although that seems reasonable, it is critical that the principal reason that HyMARC was created in the first place (the development of foundational understanding of processes and mechanisms operative during hydrogen storage reactions in solid state and liquid materials) not be overlooked.
- Using end-use needs and benchmarking against competing options is a great step toward increasing the impact of this team. The project retains a high level of fundamental expertise while moving toward directions that will increase impact. Several projects have the potential to be viable technologies in mobile and stationary applications.
- The new direction makes it much more likely that practical solutions will be found throughout the entire energy/grid spectrum. The expansion beyond transportation to include the entire well-to-wheel and energy grid requirements will open up—and seems to have already opened up—viable solutions that may have been previously discounted.
- It is difficult to see how these materials can compete against pressure vessels in weight, volume, cost, complexity, thermal management, safety, etc.

Question 5: Proposed future work

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

- The proposed future work strongly focuses on the emerging system-level analyses efforts, which could clearly reap benefits that affect multiple areas of the HyMARC project. Matching storage and transport materials with specific use cases will undoubtedly provide useful information that can guide down-selection and strategy decisions. Work in other areas seems to be a straightforward and rational extension of ongoing efforts within the consortium. Continued administrative and technological support of the Push/Seedling projects is imperative. The end-of-year go/no-go decisions should be made rationally, with close attention to progress on objective milestones. The importance of the work with ALS on characterization of sorption processes in a controlled reaction environment must not be ignored. This collaboration has the potential of producing the most important foundational findings and insight that have been obtained thus far by the consortium.
- The proposed future work was described in fairly generic terms, which was probably necessary because of time constraints, but hopefully a more detailed plan exists. One area needs attention and discussion as part of down-select criteria: the question of transportation costs of liquid carriers versus solid carriers and how that helps to identify use cases and materials and help to focus HyMARC R&D. The project may need to collaborate with the Argonne National Laboratory (ANL) team (Ahluwalia, Elgowainy, et al.). Collaborating would go a long way to identifying where solid sorbents, etc., can be employed in the hydrogen landscape.
- The project maintains discipline to stay focused to achieve optimal levelized cost, which should remain the target. Learning more about the MXene materials will be interesting. Also, increased attention should be given to flexible MOFs as a heat sink to enable thermoneutral materials/systems.
- The proposed future work was not clearly explained during the presentation, but a simple continuation of current work listed in the slides will be good. The work on room-temperature storage in MOFs is eagerly awaited.
- It is recommended that ANL and Strategic Analysis, Inc., join the team to evaluate an independent cost and performance analysis to better identify what areas of interest (if any) may benefit from storing and/or distributing hydrogen in materials.

Project strengths:

- The relatively new emphasis on TEA/LCA/levelized costs, etc., should continue to help focus HyMARC activities, if it can be ruthlessly applied to down-select materials by HyMARC leadership. The carrier work at PNNL is clearly a strength of the project and is internationally recognized, as is the work by the Long group at Berkeley. Additionally, the work that has been done at NREL in the best practices for sorption measurements and analysis is well recognized across the community and is a valuable contribution of HyMARC.
- HyMARC is a critical element of the DOE research, development, and demonstration portfolio. The new emphasis on system analysis for specific use cases will undoubtedly expand opportunities both to increase relevance and to exceed performance of incumbent systems. A strong R&D team has been assembled, and the scope and breadth of the synthesis, analysis, characterization, and simulation efforts are impressive. The strong focus on hydrogen liquid carriers is an especially noteworthy aspect of the project. Extensive collaborations with academic and industrial partners and direct involvement in Push/Seedling projects are infusing new ideas and capabilities into the consortium.
- The Levelized Cost Equation is an important activity to keep the effort on the right track, so huge credit goes to Hanna Breunig for managing this.
- The project has good, solid teams on basic science and materials characterization.
- Strengths include the people on the team, resources, and access to past DOE centers in detail.

Project weaknesses:

- Although this may not necessarily be considered a weakness, there is concern that the increased emphasis on system analyses will seriously diminish the focus on a primary element of the consortium, which is development of foundational understanding and insight. That would be an unfortunate consequence of the current restructuring. A few sub-projects, e.g., plasmonic and polymer-coated materials, lack adequate motivation, supporting data, and future promise to justify them as compelling mainstream activities. A close examination of those R&D directions is needed.

- The project has room for more actual co-work (different from cooperation) in the center to really get the most out of the people and equipment. A greater willingness to pivot from work streams that are not getting practical results would be nice to see. The project should stay in the general area but pick a promising new approach.
- Some of the catalysis work performed at NREL needs a careful look as to the viability of the approach.
- The project needs a more detailed TEA to identify areas of opportunity.

Recommendations for additions/deletions to project scope:

- It would be helpful to have a candid and forthright statement and discussion concerning specific areas where the project has advanced or augmented our current understanding on the foundational aspects of hydrogen sorption reactions and what additional information is needed. It seems that many system-level analysis activities have been conducted previously (e.g., in the Engineering CoE, ANL [Ahluwalia, et al.], Strategic Analysis, Inc. [James/Houchins, et al.]). The techno-economic cost projects derived from those projects have provided a quantitative view of system efficacy and future market penetration. It might be useful to carefully consider the results from those studies and how they might support the system analyses being conducted here. Likewise, it would be helpful to contrast the use-case studies with conclusions drawn from that prior work. A candid evaluation of sub-projects and activities is needed at this advanced stage of the HyMARC effort. (Some have been mentioned previously.) Dilution of effort on projects that may have academic interest but have limited impact on meeting DOE goals must be carefully assessed.
- The rigorous application of the TEA/LCA/etc. approach brought by Hanna Breunig, as well as Kriston Brooks at PNNL, needs to be applied more broadly across all HyMARC materials development activities (perhaps including the seedlings) to focus current and future materials/carrier development efforts more sharply.
- The project should incorporate a task for independent evaluation of the different alternatives of storage versus pressure vessels, caverns, liquid hydrogen, etc.
- The contract is not set up for this, of course, but it is time to move on from work that is not going to serve any identified end use, given the limits that the research has revealed.

Project #ST-236: Low-Cost, High-Performance Carbon Fiber for Compressed Natural Gas Storage Tanks

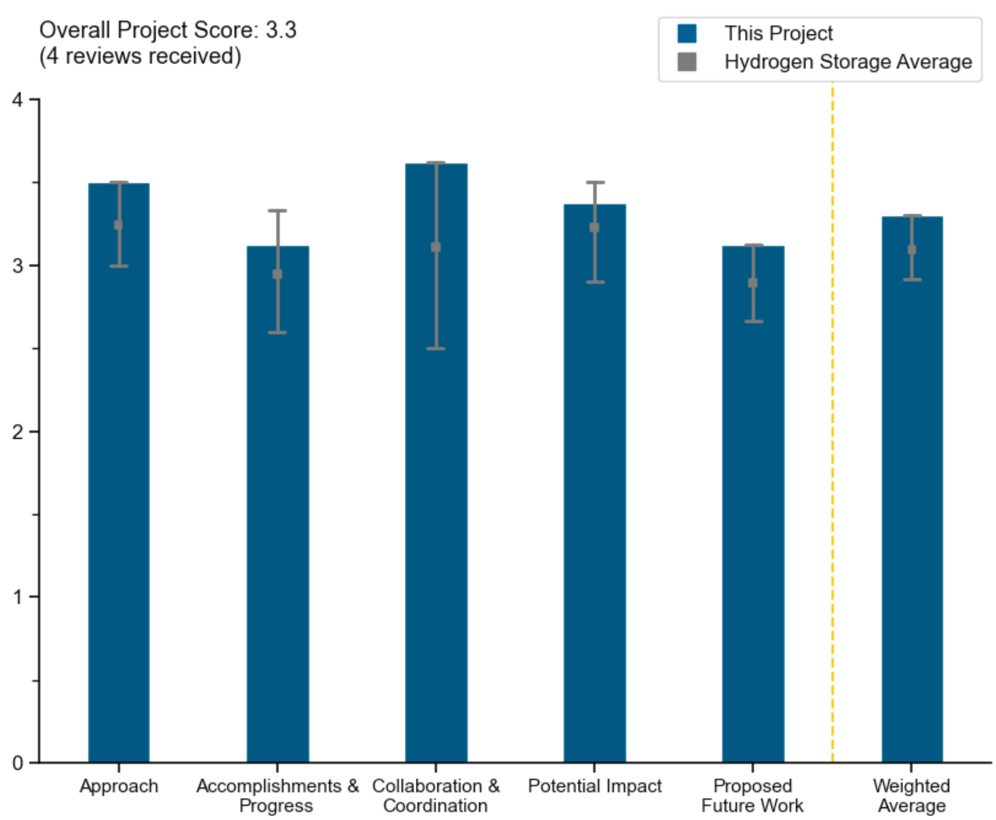
Xiaodong Li, University of Virginia

DOE Contract #	DE-EE0009239
Start and End Dates	10/1/2022–9/30/2027
Partners/Collaborators	Oak Ridge National Laboratory, Savannah River National Laboratory, Cytec Engineered Materials (Solvay), Hexagon Lincoln
Barriers Addressed	• Lightweight compressed natural gas and hydrogen storage tanks needed for vehicle energy efficiency and payload capacity • Prohibitively expensive contemporary carbon fiber (accounts for half the cost of the tanks) • Significant cost reduction of carbon fiber through low-cost alternative precursors • Reduced carbon fiber volume through carbon fiber composite matrix interface enhancement

Project Goal and Brief Summary

This project seeks to develop and validate methods for scalable production of low-cost, high-performance carbon fiber that can be used in the manufacture of compressed natural gas (CNG) storage tanks. Researchers will incorporate the carbon fiber into the design of a low-cost, lightweight composite CNG storage tank, ensuring that it meets American National Standards Institute standards for CNG containers, and establish a methodology to scale up tank manufacture. The improved design and use of low-cost carbon fiber is expected to reduce the cost of conventional fiber-wound CNG storage tanks by as much as 37%

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.

- Low-cost precursors are a natural choice for reducing the overall cost of the system since the precursor costs are a significant portion of the total cost. Practical and sustainable precursors are needed to ensure favorable life cycle solutions for hydrogen storage systems. The mesophase pitch materials proposed seem to have multiple benefits, including low initial cost, high-quality supply from other industrial processes, and lower carbonization temperature requirements.
- Pitch-based carbon fiber has been commercially available for decades, and it is well known that synthetic mesophase pitch is generally required to achieve the best performance, primarily strength, by reducing variability leading to flaws. The blending of pitch with low-cost polymers is novel, but the presentation indicates properties were low. Blend 2 using a proprietary polymer seems to be the path forward, according to the presentation. Future cost of the polymer was not discussed. Achieving high strength with low standard deviation is critical for pressure vessels. The work on interfaces should be a second priority compared to fiber mechanical property targets.
- The project could use a less expensive precursor (mesophase pitch) and coatings to get better interface-to-matrix. Lower temperature is needed to reduce process cost. This should meaningfully reduce the compressed gas tank cost if taken to the commercial level.
- The project's approach appears innovative, with low-cost pitch precursors and nanocoating application.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- The project has made 100 m at 100 filaments at a time resulting in 1 GPa strength (at this time) at 40-micron diameter. The sizing improves load transfer and shear. The product is made from recycled material. The project developed a filter to remove impurities that would otherwise cause defects.
- The team is continuously producing smaller and smaller fibers with a claim that fibers will reach 8 um in the near future. The project team has shipped material to Hexagon and already evaluated load transfer properties.
- The project met targets for modulus and strain to failure on alternative precursor fibers. It is not clear whether there is a plan to reach the strength target. The nanoparticle approach to improving the matrix–fiber interface shows promise for increased load transfer efficiency, but it is unclear how this translates into improved pressure vessel performance. Slide 15 models the effect of improved load transfer, but it is unclear what is being modeled and what net improvement is obtained from increased load transfer.

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 has excellent collaboration with industry, laboratories, and academia. It is nice to see Solvay as a partner to help introduce new entrants into the carbon fiber manufacturing field to promote competition and increased supply.
- The team is very strong across the supply chain. Once the formulation is defined, it may be necessary to bring in a supply chain partner for polymer synthesis. The reviewer was not sure whether the precursor is a compounding operation or requires custom synthesis.
- The project has one fiber partner and one tank partner. The fiber partner has used its line to try the new precursor.
- The project has good team members, although many of these also participate in many of the competing teams.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Low-cost carbon fiber is extremely important, especially to companies that make 350/700 bar tanks. There will be a continued need for these systems for 15 to 20 years. It is not anticipated that liquid hydrogen (LH2) will completely supplant compressed hydrogen (CH2) systems in the next two decades, specifically regarding medium-duty (MD) systems, such as pickup trucks, that are in a difficult position, as LH2 does not meet their duty-cycle needs. Also, the current cost of 700 bar systems is prohibitive for their customer base, as customers cannot absorb the system cost, as in a Class 8 total cost of ownership business case. Additionally, for MD applications, electric vehicle systems are too much of a payload penalty; thus 700 bar systems are the only solution for the foreseeable future, based on current technology. Additionally, many new LH2 and cryo-compressed hydrogen (CCH2) systems are now investigating composite systems for further weight reduction and improved insulation properties. This expands the need for low-cost carbon fiber beyond the needs of CH2 for MD applications to now include aerospace and long-haul trucking applications. The project team should consider increasing focus on these projects.
- A 35% cost reduction is possible, which would lower tank cost over 15%. Better use of fiber would further reduce cost. The project appears to use Hexagon to look at samples for usefulness in application.
- The project has the potential for a reduction in vessel cost if fiber targets are met.
- At this stage, it is not clear whether the new precursor can meet the project goals or whether it will result in a lower-cost fiber. The embodied energy for manufacture of current carbon fiber is a concern, but perhaps this approach will be less energy-intensive.

Question 5: Proposed future work

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

- The appropriate next steps are to continue to focus on lower-diameter fibers and evaluate load transfer effect. DOE should consider combining this project with the hollow fiber project into one larger project, assuming both hit their interim targets or demonstrate a viable roadmap to achieving targets.
- The main priority should be on the fiber performance and cost targets. The fiber surface treatment should focus on known commercial approaches.
- The main thrust of the project should focus on improving the tensile strength of the fiber.
- The proposed future work is appropriate for the project’s current progress.

Project strengths:

- The project has clear starting point materials with current large-scale industrial supply in high-quality formats, which significantly reduces development and capital expenditure risks going forward.
- The project uses low-cost material and appears to have a strong team with useful collaborators.
- The approach of looking at a new precursor blend may result in cost reduction and meet performance targets, but it is too early to tell. The project team is very strong.
- The project has an innovative approach, with potential to meet fiber targets.

Project weaknesses:

- It is too early in the project to know whether it will be successful. It is well known that unrefined pitch results in low-strength carbon fiber and that synthetic pitch is more expensive. The source and properties of the project pitch were not presented.
- The variations in the starting material are unclear—which is inevitable, as it is a byproduct—and will impact product quality.

- The project has not shown a detailed analysis of the produced materials. It would be good to have more evidence of material characteristics/carbon orientation (perhaps transmission electron microscopy [TEM] images).
- The tensile strength target has not been met, and further fiber improvement will be necessary.

Recommendations for additions/deletions to project scope:

- Even if the strength target is not met, the fiber may still be useful with intermediate modulus.
- The project should combine with hollow fiber project in the second project phase instead of forcing a down-select between the two.
- It would be useful to model a vessel with and without nanoparticles to explain and quantify the effect of increased load transfer efficiency on vessel performance.
- More evidence of material characteristics/carbon orientation (perhaps TEM images) is requested.

Project #ST-237: Carbon Composite Optimization Reducing Tank Cost

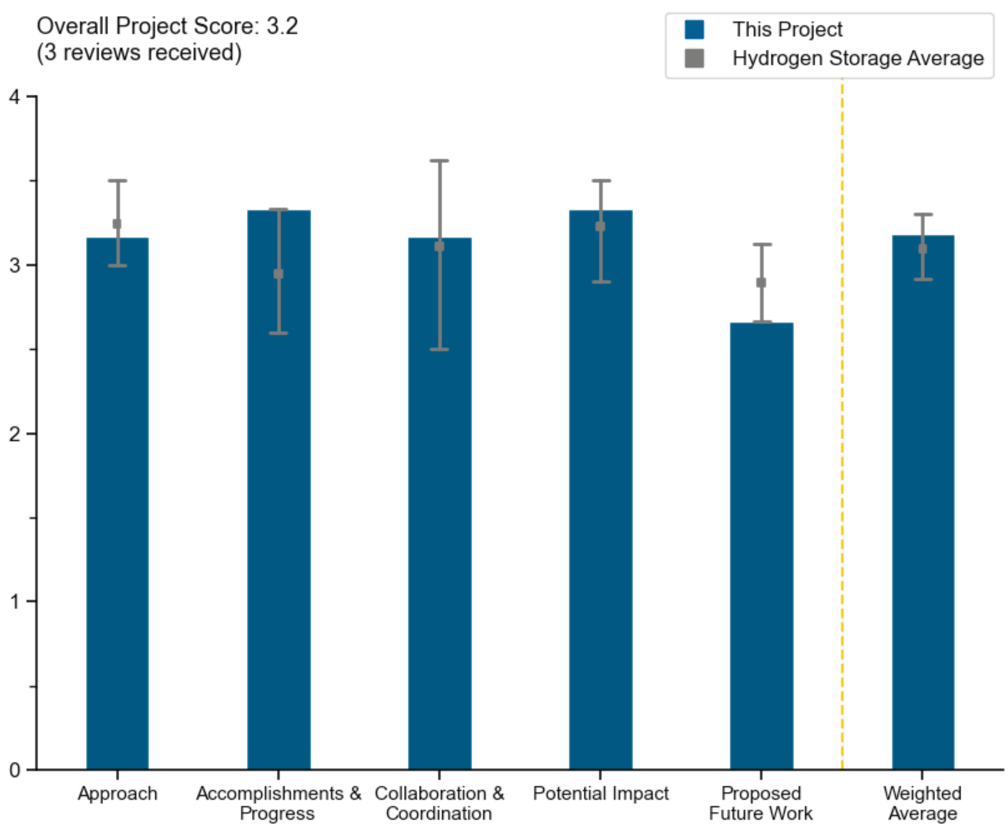
Duane Byerly, Hexagon R&D

DOE Contract #	DE-EE0009240
Start and End Dates	10/1/2021–9/30/2026
Partners/Collaborators	Cytec Engineered Materials, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Newhouse Technology, Kenworth Research and Development Center
Barriers Addressed	• Reduced carbon fiber production costs • Enhanced composite load transfer efficiency • Pressure vessel end-of-life solution

Project Goal and Brief Summary

Currently, the cost of gas storage tanks is a significant barrier to the mass deployment of cleaner vehicle fuel sources such as hydrogen and compressed natural gas (CNG), and carbon fiber accounts for approximately half of the total hydrogen storage system cost. This project aims to reduce compressed hydrogen and CNG storage costs by developing new and optimized technologies to produce low-cost, high-strength carbon fiber with a demonstrated cost of less than $15/kg, tensile strength of 700 ksi, and tensile modulus of 35 Msi. Carbon fiber technology will be enhanced through controlled fiber morphology using tuned polymer molecular structures and optimal spinning and carbonization conditions. Researchers will use high-throughput fiber manufacturing to increase production capacity, materials characterization to minimize defects, high-performance resin and interfacial engineering to enhance the composite, and modeling to improve pressure vessel design. The project also addresses environmental concerns by exploring new methods to recover resin and fibers for secondary use.

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's primary focus should be on Track 1, fiber cost reduction. The results indicate the Cytec Engineered Materials approach toward precursor synthesis is successful, resulting in greater yield and high tensile strength. Specifics on cost reduction potential, other than the cost model targets, were not presented.
- The project offers a multipronged approach of reduced fiber cost, load transfer efficiency in laminates, better tank design and interlaminate strength, and end-of-life recovery of value.
- The project's approach seems incremental, focusing on optimizing existing steps rather than trying new approaches. The project's effort seems scattered because of many tasks being pursued.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- This project team has the most progress, in that the carbon fiber strength reported exceeds the targets. The standard deviation is not reported, so it is not clear whether the strength value reported was the high or average. More technical details are needed, for example, the fiber's diameter. The project should report on any novel process conditions.
- The project showed progress with two different new polymers made at 5-gallon scale that oxidized to the target of 1.35 g/cc, increased line speed, and achieved 800 ksi fibers. The project made 100 m of 100-fiber tows. The cost model shows what needs to be achieved to get to ~$14/kg fiber.
- It makes sense that chain length may correlate with strength, but the project could clarify what the correlation is (e.g., whether the correlation is linear and how strength [or stiffness] is affected per unit of increase of chain length). Slide 15 shows results from a COMSOL simulation. The project should clarify what is being modeled, why it is being modeled, and what the results show. The cost analysis seems extremely optimistic. It is not clear that stabilization/oxidation costs can really be significantly reduced or whether that is achieved by increasing throughput. Some aspects were unclear because of the use of jargon and acronyms that are unknown to many.

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 partners include a truck company (the lead organization's customer) and a materials supplier. The project partners are doing significant tasks and not just talking.
- The project team is very strong and comprehensive.
- The presentation talks very little about individual tasks for the different organizations and does not mention who the individual contributors are. That information needs to be included in the presentation. This is especially important in this thrust, where the same organizations repeatedly show up in many of the competing projects.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The impact should be very good on the industry if the higher strength is achieved as reported, it translates well into the composite, and there is a cost reduction. Top priority should be on the fiber development, but other tracks may also be beneficial.
- Achieving $15/kg at 700 ksi would greatly reduce fiber and tank costs and facilitate hydrogen tanks in many applications.
- The project will have a positive impact on pressure vessel cost if the targets are met.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- Scale-up of the precursor and evaluation of fiber tensile properties in a composite should be the high priority. The project needs to validate that the approach will achieve a significant cost reduction.
- The proposed future work appears adequate, with an emphasis on increasing strength.
- The future work was not well defined during the presentation. The project listed two milestones in the slides but did not provide much detail on how to get there.

Project strengths:

- The project is well poised to bring the advances to market. The team intimately understands the needs. A consumer of tanks is included as well, so the next-level customer's voice is included, too.
- Hexagon R&D appears well located as a lead institution, considering that the company has a major motivation to improve performance and is familiar with necessary tasks for manufacture.
- The novel polyacrylonitrile (PAN) precursor results look promising, and there is a strong team supporting the effort.

Project weaknesses:

- Validating cost reduction is yet to be proven, which is an issue for all these projects.
- The project's incremental approach may limit potential gains.
- Details on the advances, chemically, were scarce, so they were harder to evaluate.

Recommendations for additions/deletions to project scope:

- The project should clarify other anticipated risks or barriers regarding commercialization, assuming tensile properties are maintained and expected fiber cost is reduced.
- No changes are recommended.

Project #ST-238: Low-Cost, High-Strength Hollow Carbon Fiber for Compressed Gas Storage Tanks

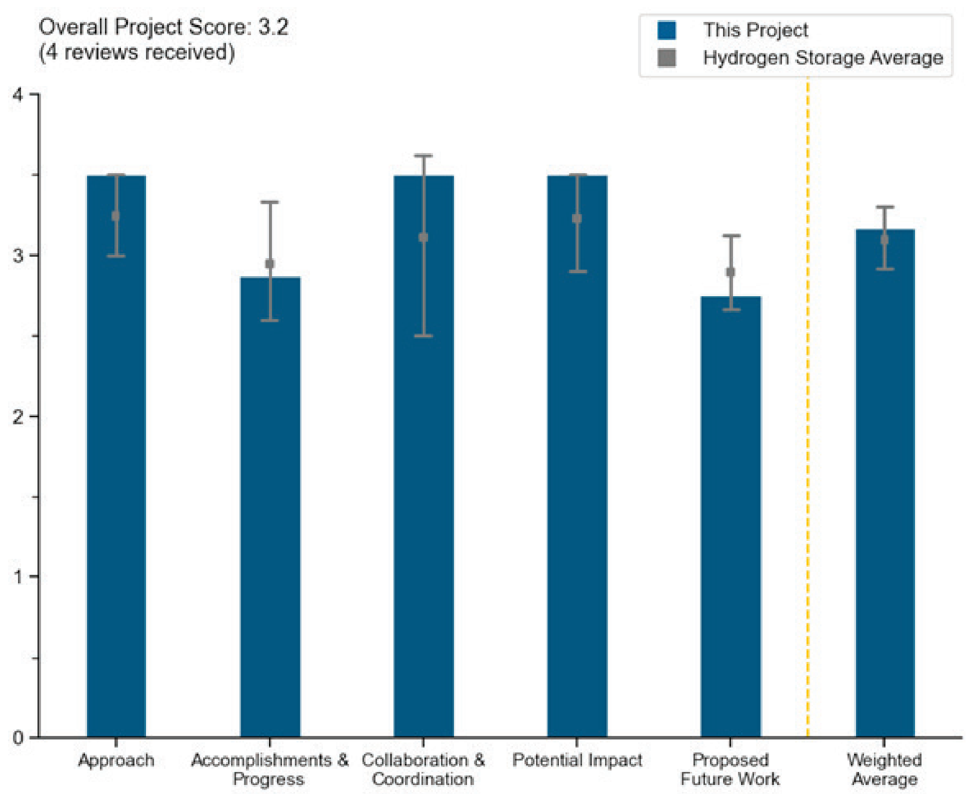
Matthew Weisenberger, University of Kentucky

DOE Contract #	DE-EE0009241
Start and End Dates	10/1/2021–9/30/2026
Partners/Collaborators	Solvay Composite Materials, Steelhead Composites, Inc., Oak Ridge National Laboratory, Advanced Fiber Technologies, Inc., Strategic Analysis, Inc.
Barriers Addressed	• System weight and volume • System cost • Materials of construction

Project Goal and Brief Summary

This project aims to develop hollow carbon fiber (HCF) with a cost target of $13–$15/kg, approximately a $10 reduction of the current cost per kilogram. Removing the fiber core increases the fiber's specific properties while maintaining tensile strength, as a disordered core contributes little to its integrity. In addition, HCF may oxidize quickly, as the reaction happens at both the interior and exterior. The development process will include advancements in fiber spinning and scale-up, as well as tailored oxidation profiling and accelerants for fast oxidation. Researchers will systematically down-select time–temperature–strain paths through low- and high-temperature carbonizations to maximize HCF strength and carbonization line speed, matching increases in oxidation line speed. Alternative uses for end-of-life tanks, as well as recycling, will be explored to determine the most cost-efficient and sustainable options. Sufficient HFC will be produced to fabricate composite overwrapped pressure vessels (COPVs) for testing. Researchers will conduct life cycle cost analyses of HCF, from manufacturing through COPV end-of-life.

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 project presents a valuable contribution of reducing fiber requirement in a tank, which is the key need in the area. The project's approach would drive lower cost and mass and, to an extent, volume of the tank. The project has an interesting concept to reduce cost and mass at the same time.
- This project centers on a novel approach to remove the fiber center core, which has reduced properties. Other precursors under evaluation could take advantage of this approach.
- Overall, the concept makes sense. The remaining questions how much strength the core contributes and how much loss there is in tensile strength of the fiber. still seems elusive. It is understood (via the transmission electron microscopy [TEM] image) that the core could be more disordered in C-C bonds and thus tensile strength, but the strength difference has not been confirmed can it be confirmed. The principal investigator (PI) seems to put most of the hope in increased strength (i.e., T700 equivalent) correlation to decreasing fiber diameters. Perhaps the decrease in fiber diameter simply increases the ratio of material cross-section area to empty core area to gain relatively more strength but yet will never fully achieve T700 parity. In the near future, the project should show a simple physics description relating the cross-sectional area of fiber-to-core to describe what ever-decreasing fibers can theoretically yield in terms of ultimate fiber strength. The project should also show a better understanding of the core zone material characteristics. The PI says it is more disordered/less carbonized than the outer core but needs to clarify by how much. It makes sense that this could be the situation since oxidation/carbonization is a diffusion-limited process, but, again, it is not clear what the difference really is and whether it is significant enough to say the core is not contributing appreciably to the strand's overall strength.
- The project approach seems very original but also high-risk.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and DOE goals.

- The project has achieved spin polyacrylonitrile (PAN) through shaped die to get a smaller and hollow filament, met the 100-filament spinning go/no-go metric, achieved under 23-micron hollow fiber, achieved 20% to 30% open area, made 100-meter lengths, and showed the hollow area remains hollow when impregnated. The project still has much of the concept to prove out: whether the target diameter can be reached without collapsing the hollow core, what the consistency of product properties will be, and what the best method is to get enough (but not too much) oxygen into the initial spun fiber.
- The project has been active for several years now and continues to miss the ultimate strength target of achieving T700 parity. Skepticism and doubt are beginning to build on whether the fundamental assumptions of the project are sound. The PI needs to clearly show that the contribution of the core toward tensile strength contributes less to the total strength than its cross-sectional area would indicate. While getting to smaller strands for increased strength is the right direction, this alone does not fully explain the properties of the material or prove that, in the end, the project will produce a fiber with the same strength for less material/cost.
- Production of hollow core carbon fiber has been achieved; however, the fiber diameter is too large, resulting in lower fiber strength. It is critical to the project's success to make a fiber with a desired diameter of 7 microns or less and show improved tensile strength.
- The project's accomplishments seem weak. The reported stress to failure is very low, and it was unclear whether the project has a plan to address premature failure. Cost calculations assume that spinning can be done for free and that the central core does not contribute any strength to the fiber. It is not clear how likely it is that these assumptions may hold.

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 several fiber makers as partners to get inputs. Also, the project has a tank maker that is the key user of the fiber and needs to be able to use it. Collaborators are doing significant work for the project.
- The project has excellent collaboration, especially with Solvay Composite Materials in the mix to hopefully increase the supply base for carbon fiber and produce new entrants in the field.
- The team is very strong and should help support a next phase if the fiber properties look promising.
- The team seems adequate.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Low-cost carbon fiber is extremely important, especially to companies that make 350 bar/700 bar tanks, and there will be a continued need for these systems for 15 to 20 years. Liquid hydrogen (LH2) is unlikely to completely supplant compressed hydrogen (CH2) systems in the next two decades. In particular, medium-duty (MD) systems such as pickup trucks are in a difficult position; LH2 does not meet their duty-cycle needs, and the current cost of 700 bar systems is prohibitive for their customer base, who cannot absorb the system cost as a Class 8 total-cost-of-ownership business case can. Additionally, for MD applications, electric vehicle systems are too much of a payload penalty; thus, 700 bar systems are the only solution for the foreseeable future, based on current technology. Additionally, many new LH2 and cryo-compressed systems are now investigating composite systems for further weight reduction and improved insulation properties. This expands the need for low-cost carbon fiber beyond the needs of CH2 for MD applications to now include aerospace and long-haul trucking applications. The project should consider increasing focus on these projects.
- The project aims to remove mass and cost but maintain capability of the fibers, which could greatly lower compressed gas tank cost.
- If all project assumptions are correct and the fiber is spun to the correct diameters, the fiber cost targets may be reached.
- The novel approach could provide desirable composite performance, but this is yet to be seen. The fiber cost may be cheaper, but this also is yet to be seen. The spinning of hollow fiber may add complexity that drives up cost. Of greatest interest is what attributes HCF might provide to composite performance.

Question 5: Proposed future work

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

- The future work plan looks appropriate.
- The project's focus is on smaller fibers to achieve higher strength. This sounds fundamentally correct, but the project should provide additional support to the theory to prove this assumption. Some questions for the project to focus on include what really is happening in the core and whether it is really contributing substantially less to the tensile strength. It would also be good to find out a bit more about the healing process and whether it creates any artifacts that could decrease the strength of the material.
- Considering the low fiber strength obtained so far, it would make sense to focus all the future effort on this important topic.
- The project's future work is not covered well in the presentation, and the slides list only goals and go/no-go criteria, not the work planned to get there.

Project strengths:

- This project has the most novel approach to reducing cost and is perhaps also the highest-risk. The project has made good progress in achieving quality fiber and now needs to reduce diameter, which hopefully results in higher strength.

- The project employs a novel approach, using a hollow and small fiber. There is less chance of defects in smaller fibers.
- The project has created fibers and identified a practical manufacturing method to produce fibers.
- The project has an original, unique approach to reducing fiber cost.

Project weaknesses:

- The project needs to demonstrate higher strength at the desired diameter to validate the concept.
- The project has little assurance of success, and the impact of defects, when they occur, is not clear.
- The project lacks a fundamental explanation as to the impact of core material on fiber strength.
- The project has made little progress toward meeting the strength target.

Recommendations for additions/deletions to project scope:

- Cost models are important, but, given the low strength of current fibers, it would make sense to de-emphasize this activity in favor of focusing on fiber strength.
- If targets are achieved next year (i.e., T700 strength with less material), the project could consider integrating a lower-cost precursor, which may lead to further cost reductions.
- The project should stay on track with its current approach.

Project #ST-240: Cost-Optimized Structural Carbon Fiber for Hydrogen Storage Tanks

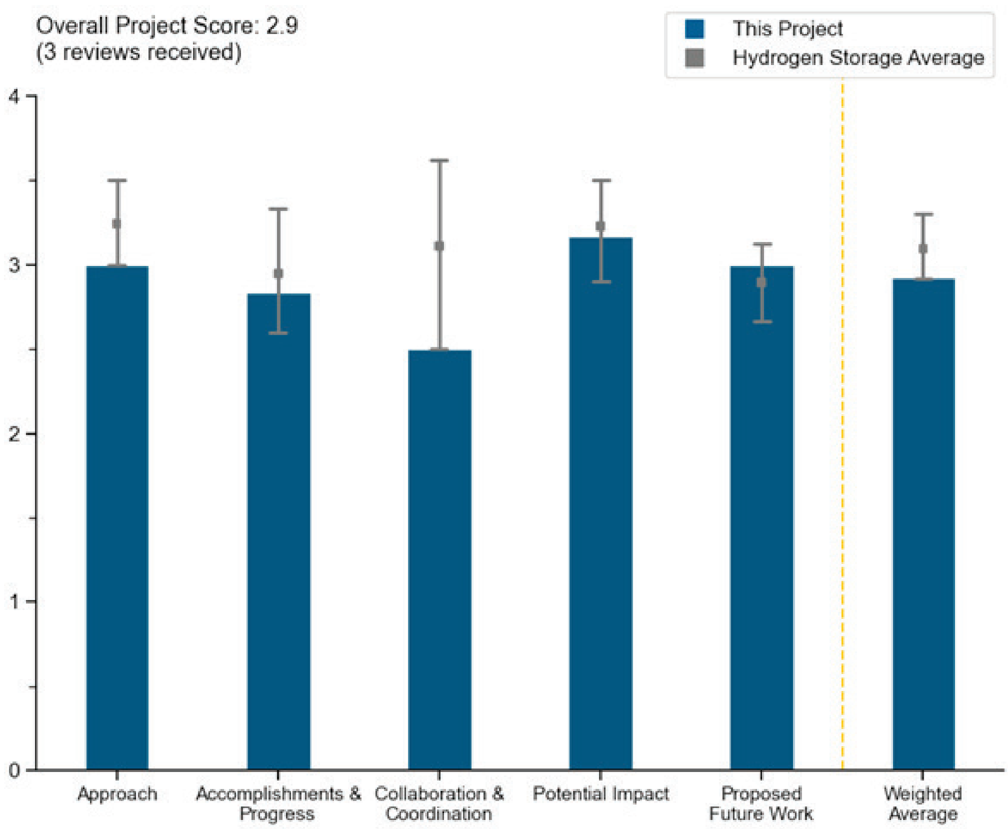
Amit Naskar, Oak Ridge National Laboratory

DOE Contract #	WBS 4.3.0.605
Start and End Dates	4/1/2021–3/31/2024
Partners/Collaborators	Pacific Northwest National Laboratory, 4XTechnologies, LLC
Barriers Addressed	• Manufacturing higher-performance carbon fiber at lower cost • Enhancing fiber–matrix load translation efficiency

Project Goal and Brief Summary

This project aims to manufacture low-cost, high-strength carbon fiber at a cost of less than $15/kg, delivering target 700 ksi tensile strength and 33 Msi tensile modulus. Currently, both precursor fiber and conversion processes contribute to high carbon fiber costs, so the project aims to employ both novel precursor and new high-performance processing technologies in manufacturing. Researchers will conduct foundational research to enhance processability of newly synthesized polyacrylonitrile (PAN)-based precursors. In parallel, both conventional and advanced plasma-based processing technologies will be studied for cost and performance optimization. The project will also conduct analyses to optimize tank design. Cost reductions in carbon fiber manufacture will lead to higher utilization of hydrogen in vehicles.

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 shows strong progress to meet the high strength performance goal using a lower-cost commercial precursor. Actual cost reduction is yet to be seen, but the approach shows promise. Small fiber diameter, in a tensile-dominant application, may be a benefit for better strength translation. This was not discussed but may be a key benefit to the approach. Ultimately, the product is designed to the low end of fiber strength, not the mean, so reduction in standard deviation (currently over 10%) is also important.
- A two-pronged approach was taken, one based on PAN and one on low-cost material with higher risk but more reward.
- The project is appropriate, with a combination of near-term and longer-term tasks.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- The project passed the 100 m/100 fiber tow milestone. Atmospheric plasma oxidation was used to get more cross-linking in the core. Up to 700+ ksi was achieved in some cases using this method—and in shorter time. The new precursor is about half the strength but at lower cost. It is in the PAN family, but the project had no data on possible cost reduction. The cost model developed is of clear value.
- Fiber strength shows the best results of all the projects reviewed. Specific costs were not presented, but using a commercial precursor should be an advantage.
- Reasonably promising results were presented from Thrust 1. Thrust 2 seems scattered and poorly described. It is unclear what is being tried. The presentation needs a better, clearer description of individual tasks and activities. It is unclear whether it is realistic to reduce residence time by 80% and whether this really reduces cost by 80%. It is unclear whether cost really scales linearly with residence time. The symbols in slide 11 were not defined.

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.

- Oak Ridge National Laboratory (ORNL) is participating in this fiber development project, in addition to three competing fiber development projects. Pacific Northwest National Laboratory (PNNL) is in another project in addition to this. It is not clear how the organizations and DOE are managing the information and the personnel to avoid conflicts of interest (or the appearance of conflict of interest), especially considering that some of these organizations (especially ORNL) are doing similar tasks in several of these projects. Slide 21 in the presentation says that the project is looking for a vessel manufacturer to join the team. Surely there are many composite vessel manufacturers willing to participate in this project.
- A stronger team would include industry supply chain partners, similar to the other projects.
- The project includes partnerships across labs but no industry.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project probably has the best chance to move a new fiber forward most quickly. The actual cost savings is as of yet unknown. A reduction in fiber diameter may provide better overall composite structure performance for damage tolerance and fatigue and should be investigated. Compression strength reduction caused by micro-buckling should not be a concern.
- Clearly reducing cost to $13/kg would reduce tank cost by possibly 15% or a bit more.
- There is a reasonable likelihood of reducing vessel cost if targets are met.

Question 5: Proposed future work

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

- Future work is suitable and builds on progress and toward goals.
- The plan includes air gap spinning as a future task, and this task is being researched as a part of the Hexagon project. It is unclear how this task migrated to this project. It may duplicate the work in the Hexagon project.
- The new precursor effort shows less promise at this stage, as compared to the commercial acrylic fiber. It is suggested that the project look at diameters of 2, 3, 4, and 5 microns as related to fiber strength and standard deviation.

Project strengths:

- This is the best effort to meet the commercial-grade fiber target. The approach should have a path to lower cost, but how far is not yet well defined. Better control over fiber diameter may prove better composite performance in a tensile-dominated structure.
- Positive results are seen so far for near-term tasks.
- The project team and its experience are strengths.

Project weaknesses:

- It is difficult to understand the way the four carbon fiber projects are structured and how ORNL and PNNL are participating in several of them and conducting similar tasks.
- It seems less focused than usual for this work at this location. It would be helpful to see a clearer presentation of how the project will get to the properties the researchers hope to achieve.
- The team should add industry partners for future transition.

Recommendations for additions/deletions to project scope:

- Whether air gap spinning should be pursued in this project is questionable, as it is being pursued in the Hexagon project.
- The project could add industry partners and establish a relationship between fiber diameter and composite tensile strength.
- Regular consultation with fiber and tank makers is recommended.

Project #ST-241: First Demonstration of a Commercial-Scale Liquid Hydrogen Storage Tank Design for International Trade Applications

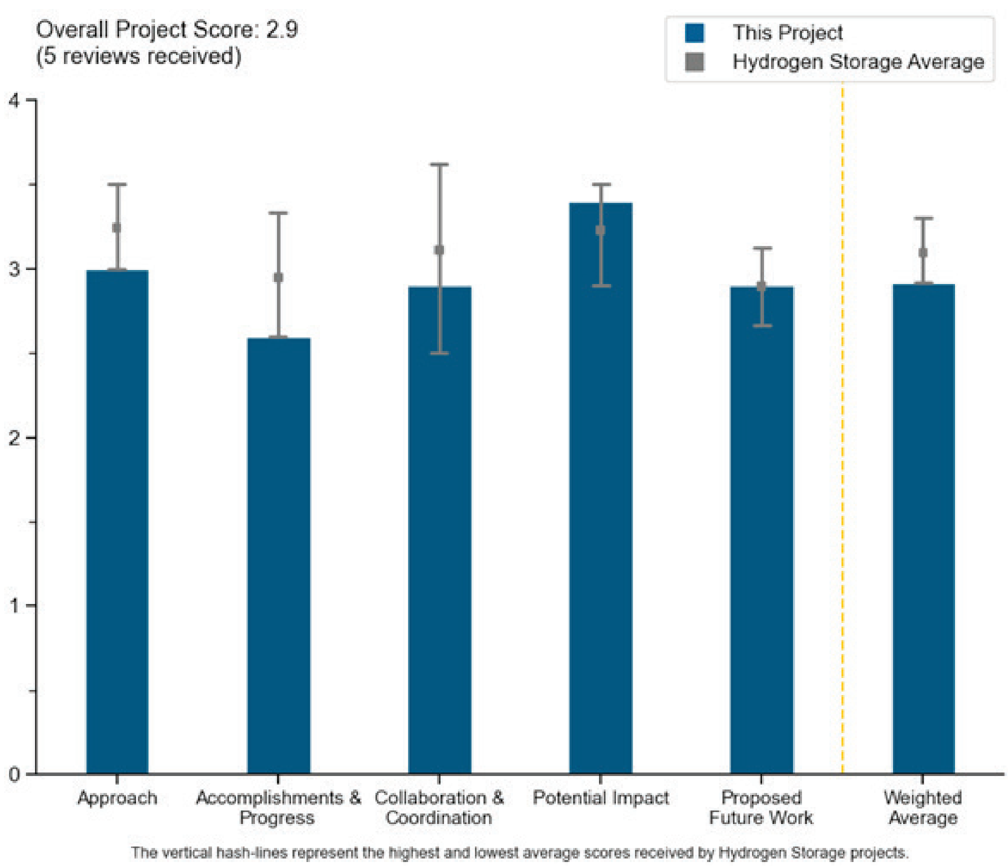
Ed Holgate, Shell

DOE Contract #	DE-EE0009387
Start and End Dates	9/1/2021–8/31/2024
Partners/Collaborators	CB&I Storage Solutions LLC, GenH2 Corporation, NASA Kennedy Space Center, University of Houston
Barriers Addressed	• Ultra-low boiling point of hydrogen (20 K) • Need to minimize boiloff product loss • High capital expenses for liquid hydrogen storage tank • Technology scale-up

Project Goal and Brief Summary

One of three priorities in the Hydrogen Program is low-cost, efficient, and safe hydrogen delivery and storage. This project aims to develop a first-of-its-kind affordable, very large-scale liquid hydrogen (LH2) storage tank for international trade applications, primarily for installation at import and export terminals. The project aims to create a large-scale tank design that can be used in the 20,000–100,000 m^3 range (1,400–7,100 metric tons of LH2). Key success criteria for the large-scale design include a targeted LH2 boiloff rate of less than 0.1%/day and a capital investment below 150% of liquefied natural gas storage cost. The project will also ensure that the technology meets safety and integrity regulations, codes, and standards.

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.

- This project will develop a large-scale stationary LH2 storage tank design for import and export terminals. The design will be applicable for tanks between 20,000 m^3 and 100,000 m^3 volume, capable of holding 1,400–7,100 metric tons of LH2. The key metrics are <0.1%/day boiloff rate, <$175 million in capital expenditures for a 100,000 m^3 LH2 tank, and compliance with safety, codes and standards.
- The approach was difficult to determine based on the limited information shared. The presentation was clear about what the end goal was, but it was not clear on the approach the project was taking to achieve that goal. The presentation had pieces of the approach, such as the two examples out of seven designs that were down-selected, using specific criteria, for a final choice. However, no details of those criteria were shared, and the reviewers were not shown the other design choice down-selection, which would have allowed reviewers to see how much worse the other choices were. The presenter shared that the project was limited on how much could be shared because of intellectual property limitations. The presentation focused on concept development and selection, concept de-risking for selected concepts, and demo tank design.
- Shell has not presented the details of studied concepts and decided to omit these because of confidentiality measures. This was subject to questioning during the presentation, and the conclusion could be drawn that presenting other candidate insulation technologies could guide the audience toward identifying the selected concept. The presenter stated that the elaborated concept is undergoing the process of securing formal intellectual property protection. The approach presented in the summary presentation appears correct. Intermediate project goals have been reported as complete, and experimental equipment is in the process of being constructed to support the evaluation of proposed solutions.
- Shell has an excellent approach to developing a large-scale LH2 tank design. The approach consists of insulation evaluation building on past NASA work within the project constraints of less than 0.1% boiloff per day and a cost of less than 150% of existing large-scale liquid natural gas systems. The project has assembled a very skilled team and presented a systematic approach to meeting the multiple design optimization criteria. It would have been helpful to see any detail regarding the down-select progress so as to support the community and avoid dead-end research or development pathways.
- The document establishes a cost target and a vent target, but it seems that it would be better to set a target for minimum cost over the life of the vessel. A quick calculation shows that the vessel, as designed, will have more than $10 million worth of vent losses per year. It seems that there should be an economical way to mitigate that in such a large system.

Question 2: Accomplishments and progress

This project was rated **2.6** for its accomplishments and progress toward overall project and DOE goals.

- The mark has been set to satisfactory because of lack of complete presentation of the results. Based on the presenter responses during the session (as well as support from DOE staff who have involvement in direct monitoring of the project and thus who have better knowledge of the results), the discrete project goals have been met.
- The project has met all milestones for Years 1 and 2. These include effective thermal conductivity measurements for bulk fill materials, concept development and evaluation, and cost analysis.
- The presentation indicated the project made progress on cost simulations and thermal insulation design based on measurement data. Unfortunately, there was not a significant amount of detail for a better review. It is believed, with the high caliber of the team, that intellectual property has limited information-sharing for review on the progress of the design and how good the system can be. It would also have been helpful to understand where the sensitivities in the Monte Carlo model are—those that impact and limit reducing the costs—or those concepts and areas that were identified.
- Shell's team has made excellent progress toward goals, but the team has not shared any details on the down-select strategy or what was used to select the final design direction with respect to opportunity costs of other technology pathways. Unfortunately, it is very difficult to gauge progress without seeing and understanding the design decision and technical down-select options. The concept selection matrix looks

quite logical but does little to inspire confidence without the technology approach being shared (for example, discussion of how this project is different from the most recent NASA-built large-scale storage).

- The presenters did not describe the systems that they are considering. It is understood that there are proprietary details that the presenters do not want to reveal, but it seems that they could do an overview of the things that they are attempting without getting into proprietary details. It is unclear how reviewers are supposed to review accomplishments if the most important details are not presented.

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 has a strong team, with Shell as prime, NASA for liquid nitrogen experiments and LH2 experimental support, GenH2 for LH2-based experiments, CB&I for demo tank construction and testing, and the University of Houston for thermal modeling support.
- The project lead identified four collaborating institutions for the project. During the presentation, partners were acknowledged for the support in performing the scheduled work.
- The team is appropriate for the project.
- More explanation of partners' input and support of the concept development, as well as down-select criteria, are needed to give a more relevant score. CB&I is an excellent partner, given the very limited number of companies that are able to construct vessels of this size. A deeper discussion of construction challenges and technology development needs would be helpful. GenH2 is an interesting liquefaction startup with a track record of developing small-scale systems. The company is an important partner for the initial testing of components. It was good to see the University of Houston listed, but it would be nice to better understand the workforce development plan or how the university can be involved in future phases of the project, beyond insulation modeling for hands-on expertise development.
- It was not clear in the presentation whose work was being presented in the slides. There is a slide for collaboration in the presentation, but there is some overlap in the team responsibilities. The reviewer had to piece the collaborators' activities together with different slides. It would be helpful in the future to share a collaborator logo or logos for team work on the slide to help with understanding who is doing the work and collaborating in sharing the information with the other team members.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project could have a very high impact on DOE goals if it is successful. LH2 boiloff is a significant challenge to large-scale hydrogen use for transportation. This scale of 1,500–7,000 metric tons will absolutely be required at any large-scale hydrogen-for-transportation hub. Hopefully, the project will be able to continue on schedule and within budget. One of the presenter's comments about supply chain risk is a cause for concern owing to uncertain delay.
- The project aims to develop large-scale LH2 storage technology to reduce capital and operational expenditures in the LH2 storage and delivery chain. Reduction of the storage costs would allow for overall reduction of hydrogen cost at the dispenser (or on tap).
- The significance of high-volume hydrogen storage is critical in several areas for large-scale hydrogen production. It is essential for industry and shipping to have significant enough storage to build the infrastructure necessary for moving hydrogen at scale forward for the nation.
- Large stationary LH2 storage tanks are needed for international trade.
- There is good impact for international LH2 commerce if targets are met.

Question 5: Proposed future work

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

- The proposed future work will continue on the design of the method, equipment, and procedures necessary to apply the insulation systems on the vessel walls, as well as the required field evaluation techniques and procedures for quality control and quality assurance or continued modeling updates to the system design. The presentation of the challenges is clear on the technical difficulties the team faces with the work. The team is rightly focused on the tasks that need to be completed.
- The project plan has been presented and follows appropriate logic. Assessment of an important barrier in project completion (tank manufacturability analysis) is yet to be completed; however, the presenters implied during questioning that the project will successfully overcome this challenge.
- It will be interesting to see the verification of tank constructability costs. It is expected that a project at this scale will have significant barriers that have not been addressed before, including material joining (e.g., welding), bringing in raw material, etc. The final performance testing will be critical to staying on budget and proving out the claims of cost and low boiloff. Unfortunately, there was very limited information about the actual technologies being pursued.
- The proposed future work is consistent with the barriers and challenges identified to date.
- It is unclear whether the list of tasks the project has Shell doing (“project lead, project management, and reporting”) is all that Shell is planning to do.

Project strengths:

- The strength of the project is the team, which is experienced in designing, testing, and building large-scale liquid storage systems. Despite the fact that design details and information were limited because of intellectual property, the reviewer believes that the team be successful with the future work.
- The project strengths stem from the outstanding list of partners, the incredible scale, and the low boiloff metrics and cost targets. The project has an incremental approach, which should keep the early costs low so the team can build a larger system in the future.
- The project consortium is considered a strength, especially considering the available technical capabilities and past experience in relevant areas (demonstrated in the presentation).
- The project’s strength is a good team of institutions.
- The well-rounded team is a strength.

Project weaknesses:

- Hopefully, the authors can be more forthcoming with information, enabling a more detailed evaluation of the project. Basic concepts can be described without revealing proprietary information.
- The key potential weaknesses have been identified as risks for the proposed concept’s manufacturability and long-term performance.
- It is difficult to assess the weaknesses, as the limited information on the design and the design alternatives makes it difficult for reviewers to ask questions about the team’s comparison of the other designs.
- The major weakness is the lack of information shared because of intellectual property concerns.

Recommendations for additions/deletions to project scope:

- More efforts with the University of Houston should be added, where possible. The reviewer requests a clear pathway from research results to implementation. A discussion of process safety management and Occupational Safety and Health Administration regulations for storage over 10,000 lbs. could also be addressed.
- Long-term stability of the newly proposed insulation materials must be verified to ensure lack of performance degradation. Overall, it is difficult to present suggestions because of limited information received because of confidentiality measures taken by the presenter.
- There are no recommendations for changes to the scope.

Fuel Cell Technologies – 2023

Fuel Cell Technologies Subprogram Overview

Introduction

Fuel cells efficiently convert the chemical energy of hydrogen or other fuels into electricity and are an important part of a comprehensive portfolio of solutions to achieve a sustainable and equitable clean energy future. Fuel cells can be used for a variety of applications across multiple sectors. The Fuel Cell Technologies (FCT) subprogram applies innovative research, development, and demonstration (RD&D) to develop a diverse portfolio of low-cost, durable, and efficient fuel cells that are competitive with incumbent and emerging technologies across applications. Subprogram activities align with priorities in in the U.S. National Clean Hydrogen Strategy and Roadmap.

The subprogram's RD&D strategy is target-driven, with application-specific targets developed to reflect the performance, durability, cost, and scale needed to address end-use requirements. In this holistic approach, the subprogram develops targets based on the ultimate life cycle cost of using fuel cell systems in comparison with other technology options. Guided by analysis and fuel cell system modeling, the subprogram develops and refines targets for emerging and high-impact applications. These include heavy- and medium-duty vehicles, stationary power generation (primary and back-up), and reversible fuel cells for energy storage. The subprogram's RD&D emphasis is primarily on heavy-duty applications where significant reductions in both carbon emissions and criteria pollutant emissions can be achieved. Advances in heavy-duty vehicle fuel cells will also offer transferable benefits for medium-duty and stationary applications.

The subprogram engages in RD&D to overcome critical technical barriers to fuel cell development, including the need to further improve performance and durability and reduce fuel cell cost. The subprogram's balanced and integrated RD&D efforts focus on materials, components, and system integration. RD&D also addresses manufacturing and supply chain challenges to accelerate the commercialization and deployment of fuel cell technologies.

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 the following:

- Develop fuel cell systems—with emphasis on near-term heavy-duty transportation applications—that are highly durable, efficient, and low-cost, while meeting application-specific constraints such as dynamic response, resilience, packaging, and heat rejection.
- Develop new materials and components for next-generation fuel cell technologies in diverse applications for power generation and long-duration grid-scale energy storage, emphasizing innovative mid- to long-term approaches, including reversible fuel cells and hybrid approaches, such as tri-generation, that can use fuel cells to co-produce power, heat, and fuel.

Key Milestones

The FCT subprogram has established the following milestones to achieve by 2030:

- Develop a 68% peak-efficient direct hydrogen fuel cell power system for heavy-duty trucks that can achieve durability of 25,000 hours and be mass-produced at a cost of $80/kW.
- Develop stationary fuel cells that achieve 80,000-hour durability at a cost of $1,000/kW.

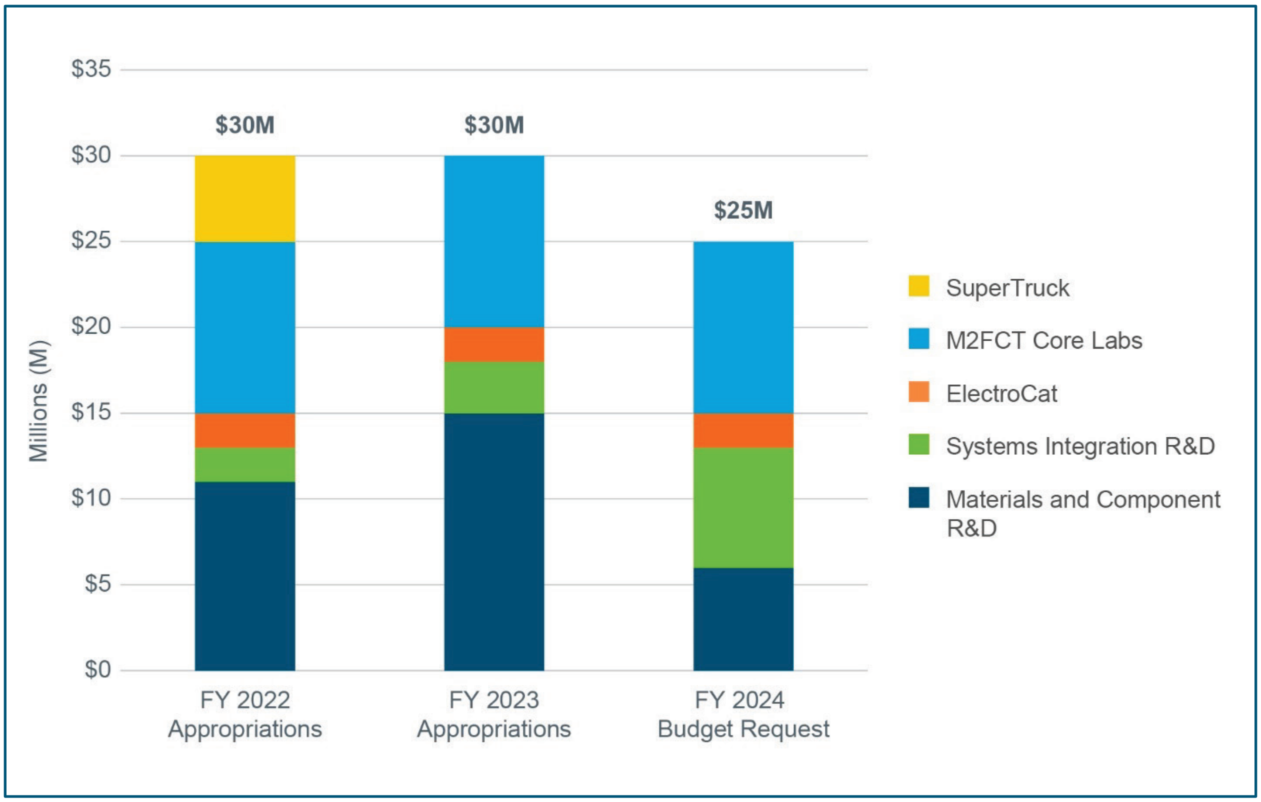
- Demonstrate heavy-duty fuel cell manufacturing capacity of 20,000 stacks per year in a single production line.
- Develop reversible fuel cells for energy storage applications that can achieve 40,000-hour durability and 60% round-trip efficiency at a cost of $1,800/kW.

Budget

The Fiscal Year (FY) 2023 appropriation for the FCT subprogram was $30 million. In FY 2023, the subprogram funded fuel cell materials and components, as well as systems integration RD&D, with a focus on reduced cost and enhanced durability and efficiency for heavy-duty applications. Funding was dedicated to the two national laboratory consortia, the Million Mile Fuel Cell Truck (M2FCT) consortium and the ElectroCat (Electrocatalysis) consortium, with M2FCT receiving a majority of the consortia funding (see the chart below).

Funding for fuel cell materials and component RD&D focused mainly on low-platinum-group-metal (low-PGM) catalysts and membrane electrode assemblies (MEAs); MEAs and stack components with enhanced durability; and PGM-free catalysts and electrodes. Funding for fuel cell systems integration RD&D was dedicated primarily to stacks, balance-of-plant components, and systems analysis.

The FY 2024 budget request for the FCT subprogram is $25 million. Activities planned for FY 2024 include continuing RD&D of low-PGM MEAs (mainly though M2FCT) and PGM-free catalysts and electrodes (ElectroCat); expanding the RD&D efforts on membranes; and meeting durability-adjusted heavy-duty fuel cell cost targets.



In FY 2024, the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law [BIL]) provisions on clean hydrogen manufacturing and recycling (Section 815) will fund manufacturing RD&D and component supply chain development and establish a recovery and recycling consortium for fuel cell and electrolyzer systems. BIL funding will also be allocated to establish a national-lab-led consortium focused on roll-to-roll manufacturing.

Annual Merit Review Results

During the 2023 Annual Merit Review, 33 projects funded by the FCT subprogram were presented, and 23 were reviewed (a breakdown by budget category is shown on the right). The reviewed project received scores ranging from 2.5 to 3.4, with an average score of 3.1. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Following are reports for the 23 reviewed projects. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Number of Projects Reviewed by Budget Category	
Materials and Component R&D	10
Systems Integration R&D	11
ElectroCat	1
M2FCT Core Labs	1

Project #FC-160: ElectroCat 2.0 (Electrocatalysis Consortium)

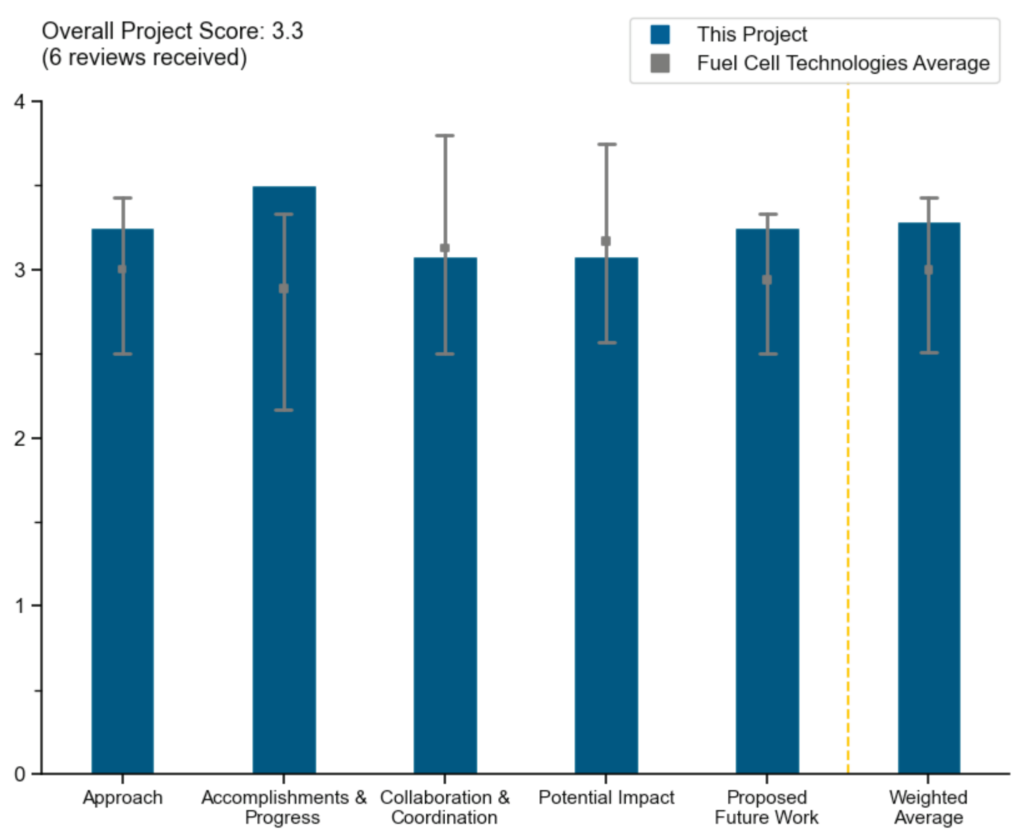
Deborah Myers, Argonne National Laboratory, and Piotr Zelenay, Los Alamos National Laboratory

DOE Contract #	Multiple
Start and End Dates	10/1/2020–9/30/2025
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 of fuel cells and electrolyzers. ElectroCat has focused its efforts on oxygen reduction reaction (ORR) catalysis for proton exchange membrane (PEM) fuel cells, as well as the hydrogen and oxygen evolution reactions (HER and OER) for low-temperature electrolyzers. The consortium has established a portfolio of unique synthesis, experimental, characterization, and modeling capabilities to focus on improving catalyst durability and activity. Specifically, ElectroCat is advancing high-throughput catalyst synthesis and characterization capabilities, coupled with machine learning, to achieve durability and activity goals.

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 principal investigators (PIs) continue to use up-to-date methods to pursue delicate tasks in revealing and improving the performance of PGM-free electrocatalysts for the ORR, oxygen evolution reaction (OER), and hydrogen evolution reaction (HER). The work is systematically done in a synchronized manner between the experimental and modeling efforts. A large volume of synthesized materials has been evaluated for activity and durability properties. The research efforts are well balanced between the participants from different national laboratories, with clearly defined roles, deliverables, and achievements. The PIs manage to fully utilize unique expertise and capabilities within the consortia network of national laboratories and perform cutting-edge research on PGM-free materials.
- High-throughput materials design, synthesis, and characterization are employed to execute the projects, which is very good. This approach can greatly accelerate the development of novel catalysts for both fuel cells and electrolysis cells. This is clearly an ambitious effort to develop non-PGM catalysts; however, the end-of-project goals are still substantially lower than the DOE targets. While this is a low-technology-readiness-level (low-TRL) project, it would be useful for the PIs to outline a techno-economic scenario in which these catalysts could be commercially viable. Assuming the best possible technical outcome, clarification is needed on the path to potential cost savings from non-PGM catalysts and whether the technology could potentially be competitive with state-of-the-art PGM catalysts. The team is doing a good job using high-throughput synthesis and machine learning techniques to refine the Fe-N-C catalysts. These approaches, however, seem to be better suited for optimization efforts and may not be suited for developing the type of breakthroughs needed to close the gap with PGM-based catalysts. The increased focus on water electrolysis applications is encouraged, as there seems to be more potential for these catalysts in alkaline exchange membrane (AEM)-based electrolysis.
- There are several PGM-free catalyst synthesis approaches. Identifying the factors limiting the active site concentration and making attempts to improve would be impactful. The use of metal dopants such as bismuth, molybdenum, and tantalum are very interesting and new. The use of electrochemical studies on the impact of sulfonate anion poisoning of the active site is commended.
- The project has a great combination of theory, machine learning, high-throughput screening, testing, and analyses. The improvement in ORR activity that the consortium has been able to demonstrate year over year is amazing. However, the consortium has not mentioned durability targets. If the material is not stable, it will never become practical. All PEM fuel cell work is focused on the Fe-C-N system, but Fe is clearly incompatible with the PEM membrane. Therefore, there is virtually no interest from industry. The shift toward AEMs is good.
- The project team is diverse and strong for the goals of developing PGM-free catalysts for both fuel cell and electrolysis applications. The only critique is that not all the critical barriers to adoption of the materials are being addressed. The truck and electrolyzer lifetime needs are distant from the project goals.
- The use of Fe in the PGM-free catalyst as the active site is not recommended from a membrane durability standpoint. Alternates such as Mn and Co are strongly recommended. Small parts-per-million quantities of Fe have major implications for membrane durability. Even though there are approaches to mitigate Fe dissolution via carbon shell coating, it will be challenging to stop Fe from dissolving completely. More information is needed on the performance targets and how they align with the high-level stack cost targets and cost walk.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- Progress and accomplishments are separated and presented by two efforts: PGM-free fuel cell cathode catalysts and PGM-free catalysts for electrolyzers. In both cases, overall accomplishments and progress are featured by quarterly milestone charts, including technical description and data analysis. The progress is justified and compared against the DOE technical targets. Regarding PGM-free ORR catalysts, a total of 12 milestones are listed, with 6 of them completed, 2 partially completed, and 4 on track. Considering the timelines, projected duration, and past legacy of the consortium, the milestone status seems appropriate and is self-explanatory testimony about the most recent progress and associated achievements. Overall, the PIs have presented a compelling track record that builds on previous results and continues to tackle challenging technical targets. The following efforts are distinguished and executed in systematic manner:

- Two-step, two heat-treatment synthesis of the Fe-N-C catalyst was evaluated for improved control of Fe dispersion, morphology, and composition within a nitrogen-doped carbon support. These efforts resulted in 59% and 44% performance improvement at 0.80 V and 0.675 V, and 23% and 15% improvement compared to the Fiscal Year (FY) 2021 and FY 2022 baselines, respectively. The performance was measured in the membrane electrode assembly (MEA) under the same conditions: cathode loading: 4.0 mg/cm^2, 1.0 bar air pressure, 100% relative humidity (RH); anode loading: 0.3 mg_{Pt}/cm^2 Pt/C, H_2, 700 sccm, 1.0 bar hydrogen partial pressure, 100% RH; membrane: Nafion-211; cell: differential; MEA size: 5 cm^2; temperature: 80°C.
- Fuel cell durability performance of the N-C/Fe catalyst after 10,000 cycles also showed improvement in the MEA, under the same or similar conditions to those listed above. Initial activity at 0.80 V was 92 mA/cm^2, while after 10,000 cycles, activity was 45 mA/cm^2, which exceeded the anticipated activity target in FY 2023.
- Novel synthesis methods were used to obtain the hollow structure of Fe-N-C catalysts from tannic acid-etched precursors based on metallic organic frameworks. The hollow structure was particularly targeted for utilization of a porous structure that leads to enhanced catalyst surface area. These structures resulted in improved specific activity measured in the rotating disk electrode (RDE), which is likely due to mesopores in Fe-N-C catalysts.

The high-throughput synthesis of the ORR catalysts is the consortium's main signature, and it brings an impressive display of over 300 different catalysts that have been synthesized and evaluated by various machine learning guided methods, including ball milling, chemical vapor deposition, and pyrolysis.

- The machine learning effort resulted in 14 new samples that were synthesized by the adaptive learning approach, which led to 600% higher ORR activity compared to similar catalysts prepared elsewhere by the same method. Moreover, these efforts exceeded the predicted target from FY 2022 by discovering four new catalysts with 33% higher activity than those in the original dataset.
- Statistical analysis of synthesis conditions was performed, and it revealed the importance of synthesis variables on the activity and demonstrated relevance of the cooling rate.
- High-throughput chemical vapor deposition (CVD) was in particular focus with utilization of the parallel CVD reactors that enabled fast screening of applied conditions. The highest mass activity of 23.1 mA/mg at 0.8 V was reported in RDE, while stability was improved upon addition of a second metal chloride.
- ORR activity of the high-throughput system was evaluated in 26 samples in initial synthesis, with the highest activity for 1.2% Fe + zeolitic imidazolate framework (ZIF)-8 after pyrolysis at 1050°C. Initial and mass activity after five potential cycles were included in the machine learning model, which predicted synthesis conditions to achieve higher ORR activity. Maximum mass activity was 19.3 mA/mg at 0.8 V, measured in RDE, while ten catalysts had no activity loss or improved activity after five potential cycles.
- Visualization of the catalyst was improved through imaging and automated spectroscopy of metal atom sites in a graphene-based two-dimensional model M-N-C catalyst system. Researchers used low-voltage imaging and electron energy loss spectroscopy (EELS) to observe at least ten N-C and ten Fe-N-C sites.
- Density functional theory (DFT) has been used to identify stability descriptors for the PGM-free ORR catalyst. In most cases, corrosion of local C/N facilitates dissolution of transition metal, while increased graphitization promotes stability.
- Effects of anions on the Fe^{3+}/Fe^{2+} redox and ORR were studied, revealing that sulfate or bisulfate suppressed Fe^{3+} reduction, enhanced ORR, and interacted more strongly with the Fe center than perchlorate anions. These findings were explained by modeling with an explicit solvation effect on Fe-redox and ORR activity and were extended toward an ionomer effect. It was found that SO^{3-} binding to Fe is a dominant effect of Nafion in a non-defected catalyst, the only system that can be assessed by modeling.

- Additional capability of the high-throughput activity evaluation was achieved by a multi-channel flow cell. Its accuracy and reproducibility were verified and compared to RDE. This effort was applied to both fuel cell and electrolyzer catalysts, and it achieved consistency within 5% between the ORR and OER mass activities measured in the flow cell and RDE.

Regarding PGM-free OER and HER catalysts, there are 13 milestones listed, with 8 of them completed and 5 on track. Considering the timelines, projected duration, and past legacy of the consortium, the milestone status in this portion of the activities also seems appropriate, and it is self-explanatory in regard to the most recent progress and associated achievements. Overall, the PIs have obtained valuable results that continue to tackle challenging technical targets. The following efforts are distinguished and have been executed:

- Established MEA performance baselines for a PGM-free anode and cathode: Anode-Ni/C/ and Cathode-$NiFe_2O_4$, with current density 1.0 A/cm^2 at 1.811 V (high-frequency-resistance-free).
- An OER La-Sr-Co oxide catalyst was optimized to improve electronic conductivity and surface area and was compared to a commercial IrO_x catalyst.
- An NiFe aerogel catalyst was evaluated before and after OER. It was found that the heat-treated catalyst showed structural change; small crystallites before testing were converted to a highly active (oxy)hydroxide layered structure, while no structural change was observed after heat treatment at 500°C, owing to the presence of large, morphologically stable crystallites. Durability of NiFe aerogel exceeded the FY 2023 OER annual milestone. The performance was 1.53 V at 10 mA/cm^{-2} at beginning of test and 0.35 mV/h in a 72-hour test.
- NiFeC nanostructured OER catalyst underwent a durability evaluation for 72 hours at 10 mA/cm^2 and also met and exceeded the FY 2023 OER annual milestone.
- OER performance was compared in an alkaline exchange membrane water electrolyzer (AEMWE) and RDE, and it was found that OER activity trends in RDE testing were only partially observed in an AEMWE. Electrode fabrication, activation, and test conditions play a key role in maximizing AEMWE performance of catalysts.
- Adaptive learning for designing OER electrocatalysts resulted in a matrix with 30 samples for synthesis and characterization in order to build an initial database for developing machine learning models.
- Atomic-scale models of OER electrocatalysts based on DFT calculations have improved the understanding of complex OER catalyst surfaces. For instance, it was found that the energy for O vacancy formation mechanisms is not energetically unfavorable.
- HER catalyst development has demonstrated an impact of the synthesis method on activity. It was found that the heat treatment under a reducing atmosphere (5% H_2 in N_2) is a key factor in improving HER activity, which is still 300 mV behind the PGM catalyst.
- PGM-free catalyst loading at the cathode has a major impact on electrolyzer performance.
- Anion exchange ionomer degradation evaluations revealed a loss of capacitance during deionized water testing, negatively affecting performance.
- Capability development was achieved by in situ Mössbauer spectroscopy for OER catalysts, which showed predominance of Fe (III) at all potentials and an increase in particle size with open circuit voltage.

- There is significant progress in developing electrocatalysts for both fuel cells and electrolysis cells. The achieved performance meets the DOE goals.
- The ElectroCat team is making good progress toward the project goals. The performance and durability data shows continuous progress compared to the benchmarks.
- This project appears to be achieving the contract goals and is demonstrating steady improvements.
- The targets are now based on hydrogen–air performance, which is good. Measuring the proton transport resistance in the thick PGM-free catalyst layers and checking its contribution to the overall voltage loss would be useful.
- The improvement in ORR activity that the consortium has been able to demonstrate year over year is amazing. However, hitting the project’s activity “target” has little impact if it is not durable.

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 Consortia established an impressive collaboration network between participating national laboratories, academic institutions, and industry partners. Considering the novelty in the approach and fundamental challenges of PGM-free materials, the selection of participants is well balanced and reflects maximal utilization of expertise and resources in highly synergistic manner.
- Multiple DOE national labs, universities, and industries are involved in this project, which is excellent collaboration among institutions. Additionally, the demonstrated achievements validate the collaboration efforts.
- National lab responsibilities are clear from the milestone tables, but in the accomplishment slides, it is not always clear where the work is being done. A note (or logo) in proximity to key technical results would help the viewer understand the roles of each of the national labs and the other collaborators. The work looks to be well coordinated and in line with project goals.
- The project has great collaboration between research institutions. Industry involvement in the work seems to be very light, perhaps because of the lower TRL for the technology. More involvement from fuel cell manufacturers and electrolysis manufacturers could be beneficial.
- National lab collaboration is strong; however, there is virtually no interest from industry or the international community.
- The list of collaborators is good.

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The outcome efforts can be seen as pioneering work that brings together outstanding resources, world-leading experts, and a cutting-edge approach. The results are greatly benefiting the Hydrogen Program by establishing a number of performance benchmarks, material discovery, and unique resources to tackle utilization of PGM-free catalysts.
- The goals of this project are ambitious and, if successful, could have a large impact on the fuel cell and electrolysis industry. However, the gap between the DOE goals and the potential of this project to meet these goals is quite large.
- The project is in line with the greater DOE objectives. The objectives for durability should be given more attention, particularly a fundamental understanding of degradation mechanisms in PGM-free catalysts.
- The electrolysis performance is good. However, there is room to further improve the efficiency. Its current density at 1.8 V is not state-of-the-art.
- The impact of PGM-free ORR catalysts is not clear. Their performance and durability certainly are not aligned with heavy-duty automotive applications.
- The consortium would benefit from surveying industries' interests.

Question 5: Proposed future work

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

- Adaptive learning is being used to determine which material sets to focus on (and presumably, which material sets are not selected for further development). The future work plan is clear. There is one minor suggestion. The higher RDE performance, yet poorer electrolysis performance, of PGM-free materials compared to IrO_2 was blamed on ionomer interactions. However, KOH-supported AEM cells do not require ionomer, yet the same trend is true. The team should investigate why the PGM-free results do not translate as well as IrO_2 from RDE to electrolyzer.

- Future work is well balanced and constantly builds on the knowledge established by the consortium. The PIs should consider how to bring closer experimental and modeling efforts, considering discrepancy between the two. Modeling effort has fundamental limitations to tackle real-world complex structures beyond ideal model systems. Along those lines, one can argue about the direct applicability of modeling outcomes toward technical targets and deliverables. An obvious outcome on the future work should be the need for additional fundamental studies.
- The future work is well organized and is in line with additional technical advances that are needed to meet the project targets. While this is a catalyst project, it would be useful to address the presence of Fe and the challenges of membrane durability for fuel cells. The rates of peroxide and other reactive species are expected to be different (perhaps lower) than those of PGM systems. Work to address this topic would help reviewers understand the long-term potential of these catalysts.
- The proposed future work is clear and feasible.
- The consortium would benefit from surveying industries' interests (i.e., identify the catalyst system with the largest impact).
- Proposed future work would benefit from an alternative to an Fe active site and efforts to include active site concentrations.

Project strengths:

- The project has done a good job of exploring multiple approaches to synthesizing PGM-free catalysts. The use of four different approaches demonstrates the team is seeking novel ways to achieve the desired structures. The templating approach to maximizing surface area is well described and supported by high-level imaging methods. Machine or adaptive learning techniques are employed to make the most use of the data generated to date and identify the best formulations or methods. DFT modeling to understand the mechanisms of catalyst activity is well presented. The team is well organized and well suited to tackle this challenging area.
- Leading experts in the field are pioneering the executed work. The outcomes from these efforts are already used by others as well-defined standards in terms of performance. The consortium is continually improving all aspects of utilization of PGM-free materials and will have long-lasting effects in the field of electrochemistry.
- The team is strong and is leveraging extensive experience and capabilities from a broad group of collaborators. The project continues to advance the state of the art for PGM-free catalysts and expand our fundamental understanding.
- High-throughput synthesis and characterization methods are employed to develop new electrocatalysts.
- The project has a good collaboration team and leading scientists in the field.
- A project strength is the strong innovation process.

Project weaknesses:

- The Consortia is meeting and exceeding expectations within the well-defined scope of the project. Having technical targets within a field that is not well grounded with a fundamental understanding is a very difficult set of goals to accomplish. The PIs are making outstanding efforts to overcome this and keep bringing new insight into the mechanism of operation for PGM-free materials. Despite many years of diligent focus on these materials, the field is still missing essential answers about the nature of active sites, electrochemically active surface area, and intrinsic catalytic activity. These topics fall into the category of fundamental research. Without a deeper understanding, it would be difficult to expect groundbreaking discoveries in PGM-free materials.
- While this is an ambitious project, discussion of where this catalyst might fit into the larger adoption of fuel cells or electrolyzers would be helpful. These catalysts will be lower-cost than PGMs, but the total system cost would be higher at today's performance (or even the project performance goals). A realistic analysis of the best-case outcome and what that means to the industry as a whole would offer some context.

- The gap in long-term durability between the application requirements and the technologies being developed is the main concern. If that gap cannot easily be bridged with incremental improvements, then improving understanding of the degradation mechanisms is needed.
- A weakness is the research on an irrelevant material set. There is no customer for the technology.
- The impacts and applications are not clear.
- There are no weaknesses.

Recommendations for additions/deletions to project scope:

- The following additions to the project would be useful:
    - Increase industry involvement, even if that is just project guidance.
    - Investigate degradation mechanisms and potential high-risk–high-reward solutions instead of incremental advances.
    - Investigate why the PGM-free results do not translate as well as IrO_2 from RDE to electrolyzer.
- One suggestion is to address the issues associated with peroxide formation and the impact on the membrane. While recognizing that this is a catalyst project, it is still relevant to understand the role of this type of catalyst on the formation and degradation of peroxide or other reactive species. A non-PGM catalyst for AEM electrolysis should continue to be a focus. This looks to have more potential than the PEM fuel cell case.
- It would be great if some layered double-hydroxide materials could be studied as the OER catalysts for AEM electrocatalysis. For an example, see Park et al., "High-performance anion exchange membrane water electrolyzer enabled by highly active oxygen evolution reaction electrocatalysts: Synergistic effect of doping and heterostructure," *Applied Catalysis B: Environment* 318, December 5, 2022, https://doi.org/10.1016/j.apcatb.2022.121824.
- Formulating a well-articulated, fundamentally focused research program based on the consortium's immense legacy is recommended.

Project #FC-317: Stationary Direct Methanol Fuel Cells Using Pure Methanol

Xianglin Li, University of Kansas

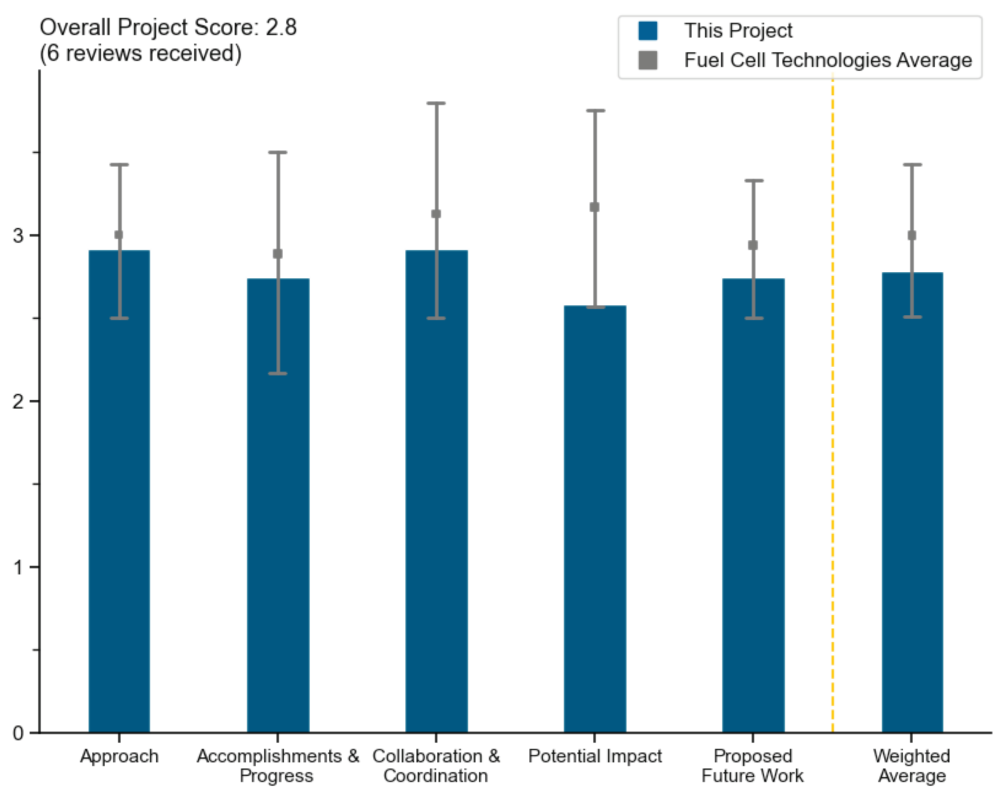
DOE Contract #	DE-EE0008440
Start and End Dates	10/1/2018–3/31/2023
Partners/Collaborators	Kansas State University, University at Buffalo, Carnegie Mellon University
Barriers Addressed	• High platinum group metal (PGM) catalyst loading • Catalyst poisoning by methanol • High fuel crossover

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: (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 ≥300 mW/cm^2 with total loading of ≤3 mg_{PGM}/cm^2. The project addresses the barriers of high platinum group metal (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 **2.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach to develop stable, PGM-free and methanol-tolerant cathode catalysts and lower the anode PGM catalyst loading is good for lowering fuel cell cost. Methanol crossover and water management are key issues for DMFCs, so working on the electrode structure and hydrophobic layer to minimize methanol crossover and manage water transport are also good approaches. Passive feed and operating with high methanol concentration are good approaches to decrease the size of and simplify the DMFC system and potentially lower system cost. The stability enhancement strategies for PGM-free oxidation reduction reaction (ORR) catalysts are reasonable and appear to be successful approaches.
- The approaches are well planned. The approach includes the importance of determining the impact of operating point on degradation rate in MEAs and performing time-efficient evaluation of degradation acceleration factors on a single MEA.
- The approach is good because the team pursued multiple changes to enable improvements in the relatively poor performance of DMFCs.
- The work shows a good approach to meeting the barriers as identified. Some additional barriers to consider will be mentioned later, but the approach, as designed, is appropriate.
- The approach to use PGM-free cathodes should enable reducing PGM loadings to the target levels and should also help reduce reactions with MeOH that has crossed over to the cathode. The goal of operating on pure MeOH could help improve overall system power density if crossover and cathode poisoning can be reduced. The project used conventional membranes. Including some membrane work directed toward reducing MeOH crossover or some advanced membranes would be beneficial to the project. The impact of MeOH concentration on degradation should be studied. Conditions for the pure MeOH experiments were at lower temperature and lower air pressure than for 1 M MeOH experiments. It is not clear how much performance can be improved with varying conditions. Sensitivity studies using pure MeOH and varying other conditions should be performed.
- The relevance of this project is difficult to understand. Working on durability after reaching the performance targets does not make much practical sense. Some of the critical aspects that have rendered MeOH fuel cells impractical have still not been addressed and are not being addressed in this project.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- This excellent researcher has made excellent progress toward the project goals. It is interesting that an MEA with a PGM-free catalyst was better. The project team has achieved the peak power density of 275 mW/cm^2 with no more than 3.0 mg/cm^2 PGM catalyst loading.
- The project goal was to demonstrate an MEA operating on pure MeOH with peak power density of ≥300 mW/cm^2 and total loading of ≤3 mg_{PGM}/cm^2. The project demonstrated good performance on 1 M MeOH, achieving 275 mW/cm^2. However, conditions for achieving 275 mW/cm^2 (on 1 M MeOH) are not normal conditions, and the temperature of 100°C at which this performance was achieved is likely problematic for durability. On pure MeOH, the project appears to have demonstrated only ~50 mW/cm^2, falling far short of the goal. At 0.5 V, near where the power density of 275 mW/cm^2 was observed, heat rejection will be an issue, as ~60% of the energy from the H_2 will be going to producing heat, and the temperature difference between the fuel cell and ambient is much lower than that for a combustion engine. The project demonstrated good performance of the PGM-free cathode and was able to increase current density at 0.5 V with the PGM-free catalyst from ~50 mA/cm^2 in 2019 to over 125 mA/cm^2 in 1 M MeOH in 2023.
- The team did demonstrate DMFCs with high power densities (>0.25 W/cm^2) and relatively modest catalyst loadings (3 mg_{PGM}/cm^2) on 1 M methanol, although this maximum power density was obtained at very low voltage efficiency (approximately 33%). This low efficiency will result in a relatively large amount of fuel required, especially when one includes Coulombic efficiency losses as well (e.g., membrane crossover), which makes both the cost and weight less attractive. Additionally, the decay rates are unacceptable (e.g.,

13% loss in 20 hours), unless most of this decay is recoverable. Unfortunately, performance recovery was not attempted, so it is unknown whether these high decay rates are due to irreversible degradation. It appears that the anode catalysts developed by this team did enable improved kinetic activity, which was the key to enabling their best DMFC performance. It is not clear that the PGM-free catalysts were advantageous, since the performance was lower and the decay rates were still high. The barriers (fuel management layer and water management layer) did enable lower methanol crossover, but the cell voltage performance was substantially reduced.

- The team demonstrated some good technical accomplishments but did not seem to achieve all technical milestones and or the goal (power density + low catalyst loading + high methanol concentration + good durability) as a whole. It would be impactful to have demonstrated 300 mW/cm^2 using neat methanol 3 mg/cm^2 catalyst loading and good durability. For example, the team achieved 275 mW/cm^2 performance with 3 mg/cm^2—but with 1 M methanol, not a higher concentration of methanol. The team has also demonstrated some durability (only 20 hours) at ~175 mA/cm^2 using 1 M MeOH. Regarding DMFC performance using high methanol concentration, the concentration was not very high (~70 mW/cm^2). Stable, high-performing PGM-free ORR catalysts were developed, synthesized, and tested, showing good performance.
- Significant progress has been made to achieve the metrics. That said, the ultimate goal of 300 mW/cm^2 was not quite achieved. The Quarter 12 goal calls out 50 cm^2; however, it was mentioned that most testing was done at 5 cm^2. It is not clear whether the project made and evaluated 50 cm^2 MEAs.
- The performance target of 300 mW/cm^2 has still not been achieved. The 275 mW/cm^2 has been achieved at very impractical conditions for fuel cell operation (<0.3 V). Thermal management of a fuel cell operating under these conditions will be a huge challenge.

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 intended contributions of each of the team members are clear. However, it is not clear how much Carnegie Mellon University contributed here, since optimization and characterization of the electrodes was not presented. Slide 19 noted a great addition: collaborations from researchers that were apparently not funded by the project.
- This project had a good team to develop a PGM-free catalyst, characterize electrodes, and manage the water transport issue.
- The project had an excellent team, and it seemed that there was quite good collaboration between the partners.
- The project had excellent collaboration among universities. No national laboratory involvement was noted.
- Coordination within the project was good. Collaboration with fuel cell companies was lacking. Collaboration with membrane companies or universities working on membranes would have been beneficial.
- The project needed to have an original equipment manufacturer onboard as a consulting entity on what is practical and what is not with some of the approaches being studied.

Question 4: Potential impact

This project was rated **2.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Because MeOH has a higher density than H_2, DMFCs could provide higher total system specific power and power density than H_2 proton exchange membrane fuel cells (PEMFCs) if DMFC power densities can be improved. If there is carbon-neutral methanol available, this could provide a path for decarbonizing energy-intensive applications.
- Unfortunately, the stated impact of the project is not well aligned with the focus of this project; it is not really clear why DMFCs are attractive for “forklift and stationary power applications” (Slide 2) or how this project will help to enable these applications. Nevertheless, DMFCs can potentially be used in a variety of

applications, if the performance and cost are substantially improved. DMFCs are not a major focus of the Hydrogen Program (the Program), which is understandable since substantial improvements to this technology are probably required in order to make DMFCs commercially viable for anything other than some niche applications. However, the Program should continue to invest a small amount of its funding into fuels for PEMFCs other than hydrogen since this gaseous fuel is not ideal.

- The potential impact of a technology (stationary DMFCs using pure methanol as the fuel) powered by methanol and emitting CO_2 is nebulous and inconsistent with the worldwide direction toward hydrogen and zero-emission goals. It is uncertain whether the project should continue to be pursued other than as a curiosity or as a U.S. Department of Defense application. DOE has driven three or four fuel cell technologies to market. The cost of developing a technology to the demonstration stage has taken at least $1 billion per technology and decades per technology. Developing to market such a technology (stationary DMFCs using pure methanol as the fuel) will take a billion dollars and decade(s).
- While DMFC certainly has its place, how DMFC improvements fit into the Program's long-term goals could have been better discussed. From the technology transfer activities, it appears that a quite small application has been targeted. It is unclear what would have to improve to increase the application of DMFC toward broader applications.
- The peak power density goal and catalyst loading goals do not seem impactful, as these targets have been achieved by others in the DMFC field.
- The impact of MeOH fuel cells is difficult to comprehend without any information on durability.

Question 5: Proposed future work

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

- Future work was proposed. However, the project is complete at this time.
- The project has ended.
- The project is completed.
- The comparison of the MeOH fuel cells being developed under this work with battery drones was confusing. It was not clear what the application of the fuel cells developed here will ultimately be.

Project strengths:

- Overall, the project did a good job of outlining the current limitations of DMFC and working to directly attack the most significant hurdles that the industry faces. Significant progress was made as compared to literature data toward the project goals.
- The researcher is an excellent, knowledgeable, and open researcher, fully expert in all the details of the project.
- The project team and approach are strengths. Some good technical accomplishments were achieved.
- The project had a good team that utilized key capabilities from multiple institutions.
- Non-PGM catalyst work was a strength.
- Catalyst fundamentals were a strength.

Project weaknesses:

- While methanol poisoning was discussed at length, it was not clear if there was a concern of CO intermediate poisoning on the anode. Some work has been published investigating additional ternary allows that could allow for further mitigation. With regard to the membrane, it was unclear whether the project investigated O_2 permeability due to the very high differential pressure favoring the cathode. Additionally, it was unclear whether fuel crossover had been studied as a function of thickness of the membrane. That would be a way to improve fuel efficiency. Seemingly, the project did not identify the degradation mechanism, given that the degradation rates are quite high (1–2 mV/hr vs. µV/hr expectations for other fuel cell types). It should be clarified whether degradation is simply catalyst poisoning (whether MeOH or CO) or whether other things contributed to membrane degradation and thinning, which can cause cascading crossover effects. Finally, for the modeling work, limiting current, crossover current, and high frequency resistance were called out as fitted values. Since it appears that, to some extent, experimental data for those values does exist, perhaps a study should be conducted on whether their incorporation (i.e., fitting fewer other values) improves the quality of the modeling.

- The principal investigator should not use the title “Technology Transfer Activities” for work that does not actually involve any direct interactions with other institutions. Simply presenting that DMFCs may be an option worth consideration in unmanned aerial vehicle applications is not at all “tech transfer.”
- Methanol crossover remains a great problem. The cathode is made less reactive to eliminate the reaction there.
- The work being conducted is impractical from an application perspective.
- The project did not seem to have reached its budget period (BP) 2 or BP 3 goals.
- Performance under pure MeOH was low.

Recommendations for additions/deletions to project scope:

- The Program should consider investing in liquid fuel options that have not received much attention to date but have the potential to be more viable than methanol. One option is aqueous rechargeable liquids that can be reversibly hydrogenated and dehydrogenated electrochemically, which is a much broader class than conventional liquid organic hydrogen carriers. More on this topic can be found in M. L. Perry, “Electrochemically-Rechargeable Liquids in Highly Flexible Energy Storage Systems,” *ECS Transactions* 104 (2021), DOI 10.1149/10401.0023ecst.
- Effort should be spent on validating application potential and durability.
- If the project continues, national laboratory involvement should be increased.
- Membrane work should be incorporated in any future work.
- There are no recommendations. The project has been completed.
- Recommendations are not relevant because the project has ended.

Project #FC-323: Durable Fuel Cell Membrane Electrode Assembly through Immobilization of Catalyst Particle and Membrane Chemical Stabilizer

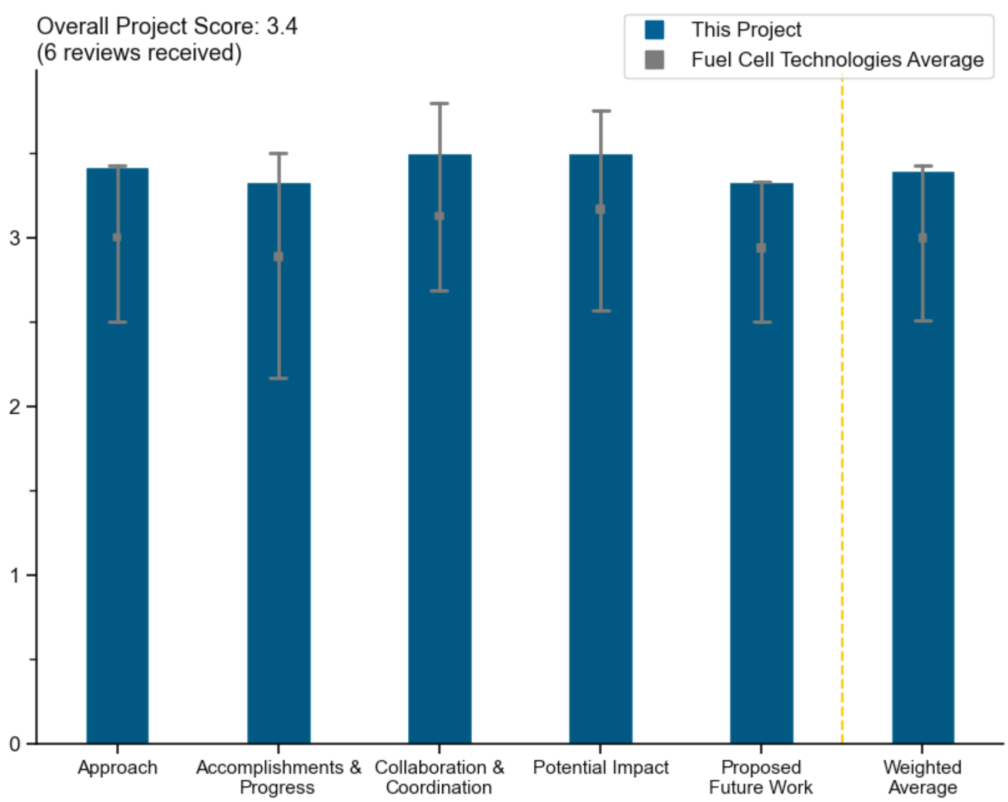
Nagappan Ramaswamy, General Motors, LLC

DOE Contract #	DE-EE0008821
Start and End Dates	10/1/2019–5/31/2023
Partners/Collaborators	3M Company, Pajarito Powder LLC, Colorado School of Mines, Cornell University, M2FCT Consortium
Barriers Addressed	• Durability: <10% power degradation after 30,000 hours • Cost: ≤0.2 mg_{Pt}/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 more durable membrane materials for use in direct hydrogen-fed proton exchange membrane fuel cell (PEMFC) membrane electrode assemblies (MEAs) in medium-duty and heavy-duty truck applications. The materials will feature low cost (using less platinum group metal), high fuel efficiency (greater than 65%), and high durability (lifetime of one million miles). If successful, this project will deliver highly durable MEAs for PEMFC applications to enable use in heavy-duty trucks and will elucidate the fundamental degradation mechanisms.

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 project is delivering durable MEAs based on improved anchoring of Pt on carbon support and Pt–ionomer modifications, including doping of the ionomer with heteropoly compounds and cerium. The project tasks are executed in a synchronized manner between the participants. Focus has been placed on improved durability for heavy-duty applications. The research efforts are well defined between the participants, including the deliverables and achievements. The project is also relying on the Million Mile Fuel Cell Truck (M2FCT) infrastructure to utilize unique expertise and capabilities within the consortia. Based on the timeline, recent achievements, and the fact that this will be the final year of the project, the approach in this effort is well justified.
- The scope and approach were focused on very relevant challenges facing broader PEMFC commercialization (stabilizing the Pt catalyst and maintaining membrane lifetime). To speed up progress on meeting these objectives, it is recommended that all DOE projects clearly identify gaps for each review period in a self-review and address these gaps in their paths forward. Regarding Pt stabilization, the approach is consistent with other work in the field, and the project demonstrated good execution, as highlighted by the spectroscopy. It was unclear whether the improved mass activity and power density at end of test was due to the Zr treatment or the mesoporous catalyst as compared to the high-surface-area carbon (HSAC) baseline. Further, based on the Pt utilization, a de-rate at lower relative humidity (RH) is expected. It is unclear how this will impact larger-scale, system-level testing and whether there will be a gap in the approach moving forward. Regarding membrane stabilization, with the goal of mitigating cerium (Ce) migration in the MEA, it was unclear how this compares to a standard powder material. The x-ray fluorescence (XRF) mapping clearly showed dissolution for both the heteropoly-acid–tungsten (HPA-W) and Ce nanofibers. It is unclear whether this was better or worse than current commercial solutions—and by how much. It would have been good to include an antioxidant baseline in the analysis and compare dissolution/migration rates throughout the testing and perform a cost–benefit analysis of these materials moving forward. The $CeNO_3$ clearly met the membrane durability targets, so it is unclear why this was not used in the Ce migration study. Further, feedback from 2021 asked if both membrane concepts could be combined, and the response was no, because they were both addressing the same problem. Given the current results showing a difference between the HPA vs. mechanical ceria-zirconia (CZO), perhaps both approaches could be effective for both chemical and mechanical mechanisms.
- Since both membrane and catalyst advances are necessary to achieve M2FCT targets for MEA durability, the proposed approach of parallel catalyst and membrane development is logical. It is not clear why the catalyst mass activity goal is only 30,000 cycles (instead of 90,000), and the platinum loading target (0.25 mg/cm^2) is much lower than what M2FCT is targeting. The 30,000 cycles is less challenging, while the loading is unnecessarily more challenging.
- The approach is excellent, with a carefully considered plan that is sharply focused on the most critical aspects of MEA performance and durability.
- The project approach is excellent and is directed at addressing the key heavy-duty fuel cell barriers of electrocatalyst durability and membrane durability.
- The approach is relevant from a scientific and industrial point of view.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The project has made good progress toward achieving project and DOE goals, specifically toward the catalyst. The ZrO_2-stabilized Pt on engineered carbon supports (ECSs) resulted in significantly improved performance and modestly improved durability after 90,000 cycles (slide 9). Per slide 9, a key challenge with the ECSs is reduced Pt utilization at low RH, potentially due to the presence of Pt within the pores of carbon with limited ionomer access. The membrane development approaches appeared to make progress in some areas but had shortfalls in others—e.g., the perfluorosulfonic acid (PFSA)+HPA blends showed improved open-circuit voltage (OCV) chemical durability, but the approaches did not appear to improve the durability over baseline under the combined chemical–mechanical test.

- Regarding Pt stabilization, good progress was made on targets (mass activity, power density per gram of platinum group metal); however, the area power density target was not achieved, and the percent mass activity loss was on the edge. It would be good to provide confidence bars on this metric. There was also some conflicting data on the Pt dissolution compared to baseline. The inductively coupled plasma mass spectrometry (ICP-MS) (slide 10) showed no difference in Pt dissolution; however, the particle size distribution showed a distinct difference in the Zr-treated sample. The presentation mentioned some anomalies in the Pt mass balance. It is recommended that the researchers look at Pt in the membrane to understand the difference between the treated and untreated catalyst. Another oddity was the corrosion conclusion in which the Zr treatment had greater carbon loss signal; however, the Pt utilization vs. RH trend remained unchanged. It would be expected that as you oxidize the carbon surface, you will activate Pt in the interior of pores, increase water sorption, and increase Pt utilization, as shown in the HSAC baseline sample. This did not occur in the Zr-treated sample. The presenter did not say whether there were any other clear corrosion signals. Further clarification of this behavior is required. Regarding membrane stabilization, the HPA exceeded the chemical stability goal and failed the mechanical durability; however, the summary table did not show clearly whether the CZO met the >500 hr target. It is not clear whether either of these were better than the $CeNO_3$ baseline shown in the summary chart on slide 4.
- The project accomplished technology advances both for catalysts and membranes that are relevant to heavy-duty fuel cells. The technologies clearly improve upon the project's baseline materials. It is not clear whether the technologies will meet the new M2FCT AST targets.
- The project is practically ended, with excellent accomplishments.
- Overall progress and accomplishments in this project have been excellent. Minor criticisms are that the "Pt–ionomer interface modification" approach was not discussed, aside from a brief mention that the approach had not been successful, and that no work on improving efficiency was reported. (The response to reviewer comments indicates that "our ultimate focus is to deliver an o-PtCo catalyst," but the project is essentially over, and no work on PtCo was reported in this presentation.)
- The project made incremental improvements in MEA performance. Most of the milestones associated with the go/no-go decision-making points are completed. The remaining efforts are dedicated to MEA optimization based on achieved strategies to improve durability. The project made progress by introduction of ECSs. The Pt-carbon interface was modified by including zirconium in the carbon support to better anchor Pt particles while maintaining high porosity and graphitization of carbon. Pt/ECS-ZrO_2 showed improvement in mass activity due to increased Pt content inside the pores, which leads to improved voltage at low current densities. The same catalyst exhibits improvement in electrochemical surface area and cell voltage at high current densities. Structural characterizations confirm homogeneous dispersion of the Zr that surrounds Pt particles. In addition, the effort focused on the membrane blended with HPA showed some loss in conductivity and difference in the hydrogen–air polarization curve during MEA testing. The PFSA-PFSA/HPA blended membrane exhibited improved durability, even with increased crystallinity, due to expanded polytetrafluoroethylene (e-PTFE) reinforcement, and 10 wt.% HPA blended membranes had higher water uptake due to the synergistic effect of sulfonic acid and HPA. The reinforcement by e-PFSA improved the mechanical property, and hence, the tensile strength was increased by a factor of two. Lastly, the CZO nanofiber additive showed improved chemical durability both in OCV durability and combined chemical–mechanical durability evaluations. Overall, the progress and accomplishments do show certain improvements. Nevertheless, the presentation and work performed fall into trial-and-error types of activities, with an obvious lack of systematic investigation. It seems that many different additives were evaluated, but it would be challenging to select what the real progress was in the design of MEAs.

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 project has a well-defined network of collaborators and participants, including connection with the M2FCT and national laboratories. The selection of participants is well balanced, and the roles of participants are clearly identified.

- There was very clear collaboration and coordination between project partners and the M2FCT. The only recommendation to bring further coordination would be to include a gaps table with input from all parties, including from M2FCT. Discussion on the perceived technology readiness levels (TRLs) for each concept would be beneficial moving forward.
- The collaboration and coordination within the project appear appropriate. The collaboration appears largely in two groups: (1) the catalyst group and (2) ionomer groups. (They did not appear to overlap, which is likely appropriate.) It was somewhat unclear which partners conducted which specific parts of the work, e.g., slides 9 and 10.
- The project showed excellent collaboration between General Motors (GM), 3M, and Pajarito Powder. Two universities were also involved, but the impacts of their contributions were not highlighted as strongly in the presentation materials. For example, it was not clear whether Colorado School of Mines developed any of the membranes.
- This is a highly collaborative project, both within the project team and with M2FCT.
- The project was well coordinated with the M2FCT consortium.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project targets are very well aligned with the Hydrogen Program. The progress made in this project provides potential solutions for further development and necessary understanding to drive broader commercialization. It is imperative that the challenges and gaps are overcome and evaluated as soon as possible in stack/system-level testing to determine the broader impact on the industry.
- The potential impact of improved MEA performance and durability through improved catalysts and membranes developed in this project cannot be overstated.
- The outcome from the project is beneficial to identifying the level of improvement in MEAs by different approaches used in the project. The project cannot be seen as highly innovative; however, the team's strong technical background comes with a substantial level of confidence that each task is properly evaluated. The project is expected to have a modest impact in terms of novelty but might have a compelling technical footprint.
- The project has demonstrated good advances toward development of ZrO_2 stabilized catalysts with high gas accessibility via engineered carbon. It is suspected that these approaches can be integrated with more advanced catalysts than pure Pt, enabling further improvements in performance/activity. However, the key gap with this approach that appears to remain is poor catalyst utilization at low RH, which may be intrinsic to the "catalyst buried within carbon pores" approach.
- The project is targeting the critical areas needed for successful implementation of fuel cells in heavy-duty vehicles.
- The project results will have an impact on the integration of domestically manufactured electrocatalysts into fuel cell systems of U.S.-based car manufacturers.

Question 5: Proposed future work

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

- The project end date was May 31, 2023, with remaining work focused on documentation and publications. Future work is to be done internally at project partner organizations.
- This is the last year of the project, and the listed set of activities is in line with the future work that should emphasize the final outcome through publication and presentations, deliverables, and scale-up of materials developed in this project.
- Given that the project is essentially over, there is not much future work, but some more discussion of overall next steps for the technology would have been helpful.

- The project only has one month remaining, so work is focused on product dissemination.
- The project has ended.

Project strengths:

- This project is executed by the leaders in commercialization of fuel cell technology. A well-balanced selection of topics presents a compelling and properly diversified strategy to tackle durability issues in fuel cells. Engagement of several industry partners warrants a highly technical and executive approach in addressing each task. Developed materials and strategies to mitigate degradation in MEAs could be applied immediately in MEA manufacturing, which would facilitate deployment of heavy-duty vehicles.
- The project was focused on two very important technical challenges for broader PEMFC commercialization. Progress was made with improved end-of-test catalyst performance and potential solutions for enhanced membrane lifetimes. Further, the project collaborators appeared to be well coordinated, with all contributing to the success of the project. A clear path forward for these materials was identified for development in GM’s internal programs.
- The project consists of a strong team with excellent material and characterization capabilities. Led by GM, the project is aligned tightly to key gaps for commercial heavy-duty fuel cells.
- The project brings together an excellent team to tackle some of the most critical challenges in MEA design for heavy-duty vehicle applications.
- The project is targeting the critical areas needed for successful implementation of fuel cells in heavy-duty vehicles and has a good team of collaborators.
- The project has ended and achieved all milestones and go/no-go design points.

Project weaknesses:

- Identifying gaps would be beneficial to better understand the remaining challenges with a broader view on (1) how system operating conditions might affect the performance of these concepts (e.g., low utilization of ECS catalysts under dry conditions) and (2) whether these concepts clearly outperform incumbent technology (e.g., whether the CZO slows down Ce migration compared to the CeNO3 incumbent). It would also be beneficial to discuss the perceived TRLs for each concept, with commentary on the manufacturability of each concept compared to incumbent baseline technologies.
- The weaknesses are reflected in the lack of a systematic, rationally based strategy to select materials and explore their properties in a novel fashion. Instead, the project appears to be a trial-and-error type of effort that utilizes already known concepts. Most of the MEA durability tests were done for 30,000 cycles. Considering the well-connected research infrastructure between the project and M2FCT, identical MEA testing protocols for heavy-duty vehicles would be expected, but this was not the case.
- It is not clear whether the technologies developed will meet the M2FCT targets, and the project has insufficient time for further development.
- More focus on increased efficiency would be appropriate.
- The stabilized additive approaches were not able to achieve the targets.

Recommendations for additions/deletions to project scope:

- Although the project has limited time remaining, MEA samples could be provided to M2FCT for benchmarking versus the state of the art.
- The project is in the final stages, and therefore, any recommendations for deletion or addition to the research scope would not be constructive.
- The project is ending and in the wrap-up phase.

Project #FC-326: Durable Membrane Electrode Assemblies for Heavy-Duty Fuel Cell Electric Trucks

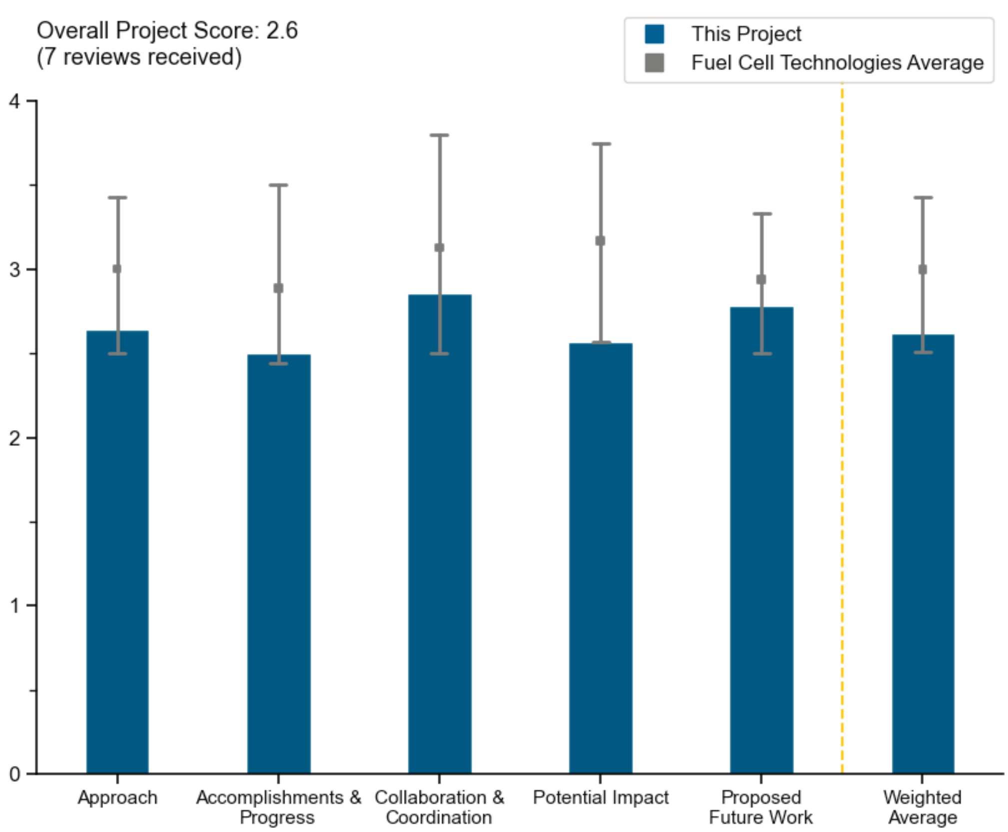
John Slack, Nikola Motor Company

DOE Contract #	DE-EE0008820
Start and End Dates	10/1/2020–12/31/2024
Partners/Collaborators	Carnegie Mellon University, Million Mile Fuel Cell Truck (M2FCT)
Barriers Addressed	• Durability: Improve stability of membrane electrode assembly for heavy-duty-truck-relevant operating conditions • 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 produce highly active and durable 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 **2.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is an innovative concept, and this project is well-designed, with a combination of experimental and modeling approaches. A good microscale model of this unique catalyst layer can enable insights into what is limiting the performance. If the modeling work is good, then this project has the potential to improve the community's understanding of proton exchange membrane catalyst layers (which should be a major goal of this project, in addition to striving to develop an improved catalyst layer architecture).
- The project goal is very relevant for proton exchange membrane fuel cell (PEMFC) heavy-duty (HD) development, where reducing local oxygen transport resistance (RO_2) will help meet cost and durability requirements. The approach to this problem is novel and has clearly demonstrated reduction in both the dependent and independent RO_2. However, this nanocapsule concept raises risks that may have impacts on broader adoption. Now that the team has been able to work through some key processing challenges, it is recommended that the project address the following risks to the overall approach:
    - The length scales for proton transport in water through the interior of the agglomerate are long, and it would be good to validate the total catalyst layer proton resistance as a function of relative humidity (RH) and compare to the model results presented. In addition, more operating condition sensitivities should be performed to understand whether any other limitations are being introduced. There is concern that lower RH performance will contribute to a lost proton path. It would be good to build on the work presented, as the performance data was quite noisy and had significant performance loss at higher current densities. Comparisons should be made to conventional structures and processes.
    - With such large (1 µm) particles, there may be layer uniformity issues that would introduce noise (as observed in the polarizations on slide 11) and potential issues at larger scale. Layer uniformity can also affect membrane degradation behavior and introduce early membrane failures. It would be good to show scanning electron microscopy (SEM) cross sections to better understand these risks.
- The project focus is on developing a novel cathode catalyst layer architecture based on "nanocapsules" that have a high ionomer–carbon (I/C) exterior and low I/C interior. This approach seems to have reasonable expected advantages for catalyst activity and O_2 diffusion, which would improve the efficiency of and performance of fuel cells for HD applications. It is not clear how this structure is expected to address fuel cell durability, and the project portions focused on catalyst development seem to have been downselected out. The nanocapsule approach seems to have significant potential risks or drawbacks related to manufacturability and cell integration, and overall, the approach seems to be a fairly narrow focus for a project of this size. There is a lack of work comparing the novel electrode architecture to conventional electrodes.
- The project approach is to develop a novel electrode structure based on a nanocapsule approach, consisting of a core catalyst with minimal ionomer content surrounded by a coating of ionomer. While conceptually interesting, it is really unclear whether this could ever be manufactured on a mass scale. (It is unclear what an "emitter"-based process at scale would look like.) Additionally, it is unclear whether there will be issues with ionic conductivity/catalyst utilization within the low-ionomer cores at low RH, a critical requirement. (All data presented was at 100% RH.)
- The project aims to improve Pt utilization and activity via limiting ionomer poisoning and improving mass transport of reactants to the catalyst surface. The proposed "ideal" catalyst layer architecture (and associated modeling) supports benefits of an ionomer-rich shell and carbon-rich core but is completely reliant on synthesizing said architecture. Relevant parameters to optimize have been clearly identified, but possible synthesis barriers did not appear to be identified prior to beginning work. It is unclear whether the electrospray process is scalable to ensure throughput and quality.
- The core shell concept is not defined clearly. Slide 7 does not make clear what the role of polyvinylpyrrolidone (PVP) in the nanocapsule is or what the emulsion is. It is not clear how feasible the electrospray approach is for mass production.

- While goals and milestones were listed, they were not described as explicitly as expected. It seems like there have been significant roadblocks that were not explained in the presentation. The whole year's work seemed to be targeted only at addressing the comments from the previous year's review, instead of also making new progress toward a durability result.

Question 2: Accomplishments and progress

This project was rated **2.5** for its accomplishments and progress toward overall project and DOE goals.

- Significant progress has been achieved on making catalyst layers with a novel architecture. It appears the team can now make nanocapsules with a variety of diameters, which could enable a wide variety of catalyst layer parameters. Exploring these parameters could lead to insights into the source of overpotential losses in these catalyst layers, especially if a validated model is developed. It is not clear how well the model fits the data or whether the modeling work is being used to direct what types of catalyst layers should be fabricated.
- Reasonable performance has been demonstrated with the nanocapsule electrodes so far, although without clear comparisons to conventional electrodes, it is not so clear what has been achieved. The principal investigator indicated that, so far, the uniformity of the nanocapsule catalyst layers was not good enough to enable clear comparison, but this is not a compelling reason not to present baseline comparisons. The catalyst down-selection was based on the supposed superior durability of the selected catalyst, although this is also somewhat unclear. The H_2/air performance of all three catalysts appears similar after the accelerated stress test (AST), and the selected catalyst performs significantly worse at beginning of test. It is not clear that the selected catalyst will give either longer life or better lifetime-averaged performance, given the presented data. Longer durability testing may be required to show a better end-of-test performance for the preferred catalyst. Recent results show an improvement in nanocapsule aggregate diameter, although it is not entirely clear that the single data point shown is not an outlier and that the process control required to get the needed uniform small aggregates has been achieved.
- The team demonstrated a clear impact on the sulfonate coverage and RO_2; however, it was not clear whether this benefited the performance and durability. It would be good to do both a performance and Pt dissolution durability comparison against a baseline with the same composition with standard processing. It would be expected that this concept may also have benefits on the Pt agglomeration rates and Pt transport into the membrane. Good progress has been made overcoming the major roadblocks (e.g., particle size). It would be good if this could be done even further and show the impact on layer uniformity. It would be good to determine whether there is a tradeoff between the particle size, layer uniformity, sulfonate coverage, and dependent/independent RO_2. It is not clear whether a dependence of the achievable particle size on the choice of catalyst and ionomer is expected.
- Overall, modest progress has been made. A limited set of durability tests was completed, additional modeling was done, and a good effort to decrease the nanocapsule agglomerate size appears to have occurred.
- Durability is in the title of the presentation, but the only mention of the actual durability of the catalyst was a brief mention of supplier AST tests. The only major accomplishment seemed to be an improvement of the catalyst layer production. There was also a good deal of comparison between the new catalyst fabrication method and the old, but there was no comparison to current state-of-the-art traditional catalysts. While the novel method and base science are very interesting, it would have been good to see more substantive comparison.
- The project has identified MEA components to be used in the project. It is unclear what rationale was used to determine optimum ionomer, membrane, and carbon support. The catalyst was chosen based on polarization performance after ASTs. The Supplier 3 catalyst had the lowest electrochemical surface area and voltage loss at 0.8 A/cm^2. Durability tests were not performed with the proposed catalyst layer architecture. No information about Supplier 3 and Supplier 2 catalyst composition was provided (Pt vs. PtCo or another Pt alloy). The primary accomplishment was achieving proper synthesis of catalyst particle nanocapsule sizes while preventing them from aggregating. Synthesis of ideal nanocapsules took 15 months and still needs to be optimized to ensure proper electrochemical performance and durability.

- The team has tested three catalysts in single-cell and short-stack. There is no mention of the number of cells/short stacks that were tested to obtain reproducible results. The mass activity loss for all the catalysts is much higher than the target <25%.

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 unfortunate that the novel catalysts from Georgia Tech and Northeastern University did not work out, but this is understandable. It is probably preferable to limit the catalysts here to more conventional materials, since there are plenty of parameters to explore here (i.e., the original project may have been overly ambitious and complex). The coordination with Carnegie Mellon University (CMU) seems good, but it is not clear that CMU's model has been validated or whether it is being used to guide the experimental work. The recent engagements with the Million Mile Fuel Cell Truck (M2FCT) consortium are good and should yield improved understanding of the catalyst layers being made here, and microscopy characterization can provide useful input to the catalyst layer model.
- There is good coordination with CMU and the National Renewable Energy Laboratory (NREL), both of which had a clear impact on demonstrating the project goals through modeling and characterization. The role of Georgia Tech and Northeastern University was unclear, given the evaluation and down-selection of commercial supplier catalysts; however, perhaps this was highlighted in past reviews.
- Nikola Motor Company (Nikola) is sending samples to national labs (the M2FCT consortium) for characterization and testing. Previously proposed collaborators were removed because of changes in scope of work. A majority of work seems to be performed within Nikola.
- In most slides, it is difficult to determine which members of the project team contributed. It appears that NREL has conducted some diagnostic measurements (sulfonate coverage) and CMU conducted some plasma-focused ion beam analysis of electrodes. Better leveraging of the great capabilities at the national labs and CMU would likely greatly accelerate progress.
- Roles for project partners were not presented clearly. It seems that CMU is providing characterization and modeling, while M2FCT is providing some characterization and diagnostics. This should be indicated more clearly in the future.
- The team has established collaborations with academic institutions and the M2FCT consortium. However, the role of academic institutions is not clear.
- There was some good explanation throughout the presentation of collaboration.

Question 4: Potential impact

This project was rated **2.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Novel PEMFC catalyst layer architectures are a worthwhile investment for DOE, since the majority of PEMFC work to date has been mostly simple variants of Los Alamos National Laboratory's 1989 PEMFC technology. This project can enhance the community's understanding of PEMFC catalyst layers, as well as having the potential to develop a PEMFC that has improved performance and/or durability.
- The potential impact of this project is high and will depend on the ability to mitigate risks and close any other gaps that exist to scale this technology to commercial levels. To this end, the team should highlight its views on technology readiness level and all key challenges and gaps to commercialization. Significant work is required to clearly show the performance and durability benefits and achieve the scaling-up milestone.
- The project will have an impact on materials advancement after successful testing of multiple larger-area single cells and short stacks.
- The nanocapsule technology has a reasonably clear route to improve fuel cell performance and efficiency, which would be useful for addressing the goals of the DOE Hydrogen Program. However, it is not clear how this approach addresses the durability needs of HD applications, which are a key consideration. Also, the nanocapsule structure does not seem conceptually ideal for a catalyst layer, and it would be good to see

comparisons to more different architectures. It is not clear how amenable the electrospray process is to mass manufacturing of catalyst layers in comparison to other processes.
- Modeling efforts at Nikola predict improved polarization performance at every point along the polarization curve vs. a "conventional" catalyst layer architecture. However, no experimental observations support this claim at this time, owing to the time needed to optimize nanocapsule synthesis. In addition, no ASTs have been performed to determine how durable the nanocapsule architecture is vs. a more conventional catalyst layer architecture.
- The system has potential, but without some durability testing or cycling data, it is hard to see how much of a realistic impact the technology would have. While the improvements to mass transport at beginning of life are good, it needs to be shown that those benefits are maintained over full useful life.
- The project is aiming at a key barrier: better utilization of catalyst for HD fuel cells. However, the approach has some real challenges, and progress appears to have been quite slow.

Question 5: Proposed future work

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

- The proposed future work appears appropriate.
- All activities identified in the path forward are clear and will help drive the concept further; however, presentation of key gaps and risk strategy would be desirable. With the project over 50% complete, it is underspending, and it is unclear whether the project will be able to achieve its goal to scale MEA production when there is considerable optimization remaining to clearly demonstrate improved performance and durability on top of the processing challenges that come with scaling up.
- Proposed future work seems reasonable overall but somewhat vague; it mostly seems to just be a continuation of current activities rather than a clear next stage. This will reasonably result in improvements to the MEA, but it would be good to see some expansion of the planned work.
- Proposed work is valuable in optimizing nanocapsule catalyst design, but based on the information provided, it is not clear that the work will yield valuable results in a reasonable timeframe. Possible barriers to further changing synthesis and the scaling-up process for large-scale MEA fabrication have not been proposed.
- The proposed future work is good, but it would be even better if the modeling work was used to guide the fabrication work, which does not appear to be the current plan. This will require a validated model in which the team has a high level of confidence, which may be challenging to develop but could substantially improve the effectiveness of the development process.
- It would have been good to see more detail in the test plans for evaluating durability. Most of the focus still seems to be on catalyst production development.
- The team has several tasks to be performed before the end of the proposed project end date (December 31, 2024).

Project strengths:

- This project did well in overcoming processing challenges to successfully demonstrate the nanocapsule concept and demonstrate reduced sulfonate coverage and reduced oxygen transport resistance. Further, there was effective collaboration to characterize and employ modeling to establish some design boundaries. Specifically, the maximum particle size versus proton conductivity relationship helped address risk. The path forward should build on this analysis to further de-risk the concept before scaling up the process.
- The nanocapsule electrode structure seems to provide reasonable opportunities to improve catalyst activity and oxygen transport from limiting ionomer coverage on the catalyst. This may lead to practical electrode improvements but also presents an opportunity to learn from the behavior of an unconventional electrode structure.

- The project has a good team with the appropriate capabilities, including relevant experience in both the unique experimental processes required and catalyst-layer characterization and modeling. The concept is innovative and outside the classic PEMFC catalyst layer "box."
- The presenter gave a great description of the progress made toward addressing the previous year's comments. Also, there are really interesting results with the insensitivity of Fickian diffusion to relative humidity.
- The nanocapsule design allows for improved mass transport of reactants.

Project weaknesses:

- Providing clarity in the following areas would strengthen this project and build confidence that this methodology can have significant impacts in the DOE Hydrogen Program:
    - Confirm and validate the modeling results through measurement of the catalyst layer proton resistance. Additionally, measurement of the Pt availability at lower RH is required to better define catalyst functionality.
    - Demonstrate the translation between measured low R_{O2} and performance and durability, as compared to conventional structures and processes. Further depth in the analysis, such as catalyst activity and a voltage loss breakdown as a function of current density, would be beneficial.
    - Identify gaps and develop a risk strategy for scaling this concept. Expectations on processing should be provided throughout to address high-volume manufacturing requirements.
    - Address the uniformity risk to membrane degradation (future action).
- The project appears to have some very significant challenges in terms of approach and execution. The nanocapsule approach challenges include (1) questionable manufacturability, (2) potential fundamental challenges associated with catalyst utilization within the nanocapsule at low RH, and (3) conceptual structural collapse of the nanocapsule with carbon corrosion.
- The project scope is relatively narrow, focusing only on development of nanocapsule catalyst layers. It is not clear how this approach addresses durability challenges for HD applications. The project is lacking in comparisons to standard baseline catalyst layers to help understand the impacts of the nanocapsule structure.
- Ideal structures seem difficult to make. At scale, a post-fabrication acid wash is necessary to remove stabilizing additives required for the electrospray process.
- It is not clear that this project is fully utilizing modeling; instead, it appears to be primarily empirically driven.
- The team should interact more with M2FCT consortium member labs.
- So far, the project does not address the main problem of durability of the novel catalyst design.

Recommendations for additions/deletions to project scope:

- Providing clarity in the following areas would strengthen this project and build confidence that this methodology can have significant impacts in the DOE Hydrogen Program:
    - Confirm and validate the modeling results through measurement of the catalyst layer proton resistance. Additionally, measurement of the Pt availability at lower RH is required to better define catalyst functionality.
    - Demonstrate the translation between measured low R_{O2} and performance and durability, as compared to conventional structures and processes. Further depth in the analysis, such as catalyst activity and a voltage loss breakdown as a function of current density, would be beneficial.
    - Identify gaps and develop a risk strategy for scaling this concept. Expectations on processing should be provided throughout to address high-volume manufacturing requirements.
    - Address the uniformity risk to membrane degradation (future action).
- The project team should consider developing a robust and validated catalyst-layer model. Ideally, this model should also be relatively simple. An approach to developing an analytical solution for multiscale PEMFC catalyst layers has been described by Rob Darling (e.g., *Journal of The Electrochemical Society*

2020), which may possibly be modified and used to model these unique catalyst layers (e.g., treat the nanocapsules as agglomerates). It is suggested the team focus on improving a fundamental understanding, as much as striving for improved performance. For example, varying nanocapsule size may help to differentiate between the impacts of changes in activity and ohmic and transport losses, especially if this is combined with state-of-the-art characterization (for key catalyst layer dimensions) and a validated model.

- It is essential for the project to compare novel electrodes to good standard baselines for the future budget periods. The project should consider whether there are any electronic conductivity issues in the catalyst layer or loss of catalyst utilization from the nanocapsule structure, which may block electronic conduction out of each capsule with an ionomer. This seems to have been assumed but needs to be measured with cell diagnostics such as impedance. The project should also consider the manufacturing aspects of the nanocapsule electrodes. Clarification is needed as to whether this electrode structure can be manufactured at a high volume for a reasonable cost.
- The project should conduct extensive performance and durability comparisons against state-of-the-art conventional electrodes and make an assessment toward whether the approach is worth continuing. Additionally, the project team should assess and report on the manufacturability of the nanocapsule fabrication approach using the emitters.
- It is suggested that parallel investigations into nanocapsule catalyst layer activity and durability be moved up in the timeline to ensure that the project can optimize for them, given how long synthesis has taken so far.

Project #FC-327: Durable High-Power-Density Fuel Cell Cathodes for Heavy-Duty Vehicles

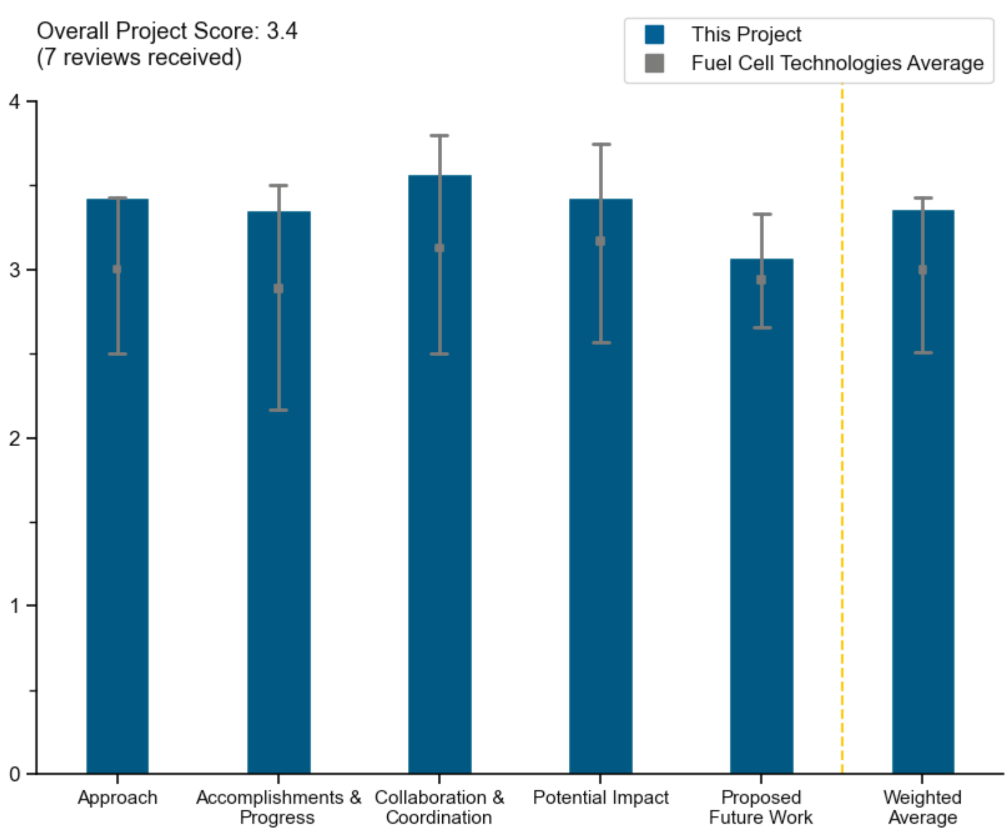
Shawn Litster, Carnegie Mellon University

DOE Contract #	DE-EE0008822
Start and End Dates	10/1/2019–3/31/2024
Partners/Collaborators	The Chemours Company, Ballard Power Systems, Inc., Million Mile Fuel Cell Truck (M2FCT) Consortium
Barriers Addressed	• Cost: Reduce proton exchange membrane fuel cell costs by reducing platinum group metal loading • Performance: Increase catalyst activity, utilization, and effectiveness by increasing solubility and permeability of ionomers • Durability: Increase the lifetime of proton exchange membrane fuel cells by reducing the loss of efficiency and power

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 cathode catalyst layer for heavy-duty vehicle 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.

- Developing high-oxygen-permeability ionomers (HOPIs) and addressing concerns for device integration appears to be an effective approach to improving fuel cell performance, efficiency, durability, and cost for both light- and heavy-duty applications. The presentation makes a clear case that HOPI provides significant durability and efficiency advantages for heavy-duty applications, and the value for light-duty is clear as well. Project activities cover the main important aspects of the topic, including diagnostics for fundamental understanding of HOPI, durability testing, and investigations of manufacturability.
- The focus on HOPI as an improvement in electrode performance is obvious and logical. The team has unique capabilities to perform novel materials synthesis and to perform the characterization presented. The focus on crack improvement is reasonable.
- The team has done a great job highlighting the limitations and addressing them. The focus on integration has allowed the team to surpass many of the initial hurdles.
- Improving oxygen transport in the cathode is key to improving performance and reducing Pt loading. New ionomers specifically designed for use in the cathode are an excellent approach to overcoming this barrier.
- Advanced electrode ionomer is a promising research area. Even for heavy-duty applications with relatively high Pt loading, the improved oxygen reduction reaction activity and oxygen transport give great benefits. Cost-wise, because Pt loading is already relatively high in heavy-duty applications, performance gain is limited by further increasing Pt amount. It is likely more cost-effective to invest in advanced ionomers. However, much effort was put into optimizing electrode coating and mud crack mitigation. These areas are very specific to the material sets and processes used, and the learnings are unlikely to be transferrable to other material sets or other labs. Therefore, they are not very valuable to the community.
- The approach is well designed. A recommendation is to correlate the flux-based measurements for oxygen permeation with the microelectrode-based studies. The latter provides both the diffusion coefficient and solubility. A proper correlation between the oxygen permeability and HOPI structure is an important outcome of this project.
- The presentation outlined the project goals and progress well. It would have been good to see more detail on cracking after the accelerated stress test (AST) instead of just during the manufacturing process

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- Good progress has been made on all the project tasks, making clear evidence for the advantages of HOPIs and providing useful fundamental understanding through diagnostics, modeling, and characterization. Good work was done to address comments from previous Annual Merit Reviews, including durability testing to understand the stability of the HOPI itself. Manufacturability research is addressing concerns about cracking and brittleness of catalyst layers fabricated with HOPIs. Results are being disseminated through publications and presentations.
- The team has shown new data on HOPI A and HOPI B that included additional free-standing film data, cell performance, and durability. HOPI-based electrodes clearly show improvements in performance, and the increased focus on durability is reasonable.
- The novel polymers have shown significant improvements in performance and durability compared to the baseline, especially at high current density and low RH. There has been good development of the fabrication process to consistently and repeatably benefit from the improvements in ionomer.
- The project has hit nearly all of its goals and has surpassed nearly all of the performance technical targets. The researchers have developed some important insights that will be useful for other systems and materials.
- The project was able to replicate many of the findings demonstrated earlier. Modeling of the HOPI molecular structure and the effect on oxygen permeation is interesting and may be useful for future materials development. Reduction in electrode degradation rate is worth deeper investigation, as the reason

is unclear. The principal investigator has the capability to do degradation modeling. It would be interesting to elaborate the mechanism. The testing should also be confirmed in other labs. It is unclear what ASTs were used. Unfortunately, the most promising results were achieved only on non-state-of-the-art catalysts. It is necessary to understand why improvement was not obtained on state-of-the-art mesoporous carbon or Pt alloy catalysts.

- There were many very clear accomplishments that were outlined in the presentation. The HOPI B post-AST polarization curve is higher than the beginning-of-life sample in the mass transport region, which begs the question as to whether the sample was adequately broken in prior to the AST testing. If the polarization is still increasing, cycling should continue until a degradation rate can be determined, or a different break in procedure should be established to be able to meet peak performance sooner. Clarification is needed as to whether the current format of the AST does enough to address the brittle nature of the HOPI layer. More dramatic RH swings and post-test imaging should be performed to determine whether the cracking issue is resolved for lifetime durability.
- The accomplishments are well in line with the timeline of this project. However, it is important to design deposition methods that would entail lower variation of ionomer–catalyst interactions.

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 good integration between team members and the Million Mile Fuel Cell Truck (M2FCT) consortium. Results from the different labs are clearly focused to address the project goals, and key project tasks appear to have input from multiple partners combining their strengths.
- The mix of team members is appropriate, as well as the engagement with M2FCT. In particular, the participation of Chemours in this project is critical to its success.
- There are very relevant and interesting performance test results from Ballard. The project has good collaboration with Chemours and M2FCT.
- Good collaboration between partners Chemours and Ballard is evident. Collaboration with the national lab partners is well under way.
- The team has good focus, with clear roles and responsibilities.
- The team has worked well together.
- Collaborations were well explained and defined.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has clearly demonstrated that HOPIs can have significant advantages for heavy-duty fuel cell efficiency and durability, which are key goals. While not necessarily transformative by itself, this appears to be a clearly valuable technology that can advance heavy-duty fuel cells and can be combined with advancements in catalysts and operating strategies. The project work is clearly addressing key barriers for the DOE Hydrogen Program and has addressed concerns about the viability of the HOPI approach.
- Improvements in performance are important and enabled through the use of HOPI materials. Durability is rightfully an increasing focus, owing to the critical nature of improved durability.
- Improved understanding of the catalyst–ionomer interface will lead to future advancement.
- This ionomer has the potential to address many of the cathode limitations targeted by DOE.
- Cathode performance and durability are key for heavy-duty vehicle applications.
- This project needs closer commercialization partners for scale-up and large-scale MEA fabrication.
- It would be good to see more information on the scalability of the process, but the improvements are very promising.

Question 5: Proposed future work

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

- The project is approaching completion within the next year, and much of the proposed work seems to be "wrapping up" the project work scope. Future work activities that are viewed as high-priority before the project ends include understanding whether interactions between the HOPI and the catalyst surface may influence the catalyst degradation directly (in addition to minimizing the negative impacts of surface area loss, which has been clearly demonstrated). For instance, the observed trends for the PtCo catalyst with HOPI (less roughness factor loss, more high-current performance loss) may suggest accelerated Co leaching.
- The future work seems to be a continuation of existing work, which is reasonable but not particularly compelling. Crack mitigation strategies are presented as continuing, but it is not clear that this is the primary or only mechanism of performance loss of concern. A stronger focus on degradation and mitigation would be preferred.
- If possible, the project should develop an O_2 solubility/diffusivity protocol for HOPI thin films that can measure these values for film thicknesses that are more relevant for catalyst layers, i.e., below 500 nm.
- Much of the future work centers around continued process improvements. Some focus should be placed on evaluating mechanical durability and cracking under mechanical strain.
- The output from this project needs proper commercialization partners for scale-up and implementation in stacks.
- The best features of polymer, catalysts, and supports tested should be combined into a best cathode.
- Future work in the last year appears to be a continuation of previous tasks.

Project strengths:

- The project has clearly demonstrated advantages of HOPIs for fuel cell efficiency and durability, which addresses key barriers for heavy-duty applications. The project is effectively contributing a basic understanding of HOPIs, as well as addressing concerns with manufacturability of HOPI-based electrodes. The team appears well-integrated.
- The project deals with one of the most important aspects of the performance and durability of an MEA, as it focuses on controlling oxygen permeability at the catalyst–ionomer interface. This is also the first line of defense for MEA durability, especially for its long-term stability under low-RH conditions.
- The project has demonstrated scaled synthesis with distinct control of material chemistry and properties. The team has conducted detailed analysis and correlation between material properties and performance. The emphasis on integration has led to significant performance improvements.
- The HOPI shows better diffusivity of oxygen and a reduction of platinum loss into the membrane. There is a solid foundation in this project on both the basic science and the application.
- Strengths include a strong team, relevant materials, and a novel approach. Results to date have been promising.
- This is a great team effort, with good results.

Project weaknesses:

- It does not look like the researchers have measured the impact of the HOPI chemistry on sulfonate specific adsorption. Loss of performance enhancement is occurring at higher cathode loadings. It is likely that the project will need to develop strategies to improve the mechanical properties of HOPI.
- There is not enough work on scale-up and commercial implementation in terms of stack performance and durability data. More concerted efforts on developing deposition methods are needed.
- An increased focus on degradation, and perhaps additional mitigation strategies, would be potential areas of improvement.

- The future work scope seems like it may be mostly just a continuation of ongoing activities, and distinct efforts for final project goals are not that clear.
- The project could have better post-AST imaging and characterization of the membrane and ionomer layer.

Recommendations for additions/deletions to project scope:

- This is a well-run project, and performance to date has been as per targets laid out for the project. However, this project needs careful consideration for scale-up of the MEA and stack results.
- Optimization of electrode coating and mud crack is very specific to the material sets and processes used, and the learnings are unlikely to be transferrable to other material sets or other labs. Therefore, they are not very valuable to the community. The project team is advised to focus efforts on learnings that are more valuable to the community, such as understanding the mechanism that leads to improved electrode durability with HOPI and understanding why HOPI did not perform as well on PtCo/high-surface-area carbon (HSAC).
- Increased focus on durability/degradation as the primary remaining barrier would make the most sense. The project could forego some of the more fundamental studies, including medium-duty simulations that are less likely to have an impact in the project time remaining.
- An important priority for upcoming work would be to understand whether HOPI interactions are altering the catalyst degradation. It would also be useful to consider testing with another catalyst such as an annealed Pt/HSC, which may be more representative of catalysts selected for heavy-duty fuel cells in comparison to higher-surface-area Pt/HSAC and PtCo/HSAC.
- Additional equivalent weights should be tested, and the team should find a way to indicate different side chain chemistry (without revealing proprietary information) to facilitate interpretation of results.
- The data shows that an improved break in procedure might be called for prior to AST testing to develop a true degradation rate.

Project #FC-330: High-Efficiency Reversible Solid Oxide System

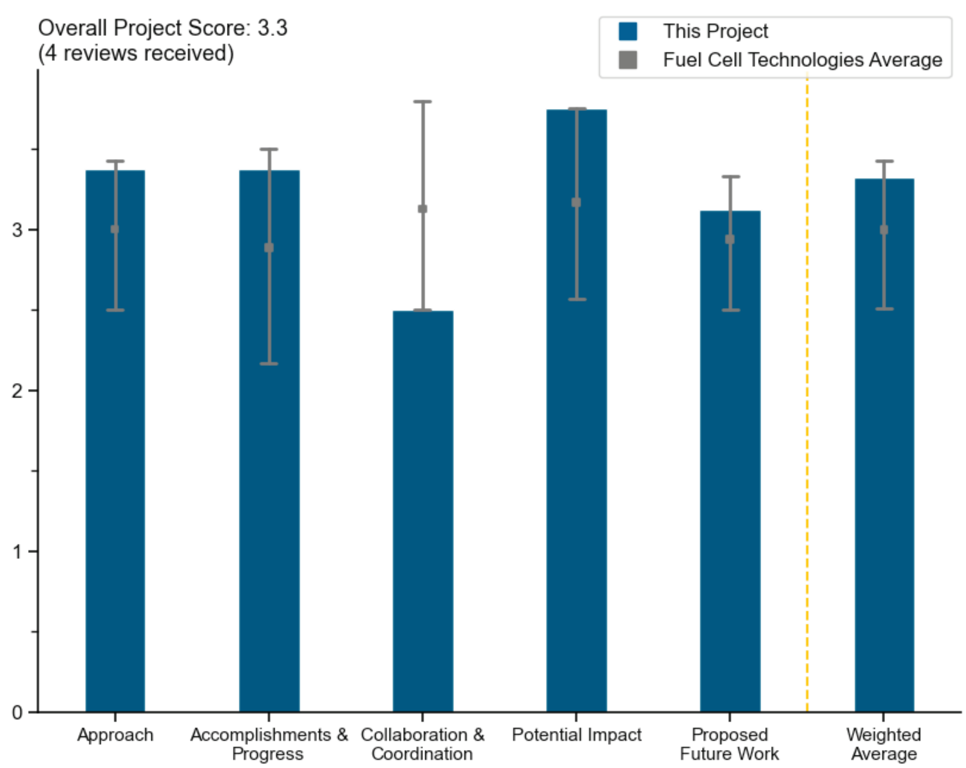
Hossein Ghezel-Ayagh, FuelCell Energy, Inc.

DOE Contract #	DE-EE0008847
Start and End Dates	10/1/2019–3/31/2024
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. Techno-economic analysis (TEA) will validate the projected system costs, which are expected to be \$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 RTE degradation of less than 5%/1,000 cycles 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 **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is excellent:
  - 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.
  - Perform RSOFC stack testing to validate system-identified operating conditions (such as stack pressure of up to 10 bar) and to verify RTE degradation of less than 5%/1,000 cycles over 100 cycles between fuel cell and electrolysis operating modes.
  - Build and test a thermally self-sustaining RSOFC demonstration system, rated at 3 kWe output and 15 kWe input, and verify >50% RTE (equivalent to >60% RTE in larger systems) and RTE degradation of less than 5%/1,000 cycles.
  - Develop a technology-to-market (T2M) plan, including commercialization strategies and product specifications, by organizing an industry committee consisting of utilities and potential users.
- The approach of targeting high RTE is a wise choice, even if it compromises the traditional target of high-current-density operation in fuel cell mode. Circular cells make sense for limiting delta T (the difference between temperatures) for thermal management in fuel cell mode. It is unclear whether the assembly cost would increase drastically if larger-diameter cells were employed.
- FuelCell Energy has extremely high-performing cells but chooses to operate their RSOFC system at very conservative current densities (0.2 A/cm^2 in the solid oxide fuel cell [SOFC] mode and 0.6 A/cm^2 in the solid oxide electrolysis cell [SOEC] mode). By operating at low voltages in the SOEC mode, cell voltages are below the thermoneutral voltage point, so energy will be needed to keep the stack hot. It seems that this would reduce system efficiency. No details were provided on the demonstration test system.
- The overall approach is energy-balanced. However, the maximum efficiency of SOFC using H_2 as fuel is 76%. On slide 15, the table shows power generation efficiency of 80%, which is questionable.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- More than 400 cycles at high RTE are shown. This is a significant accomplishment. The degradation also appears low.
- Good progress is being made. The focus is on demonstration. The project is achieving the major demonstration of a 150-cell pilot-scale RSOFC commissioned under the Hydrogen and Fuel Cell Technologies Office.
- Excellent progress has been made in both electrolysis mode and alternating SOFC and SOEC modes. The project achieved milestones in H_2 production rate, RTE, and degradation rate.
- Achieving >400 cycles over >2,000 hours in a 50-cell stack is a significant accomplishment, but 50-hour cycling times seem a bit too high relative to application requirements. Performance degradation levels seem relatively high but are reasonable given the state of RSOFC technology and the fact that FuelCell Energy is not scoped for cell development on the project.

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.

- The project demonstrated no university or national laboratory involvement, which may not be needed at the demonstration stage.
- It is hard to consider Versa Power as a collaborator since Versa is 100% owned by FuelCell Energy.

- A subsidiary of FuelCell Energy is the collaboration partner responsible for making cells and stacks.
- It appears that the collaboration is only with a wholly owned subsidiary.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- RSOFC is one of a few technologies with potential for long storage durations. Although there is a long way to go, FuelCell Energy has demonstrated the promise of its RSOFC technology for grid-scale, long-duration energy storage.
- The project goals definitely meet the DOE objective of developing an RSOFC product with high RTE.
- The progress made demonstrates the great potential of SOEC technology for high-efficiency production.
- The potential impact of the technology is great but was not adequately discussed. Not a single slide was presented.

Question 5: Proposed future work

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

- Future work is appropriately focused to complete the following:
  - 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.
  - Perform RSOFC stack testing to validate system-identified operating conditions (such as stack pressure of up to 10 bar) and to verify RTE degradation of less than 5%/1,000 cycles over 100 cycles between fuel cell and electrolysis operating modes.
  - Build and test a thermally self-sustaining RSOFC demonstration system, rated at 3 kWe output and 15 kWe input, and verify >50% RTE (equivalent to >60% RTE in larger systems) and RTE degradation of less than 5%/1,000 cycles.
  - Develop a T2M plan, including commercialization strategies and product specifications, by organizing an industry committee consisting of utilities and potential users.
- It is suggested that FuelCell Energy perform more single-mode electrolysis durability testing at multi-cell stack level for H_2 production, which is a major barrier for high-temperature electrolysis technology advancement. Performing more degradation diagnosis on the cells and stacks is also suggested.
- FuelCell Energy's future plans seem reasonable. Its plan to explore different conditions in its system makes sense, and the TEA may further inform condition space that should be explored. It is not clear what level of thermal integration is being attempted in the demonstration system.
- A clear understanding of T2M and TEA is pending. Results will provide guidance for the near-term applicability of this technology.

Project strengths:

- The project team demonstrates a good understanding of operating conditions for achieving high RTE. More than 400 cycles with stable performance in both modes is impressive.
- The project is demonstrating long-term, high-performance H_2 production at multi-cell stack level, which is the foundation of future high-temperature electrolysis H_2 production systems.
- FuelCell Energy is performing the work in a logical and relevant progressive manner.
- Project strengths are (1) high-performance cell and stack technology and (2) long-term durability testing as a major project focus.

Project weaknesses:

- Cell size is a great concern. The number of cells required for a large energy storage system using RSOFC may add complexity to the system and increase assembly cost. It is difficult to estimate the complexity of the gas manifolds and the manner in which hydrogen will be collected, especially if the electrolysis is done at pressure.

- Researchers need to be aware of the thermodynamic limit for alternating operation of SOFC and SOEC when reporting RTE value. The best way to report RTE is the ratio of energy in H_2 produced and total energy consumed to make the H_2. In addition, the degradation rate is still significant in the single H_2 production systems.
- Testing conditions may not be completely relevant to the application (e.g., low current density in electrolysis mode, long cycle times). Another weakness is lack of true collaboration.
- The project team needs to quickly organize an industry committee consisting of utilities and potential users.

Recommendations for additions/deletions to project scope:

- The TEA should clearly state the effect of cell size on the overall economics of implementing the technology.
- The project team should (1) double-check the efficiency numbers reported and (2) perform degradation mechanisms analysis.

Project #FC-331: A Novel Stack Approach to Enable High Round-Trip Efficiencies in Unitized Proton Exchange Membrane Regenerative Fuel Cells

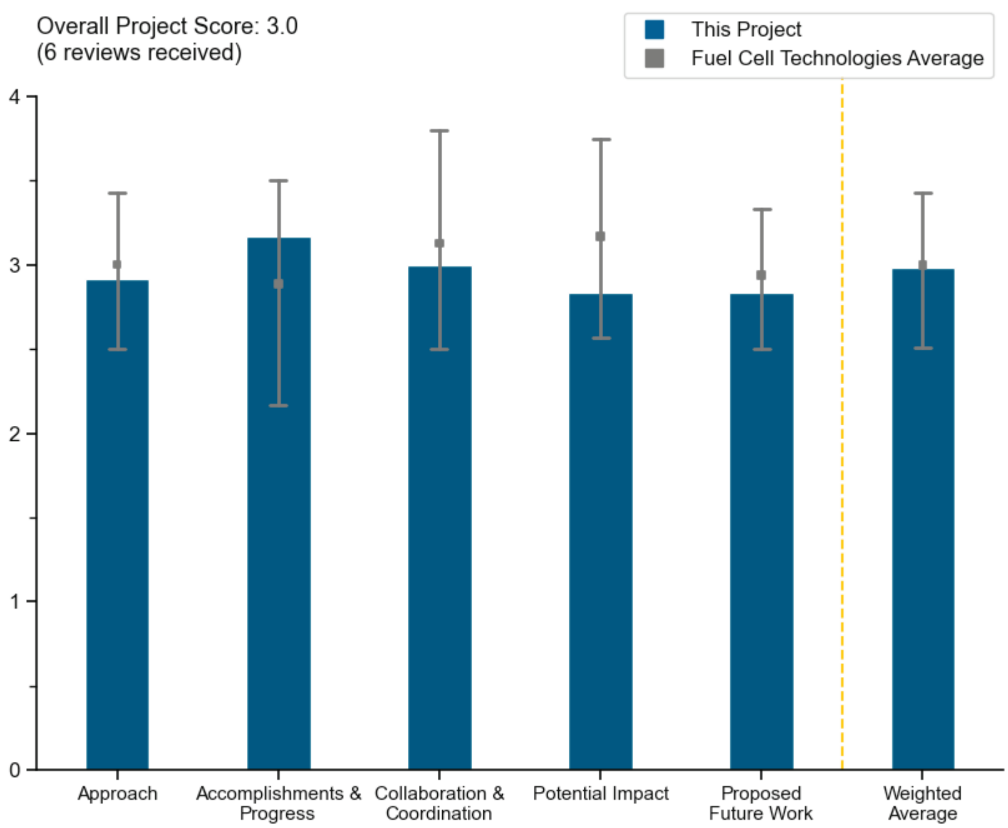
Katherine Ayers, Nel Hydrogen

DOE Contract #	DE-EE0008848
Start and End Dates	4/1/2020–3/31/2024
Partners/Collaborators	Electric Power Research Institute, Southern Company, Lawrence Berkeley National Laboratory, Gaia Energy Research Institute
Barriers Addressed	• No barriers specific to regenerative fuel cells • Barriers regarding optimization between fuel cell and electrolyzer: • 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 proton exchange membrane (PEM) technology that can achieve 50% round-trip efficiency (RTE) and reliable performance under relevant duty cycles, with projected costs below $1,750/kW. An early focus of this project is to develop a low-pressure electrolyzer membrane electrode assembly and stack design that much more closely resembles the fuel cell construction (i.e., 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 **2.9** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is an amazing project with an approach that could be developed only by a leading electrolyzer developer. The perspective is unique. The approach is tailored to achieve the goals by addressing the key challenges.
- While there are no specific barriers to URFCs, the project does an excellent job of outlining the barriers individually to electrolyzers and fuel cells and working to balance those into a most ideal URFC. The team should define how this reversible fuel cell (RFC) project differs from previous attempts known in the public domain. The overall approach is good and effective. The approach to work at stack level and build an integrated test system to demonstrate URFC is good. The system analysis and use case is also useful for determining an impactful use case for URFCs. The usefulness of the outreach task for this project is unclear. Perhaps its target is to educate the electric utilities, and that is why the Electric Power Research Institute (EPRI) is involved. It is not clear why there are two milestones related to demonstrating 100 hours of electrolysis operation (one in Fiscal Year [FY] 2021 Quarter [Q] 2 and one in FY 2023 Q1). The project should clarify if something changed to warrant another electrolysis durability test and explain the reason there is no milestone for fuel cell durability testing. It may be useful to have a milestone related to optimizing thermal management, pressurization, and water transport for the URFC.
- The goal of this project is daunting; work on RFCs has been pursued for decades, but the status of the technology is still a long way from being commercially viable for most terrestrial applications. The approach is good, with the overall strategy being to make the proton exchange membrane water electrolyzer (PEMWE) more like a proton exchange membrane fuel cell (PEMFC). This makes sense because the PEMFC supply chain is more mature than that of the PEMWE, and this project may thereby result in a spin-off benefit of improving the cost of PEMWEs. It is not clear what the actual targets are here with respect to both performance and durability (in either mode). The team should establish these targets and should consider the use of accelerated stress tests to assess durability.
- It sounds logical to leverage the principle of using the electrochemical cell for both directions of storing and consuming energy using hydrogen as the energy carrier, provided the stack is the most expensive component of the balance of plant (BOP). However, the targeted system scale is not clear from this presentation, being 50 W for the experiment or 500 kW for the model, and the expected cost breakdown for the system components for each case could help here (already requested last review).
- The challenge with the project approach is to start at the scale of a full stack. The RFCs face numerous technical challenges that are more appropriate to solve at the subscale/single-cell (full size) level. The key metrics for the project are loosely defined with performance and cost goals. There are no durability metrics. Nel Hydrogen (Nel) is a world expert in electrolyzers. Having just Nel work solely on both the electrolyzer and fuel cell technical challenges is surprising.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The project had excellent outreach and webcasts. Progress was made in identifying the key challenges:
    - Electrolyzers currently use thick membranes to tolerate the high differential pressure.
    - Modeling is needed to understand water transport in the URFC cell with respect to membrane properties and operating conditions.

  The work conducted on improving the performance and stability of cell operation has clearly been successful. There is good understanding of potential improvements that can still be implemented. Separate modeling shows how the operation time windows could change for different regions and applications (only briefly presented). However, collectively, these results do not underline any benefit of having only one (compromised) stack for electrolysis and fuel cell mode.
- The voltage and current plot as a function of time, demonstrating the 20 one-hour cycles accomplishment, shows that degradation is higher in fuel cell mode. It is good that the issue was identified as to why this was

happening (a mismatch in reactant feeds and stack temperature resulted in condensation) and resolved. It is good that the learning is shared with the community, but it is very generally described. More detail on the solutions would be beneficial to the community. It is not clear whether the size of the "one-cell URFC stack" (one cell is not a stack) used for the 20-cycle test was 25 cm2. If so, it is not clear that the cell size is sufficiently large to be useful. It is not clear whether the oxygen evolution reaction catalysts were tested with the Chemours reinforced membranes commercial catalyst, what the catalyst was loading, what the composition was, etc. More details should be given to the community. The targets for electrolysis and fuel cell mode to achieve 50% RTE should be clearly stated, along with what the achieved RTE is currently, from the test results. It is good to see that the electrolyzer continuum model fits the data well, as this gives confidence in the applied voltage breakdown to help guide where improvements can be made to improve the electrolyzer cell performance. It was not clear whether the model was validated with fuel cell data, too, or what it looks like. If the model was not validated, the team should explain. It is unclear whether the model can predict the durability of the URFC cycling between fuel cell and electrolyzer mode or whether the model can provide information about the operating conditions that will optimize the URFC performance and/or durability. It was unclear what will be done to translate the 25 cm^2 cell performance and durability to 86 cm^2 cell and then stack.

- The team has passed their budget period (BP) 1 go/no-go milestone and is continuing to improve the technology. Progress is being made, but since clear targets have not been established, it is not clear what the gap is between the performance demonstrated, to date, and what is required to be potentially viable. The fuel cell performance goal was not achieved at the stack level. The stack testing issues with the test stand/ test article point to a lack of priority on this project. More resources should be provided to this project so that it can get back on track.
- The project has satisfied nearly all of the targets to date, following the no-cost extension on BP 1. The fuel cell performance, listed as >0.75 V, is close to completion but not quite there yet.

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.

- It seems that appropriate partners are in the project to perform the tasks. The tasks seem to be independent and do not need much coordination between the project partners. Good progress and results for the tasks are shown from the project participants.
- The outreach component and modeling are good, although the impact of modeling results is not subtracted from the RTE.
- There is excellent collaboration with a national laboratory, industry coalition group, and a power company. No university was involved.
- The role of the project's formal collaborators is clear (e.g., slide 17), but it is less clear what each of these institutions has contributed to date in some cases. This includes Gaia Energy Research Institute, since it does not appear that much techno-economic analysis work has been done to date. EPRI has been engaged with the outreach efforts, but it is less clear what Southern Company is doing. It is also not clear why much outreach is appropriate in this project, since the technology readiness level of regenerative fuel cells is not high enough yet to warrant this work; however, educating utilities on how hydrogen can be used with more mature technologies (e.g., PEMWEs and/or PEMWEs + PEMFCs) is valuable.
- While it does seem that the various partners have accomplished what was designed, the input and contributions from the other partners are far less than Nel's scope. The scope that the other partners are contributing to the success of this project should be more clearly identified.
- Lawrence Berkeley National Laboratory (LBNL) is listed as a collaborator performing modeling. The fuel cell performance goal was met in a subscale cell. LBNL should be working with Nel to see how the performance goal in fuel cell mode can be achieved at the fuel cell size or stack level.

Question 4: Potential impact

This project was rated **2.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- While URFCs have a very small space in the hydrogen world, as compared to isolated electrolysis and fuel cell systems, this project is doing an excellent job of applying fuel cell methodologies and thinking to electrolysis. This could ultimately lead to changes in BOP and system development that benefit both electrolysis and fuel cells and should be a growing funding opportunity for DOE.
- Nel correctly identified the greatest market impact and role of reversible PEMs: long-term storage, greater than 8–12 hours.
- The overall RTE target is set high at 50%, limiting current density to a level at which separate fuel cell and electrolyzer systems have difficulty justifying the capital expenditure investment needed (return on investment). Even if the combined BOP could be significantly simplified (not clear), the current performance is 100 mV shy of the target (which could be improved in the next year), but it does not leave any room for the proposed electrochemical hydrogen compressor (EHC) step to be implemented. Bottom-line advanced material solutions are needed to allow efficient, pressurized operation in both modes, since more complex BOP (work-around solutions) will defy the purpose of using a single stack.
- This technology is not critical to the Hydrogen Program because the same objectives can presumably be achieved by using a combination of a fuel cell and an electrolyzer. The primary benefit would presumably be reduced cost with a single system, and some key targets for this technology should be established so one can assess the potential impact, which apparently has not yet been done. Crudely, one would expect that the performance may be roughly one-half that of state-of-the-art PEMFCs and PEMWEs, since only one device is required here and one could tolerate a cell that costs twofold.
- The approach of this work to start from a stack renders this project less capable of success than if Nel started from subscale experiments and modeling. As such, the potential impact of this project will most likely be limited to a demonstration-type project.
- Ideally, the URFC can be higher-efficiency and lower-cost, but it is not clear whether there is a market pull for this.

Question 5: Proposed future work

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

- Proposed future work is excellent:
    - Electrolyzers currently use thick membranes to tolerate the high differential pressure. Future work will involve retuning the cell design to enable the use of more efficient, thinner membranes.
    - Future work will leverage Nel cell optimization experience to make cell stack design compatible with efficient fuel cell operation.
    - Future work will utilize basic computational fluid dynamic modeling to optimize flow field geometry.
    - Future work will use the LBNL model to understand the water transport in the URFC cell with respect to membrane properties and operating conditions.
- All of the planned future work is good, but one additional item should be added: establish preliminary performance and durability targets.
- While left vague in some cases (refine system cost models), the remaining proposed future work does specifically target the remaining milestones that are to be accomplished during the remainder of BP 2.
- The “refine system cost model” is long due and should be updated continuously with a clear application and scale in mind. This would also dictate the type of drive cycle pattern. Interestingly, the target rated capacity of 1 A/cm^2 fuel cell current vs. 2 A/cm^2 electrolyzer capacity already implies that the energy consumption rate is half that of the energy storage rate, perhaps corresponding to a day–night cycle, so it is not clear how long-term storage fits into this application. A minimum of 200 hours of testing is needed to flag inherent issues when considering the burning-in timespan of applied catalyst-coated membranes.

- One of the proposed future work items is to demonstrate 200 hours of operation under down-selected duty cycles with 50% RTE. It is unclear how the duty cycles will be selected, whether they will be based on realistic operations for energy storage applications, and what criteria will be used. It is unclear that the EHC system and cost model will be useful. This task seems to be extraneous. It may be more beneficial to focus on system analysis and use cases and whole-system cost analysis.
- The team should focus on meeting performance goals for the RFC at the stack level and show at least 100 hours of continuous operation. Then the team could look at improving the durability.

Project strengths:

- This is a very strong project. It does an excellent job of evaluating URFCs, which are understudied as a whole. The work does a great job of taking highly studied aspects of fuel cell technologies and trying to incorporate them into electrolysis to try to toe the line in terms of the system differences and needs.
- The project partners have deep knowledge and expertise in the fields of fuel cell and electrolyzer systems and their operation.
- Nel and LBNL could be very strong collaborators if the partnership is aimed at understanding the fundamentals of gaps in achieving performance goals.
- It is a good team with a nice combination of experienced industry and national lab members.
- One of the most capable and relevant electrolyzer entities is leading the project.
- It is a good team. The team made good progress.

Project weaknesses:

- There are a few minor notes that can be addressed. It is unclear what Nel believes a realistic drive cycle is going to look like (hours electrolysis vs. hours fuel cell, operating conditions, complexity of switching between different operating conditions at changeover to/from fuel cell). Some of the data presented, including the key fuel cell data, is missing many operating conditions for reference. In the modeling work, while the agreement is, in general, quite good, there appears to be some deviation in Catalyst 2, 50°C, at higher currents. It is unclear whether Nel or LBNL has theories as to why and what can be done to improve those fits. It was mentioned that the cost target is $1,750 and that right now it is "about double" that target. More specifically, it is unclear which approaches are being implemented going forward to move toward the goal, or whether it is largely an improvement in manufacturing at scale that should be expected.
- The membrane material inherently suffers mechanical stresses when switching between immersed conditions in electrolyzer mode and "dry" conditions in fuel cell mode, and it is a well-known failure mode. It will be a huge challenge to run both modes efficiently with the same humidified gas conditions and deliver the same current density, but it is practically impossible to design a moisture-insensitive membrane. The application of thinner membranes may reduce resistance, but likely at the expense of lifetime.
- No fuel cell developer is included. If the goal is to "make a PEMWE more like a PEMFC," then it is unclear why a PEMFC developer is not included. Not enough emphasis is made on establishing key targets.
- Not much detail is included about components, materials used, or operating conditions.
- There is a lack of subscale understanding.

Recommendations for additions/deletions to project scope:

- There are no recommendations to change scope; the work is appropriate as designed.
- The project should openly compare its current stack/system cost structure projected at different scales and compare against alternative commercial solutions such as pumped hydro (large-scale) or redox flow (small-/medium-scale). This will highlight the scope of the current business rationale.
- It is unclear that the EHC system and cost model will be useful. The task seems to be extraneous. It may be more beneficial to focus on system analysis and use cases and whole-system cost analysis.

- The project should add university input in the area of membrane electrode assembly optimization and thinning.
- The project should establish preliminary performance and durability targets.

Project #FC-333: Advanced Membranes for Heavy-Duty Fuel Cell Trucks

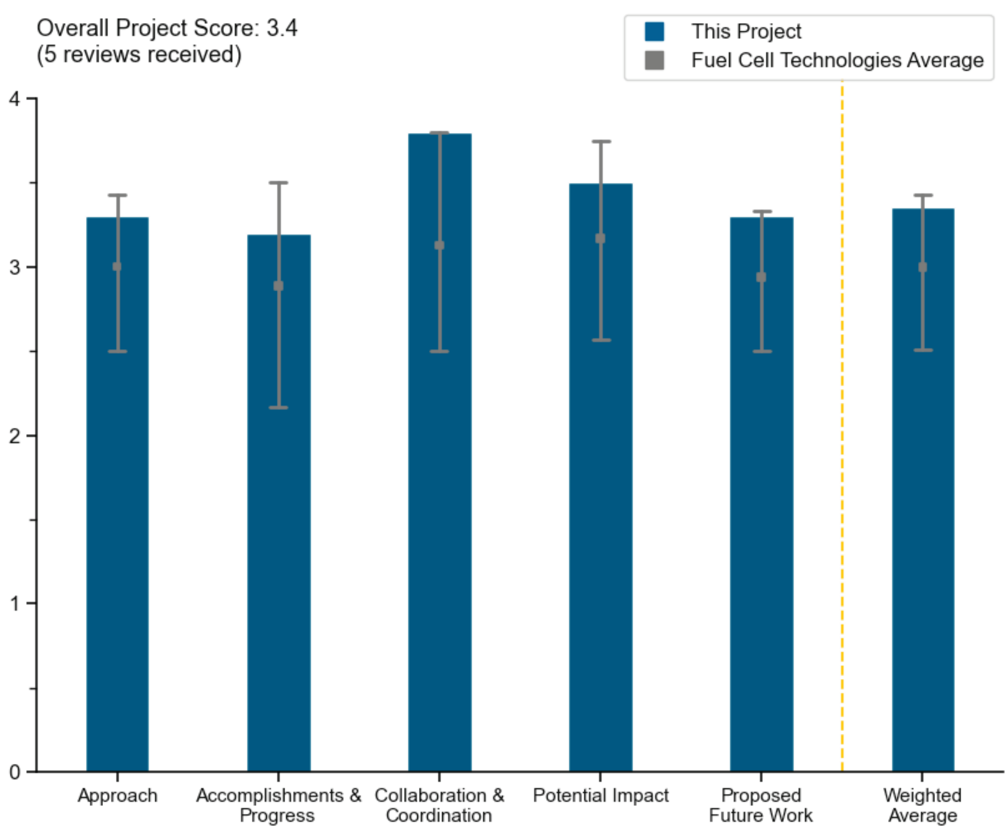
Andrew Baker, Nikola Motor Company

DOE Contract #	DE-EE0009243
Start and End Dates	10/1/2021–4/1/2025
Partners/Collaborators	The Chemours Company, Million Mile Fuel Cell Truck (M2FCT)
Barriers Addressed	• High-temperature and low-relative-humidity operation reduces conductivity and durability • Deleterious radical scavenger cation transport, especially at high temperature

Project Goal and Brief Summary

This project aims to develop membranes with optimized architectures that incorporate thermally stable ionomer chemistries and immobilized radical scavengers. If successful, the project will improve the lifetime efficiencies of membrane electrode assemblies in heavy-duty (HD) fuel cell vehicles, reduce the lifetime operational expenses of HD fuel cell systems, and improve their commercial viability relative to diesel energy sources. Nikola Motor Company (Nikola) is collaborating with The Chemours Company (Chemours) 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.

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 is taking all the appropriate approaches for assessing proton exchange membrane (PEM) composite durability and performance metrics for HD fuel cell vehicles. The project can be improved by understanding the structure and distribution of the weak acid polymer within the perfluorosulfonic acid (PFSA) blend. The M2FCT consortium partners should be able to help Nikola with this via advanced electron microscopy or x-ray scattering. The Fenton test should be abandoned. Although it is easy to perform, it is not recommended as a good predictor of a membrane's prospect to be stable in a fuel cell. It would have been helpful to see a techno-economic analysis on the manufacture of the new composite membranes with the weak acid monomer or weak polymer blended in. This should include the addition of cerium and the advanced cerium to the membrane matrix and reinforcement (HD-PFSA).
- The project has a major focus on immobilizing cation (cerium) additives for the purpose of increasing membrane durability. Other targets such as resistance, crossover, and mechanical durability seem to rely on state-of-the-art ionomer properties. The team has done a good job identifying two approaches to immobilizing additives: modifying the PFSA ionomer and blending a hydrocarbon that coordinates with the additives.
- Membrane durability is critical to achieving >25,000-hour operation in HD fuel cell systems. The approach builds on previous lessons learned to improve chemical stability of the membrane while also protecting it from attack by reactive species. Fenton's test is not the most representative test.
- This is a design of experiment to improve fuel cell membranes with cerium ions. The relative effect of the additive on durability conductivity and performance is not clear.
- The workplan should be a bit more systematic and designed to better deal with the issues that are appearing as the work is completed.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The Nikola team has shown the effectiveness of weak acids to strongly hold the cerium additive and prevent or minimize migration. Ideally, the weak acid functionality would be incorporated into the PFSA ionomer. The team showed progress to date, explained the issues encountered, and provided a plan to test alternative functionality for polymerization characteristics. This reviewer looks forward to next year's progress where weak acids are incorporated into the PFSA. The results show the hydrocarbon sulfonic acids are (surprisingly) good at minimizing cerium migration. This may have farther-reaching implications beyond stabilizing PFSA systems.
- Overall, progress is excellent. Most milestones have been met. The project has demonstrated significant performance improvement of HD-PFSA compared to current commercial PFSA membranes.
- The team has made progress on new membranes that satisfy or exceed area-specific resistance (ASR) and H_2 crossover performance metrics. The project also shows no significant membrane degradation after 3,250 cycles following General Motor's (GM's) highly accelerated stress test (HAST) protocol. However, there are conflicting (or confusing) results: the addition of hydrocarbon sulfonic acid (HCSA) and hydrocarbon weak acid (HCWA) lower membrane conductivity, even though an early slide shows the team exceeding state-of-the-art ASR. Perhaps the team helped this occur by using a thinner membrane (HD-PFSA).
- While the project has hit its early targets, there appear to be issues with the proposed Ce stabilizing chemistry, and it is not clear whether they can be easily addressed.
- The project addresses DOE goals, but this is not the first time this approach has been tried in this way.

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.

- Nikola has demonstrated effective collaboration with Chemours (new PFSA membrane development with weak acids; polymerization and testing of the project concepts via a blend of weak acid polymer with PFSA), Los Alamos National Laboratory (LANL) (cerium mobility testing), Oak Ridge National Laboratory (ORNL) (cerium particle imaging), the National Renewable Energy Laboratory (fuel cell testing and durability assessment), and Argonne National Laboratory (on-line inductively coupled plasma – mass spectrometry [ICP-MS] to monitor cerium dissolution from the membrane).
- Collaboration with two highly relevant industrial partners and very capable national labs (M2FCT) has resulted in excellent fabrication, testing, and analysis in a relatively short amount of time to expedite the membrane development.
- The collaboration with Chemours to identify a suitable weak acid monomer looks to be working well.
- It is good to see LANL has contributed cerium migration data and ORNL imaging data.
- Nikola is in close contact with DOE labs and team members to get feedback and guidance to develop these new membranes.
- The team is making good use of M2FCT resources.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- HD vehicles are ideally suited for conversion to fuel cell electric power trains because of the long-range requirements and large impact on transportation sector decarbonization. HD vehicles' use as fleet vehicles facilitates their market introduction, maintenance, and establishment of a suitable refueling infrastructure. Other vehicles will be able to benefit from this infrastructure build-out to accelerate adoption of hydrogen fuel.
- The project's approach and results to date demonstrate that the strategy of weak acid additives is effective for retaining cerium within the membrane. The HD-PFSAs with advanced CeO_2 are showing promising durability results after HAST. The project team's approach should be changed to create a more chemically resilient PEM in the near term over state-of-the-art NC700 (Nafion™). There are some conflicting results between conductivity and ASR, but the project team plans to use low-equivalent-weight ionomers to offset the conductivity losses from the addition of the weak acid. Hence, there seems to be additional optimizing steps the project team can take to further improve the membranes' performance while also enhancing stability and resilience for HD vehicle applications.
- If successful, the new ionomer materials have the potential to greatly enhance polymer durability at high temperature and low relative humidity (RH).
- The potential impact seems to be primarily in immobilized cerium. If these strategies are successful, one would expect this approach to result in increased membrane durability in line with project and DOE goals.
- This approach is reasonable but a small innovation that is an incremental improvement of water-based PEMs.

Question 5: Proposed future work

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

- Using low-equivalent ionomers is a good idea to offset the loss in conductivity by the addition of HCSA and HCWA. It is suggested that the project work with a university partner or national lab to study the phase behavior of the HCSA/HCWA-PFSA blends.
- The milestone-driven targets for future work are well organized. Demonstration of a PFSA terpolymer with improved cerium migration properties has the potential to advance durability of this class of membrane.

- The plan is excellent. The reviewer is looking forward to ASR data for the new membranes.
- The project needs to develop more defined strategies to address the limited degree of Ce immobilization in the composite polymer. The project should add water uptake and Grazing-Incidence Small-Angle X-ray Scattering (GISAXS) to look at phase separation under relevant conditions.
- There is little innovation proposed. There is only an offering of more of the same.

Project strengths:

- The project has made very good progress toward the project goal of realizing a more chemically stable composite PEM via the addition of weak acid polymers incorporated into the PFSA materials and use of an advanced CeO_2 additive. The weak acid polymer retains the cerium within the membrane (maybe via a chelating effect). The new composite membranes satisfy the project goals' ASR and H_2 crossover metrics. The HD-PFSA demonstrates little to no degradation after 3,250 cycles of GM's HAST. Nikola has done a good job directing the project and engaging all partners to achieve the project goals.
- The team is focused on understanding the fundamental issues associated with cerium migration and implementation of commercially viable solutions. There is good coordination among Nikola, Chemours, and M2FCT.
- This is a reliable lab and team with good resources for developing a targeted application (heavy truck power) to make a case for fuel cells in the transportation sector.
- Beginning-of-life performance of the Ce-stabilizing ionomer shows promise. Ce-stabilizing membranes show good stability.
- The project has a good approach and a strong team, and there is good progress to date.

Project weaknesses:

- The slides and presentation were confusing at times. It seems that the team has yet to test the fuel cell performance and durability with the hydrocarbon ionomer with weak acid groups in the PFSA, as mobility was not completely mitigated and the membrane conductivity was lower. Hence, the progress made by the team has been a reinforced PFSA polymer with advanced CeO_2 (doped material). Plans are proposed to improve membrane conductivity with the hydrocarbon weak acid ionomers by using lower-equivalent-weight PFSA materials. However, it is unclear what is being proposed to immobilize cerium better.
- It appears that the first proposed mechanism of Ce immobilization is not likely to work as intended. More characterization of the impact of polymer mixing is needed, i.e., water uptake, phase behavior as a function of RH, etc. The current generation of new Ce-stabilizing ionomer does not appear to perform any better than the commercial standard. The work needs to be more systematic in analyzing/characterizing the material properties of the new ionomer and for the development of strategies to address all of the limitations that are coming up in the work.
- The technology is not very innovative. The project is mainly using known technology at large scale to meet a targeted application.
- The project has not yet deconvoluted the effectiveness of HCWA itself in quenching radicals vs. using Ce as radical scavenger.
- This project is effectively a cerium migration project (which makes sense, given the small budget size).

Recommendations for additions/deletions to project scope:

- The project team should:
  - Perform parametric testing of hydrocarbon membrane and PFSA–hydrocarbon blends without radical scavengers to determine in which cases they are truly beneficial.
  - Study radical scavenging of polymer as a function of pKa.
  - Compare pure HC with Ce to PFSA with Ce.
  - Use a hydrocarbon membrane with the same crossover current as PFSA.

    - Consider replacing Fenton's test with more representative tests (e.g., 100-hour life tests at steady-state, dry conditions).
- The Nikola team looks to be addressing the main challenges with cerium immobilization. Implicit in this work is the need to show cerium is still effective, even if it is held captive by a weak acid. This is an implicit goal of the project but could be added as an explicit goal.
- The dramatically lower conductivity of the PFSA–hydrocarbon blends is a puzzling result and should be further explored with the M2FCT team.
- The project should innovate more. The team should consider higher-temperature proton conductors, such as ion-pair, protic ionic pendant groups, etc., to minimize water in the membrane as a route to membrane improvement.

Project #FC-336: A Systematic Approach to Developing Durable, Conductive Membranes for Operation at 120°C

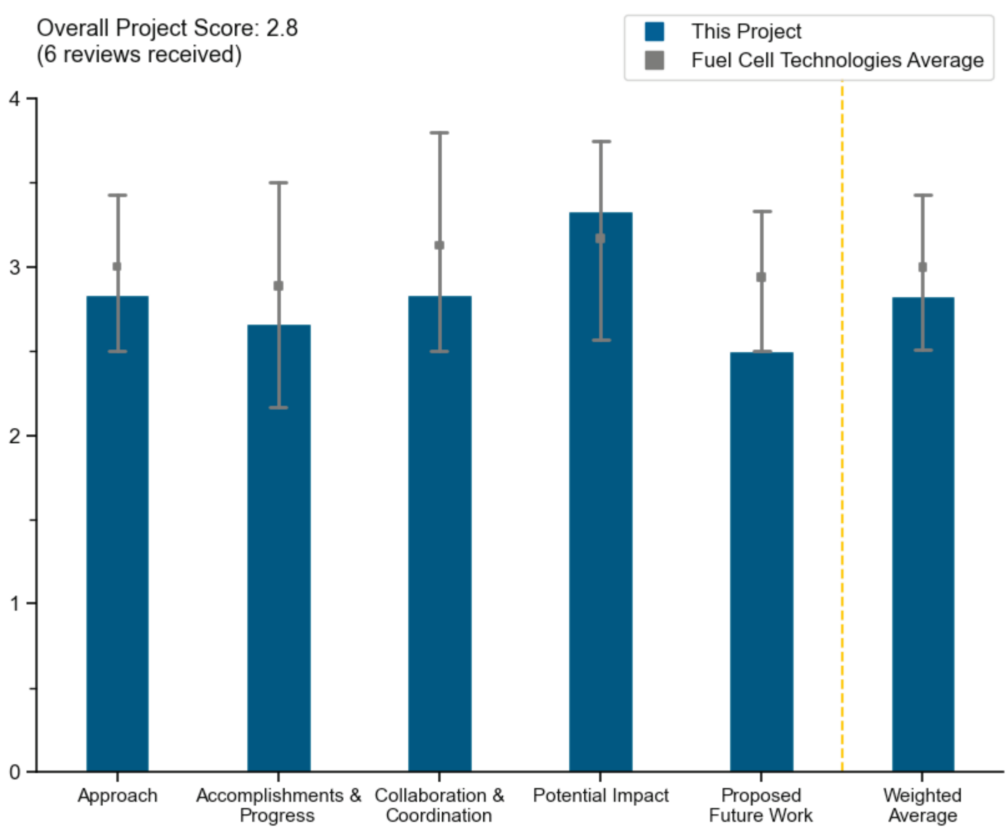
Tom Zawodzinski, University of Tennessee, Knoxville

DOE Contract #	DE-EE0009246
Start and End Dates	4/1/2021–3/30/2024
Partners/Collaborators	Oak Ridge National Laboratory, Akron Polymer Systems
Barriers Addressed	• High conductivity (interim target: low area-specific resistance <0.08 ohm-cm^2 @ 120°C, 50% relative humidity) • Durability: on path to 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 proton exchange membrane (PEM) fuel cells 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.

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 project has a multi-pronged approach to modifying the acid groups of legacy polymers and non-fluorinated (hydrocarbon) polymers, as well as doping nanoparticles. The approach is promising and feasible for developing a high-temperature membrane for HD fuel cells.
- The project aims to develop hydrocarbon PEMs with adequate proton conductivity at 120°C and low humidity (35%–50% RH). The team aims to modify poly(arylene ether sulfone) (PAES) and Nexar with sulfonamide linkages that contain "ball" of sulfonic acid groups (i.e., branched aryl groups with sulfonic acid). The strength of this proposal lies in its straightforward chemistry to modify commercially available polymers (polysulfone) and Nexar to test whether the large concentration of sulfonic acid groups promotes proton conductivity under dry conditions. It is unclear why the team is working with Kraton's Nexar. Early PEM separators based upon sulfonated polystyrene by NASA were shown to rapidly degrade in fuel cell stacks. Perhaps the researchers should perform the chemistry they describe with thionyl chloride with the sulfonated branched polyphenylene by Ionomr Innovations (sold commercially).
- This approach is an attempt to modify pendant groups and polymer structure to raise the temperature to operate a fuel cell. The ball of sulfonates (BoS) approach has the potential to advance hydrocarbon ionomers and address a long-term challenge of low conductivity due to poor phase separation of the back-bone aromatic sulfonates. While the overall approach looks promising, the project organization and data presentation are not very clear. A better view of the technical plans and partnership with the Million Mile Fuel Cell Truck (M2FCT) consortium would be appreciated. This project is well positioned as the concern over polyfluoroalkyl substances (PFAS) grows.
- Many of the ideas being evaluated have been tried before and have not been competitive with conventional low-equivalent-weight perfluorosulfonic acids (PFSAs), even at 80°C, let alone 120°C. The one novel concept is the BoS, but there is no reason to expect these will not have similar issues to sulfonated poly para-phenylenes, such as poor mechanical durability and high swelling at the high ion exchange capacities (IECs) needed to meet resistance requirements.
- There is an abundance of alternative membrane chemistries proposed in this project. However, orderly progress toward the goal is limited. The project should show how something along the lines of "turning a particular knob" in the sample preparation has a certain impact on membrane conductivity.

Question 2: Accomplishments and progress

This project was rated **2.7** for its accomplishments and progress toward overall project and DOE goals.

- Given that a no-cost extension had to be performed in budget period (BP) 1, the project has made very good progress, as the team has prepared membranes with the proposed chemistry of BoS on commercial hydrocarbon backbones. The team has shown a proton conductivity of 10 mS/cm at 120°C and 50% RH. Because the team is using a thin membrane, the project hit the project milestone of area specific resistance (ASR) of 0.08 ohm-cm^2 at 120°C and 50% RH.
- Identifying that the imide linking results in low yield and pivoting to the diazonium coupling is a significant accomplishment in advancing the materials development. The conductivity data was confusing and not well organized. Many results were presented as >100 mS/cm, while other results were presented to two decimals (i.e., 90.92 mS/cm). If two-decimal accuracy is possible in some cases, it is unclear why other cases were reported in such vague terms. The nomenclature of the samples is unclear. It would help to know the variables that were modified and how they related to the results reported. Water uptake, swell, and conductivity are poorly reported. These properties are interrelated and usually come with trade-offs. Summarizing these results more clearly is necessary for the reviewers and audience to see differentiation between this approach and other hydrocarbon ionomer systems. Understanding that the project is still in the early stages, it would help to have some basic mechanical property data (dynamic mechanical analysis, stress–strain, etc.) to know how this approach compares to others.
- The 0.08 ohm-cm^2 interim ASR target was met by measuring conductivity and calculating ASR assuming a 10-µm-thick membrane. A 10 µm membrane will no doubt require a mechanical support, which invariably

increases resistance, so it is questionable that the interim target has been met without an actual ASR measurement. There is no evidence that BoS in and of itself is more conductive than biphenyl sulphone: H form. The principal investigator (PI) claims that one of the goals is to advance the understanding of factors that influence performance and lifetime. However, the approach has not been systematic enough, nor has the analysis been in-depth enough as yet, to gain that understanding.

- There are limited measurements of conductivity at room temperature and higher temperatures for some other membranes. One figure was provided for conductivity vs. temperature, which, however, shows a decrease in conductivity starting at 100°C. The reduction could be due to reduced water uptake or a change in thermal stability, which should also be measured and investigated. The project could also benefit from a better comparison of the existing vs. new (developed) materials and how an improved screening method.
- A limited amount of data related to the major goal of the project was presented: an ASR of .02 ohm-cm^2 at 120°C and 50% RH. However, only one data point was shown at 120°C, namely 10 mS/cm, which is a bulk conductivity; significant impact on ASR comes from how thin one can make the membrane.
- The project is starting back up from previous work. This is the first year after a 10-year hiatus. Polymer development takes a long time. A review of earlier work was given, but minimal new results were offered.

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.

- APS has provided some polymers, and ORNL applied a Nexar-based model.
- The team makes good use of DOE resources and collaborators.
- The project team is appropriate, and there seems to be good collaboration between Saito at ORNL and Zawodzinski at UTK. It is unclear what APS has done on this project at this time.
- UTK and APS look to be coordinating well, but there is a lack of M2FCT contribution. Engaging the national labs where possible should advance the project.
- The project should collaborate with the M2FCT partners more for assistance with material selection and characterization.
- Collaboration with another organization was reported; however, it was not clear how much technical interaction happened

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The proposed work has much potential. Simplifying the heat and water management in the fuel cell stack and shrinking ancillary balance-of-plant units (e.g., the radiator) necessitates materials that can operate at 120°C and 50% RH. Furthermore, it is important to devise new PEM materials that are non-fluorinated, given regulatory concerns of PFAS that may lead to the phase-out of PFSA ionomers. This project can satisfy said research areas.
- Hydrocarbon membranes have long fallen short of fluorocarbon membranes, especially in the areas of conductivity at low humidity and mechanical properties. If the BoS approach proves successful, it could provide a pathway to competitive fluorine-free ionomers.
- The project goal for developing new membrane materials that can operate at higher temperatures could improve membrane electrode assembly (MEA) efficiency and durability, which supports the fuel cells subprogram goals and objectives for achieving the HD targets.
- If the goals of this project are met (ASR and durability at 120°C), it would provide a great step to enabling commercial HD fuel cell system designs.
- Although a membrane that meets the goal of .02 ohm-cm^2 ASR at 120°C and 50% RH would provide a large benefit to system design, it was not clear how close the team is to getting to the target with this project.

- This approach is to modify the pendant group and polymer structure to raise the operating temperature of fuel cells. However, the rationale for and the effects of changes are not clear, so prospects for improvement are not promising.

Question 5: Proposed future work

This project was rated **2.5** for effective and logical planning.

- The listed activities are in line with the overall project timeline and goals.
- No clean plan was presented to indicate this project will meet either the performance or durability targets. A 10-µm-thick unsupported membrane is required to meet the interim ASR target, and a 4× reduction is needed, so there is no more room to go thinner. Increasing IEC is likely to increase swelling and solubility. No plan was provided for how durability will be assessed. This family of materials (sulfonated aromatics) has proven to be less durable than PFSAs. The future work included controlling solubility and swelling, but no clear indication of how was provided.
- Some effort should be spent on PEM durability and examining other hydrocarbon backbones beyond PAES and Nexar. The fuel cell durability was mentioned briefly at the end and during the question-and-answer session. The budget for the project is relatively small, and it limits extensive durability testing. The investigators should publish their review (in preparation) on hydrocarbon PEMs. A good deal of work was performed in the past. Summarizing the previous results will help the community move forward. However, not much has been done on hydrocarbon PEMs under hot and dry conditions.
- This approach is to modify the pendant group and polymer structure to raise the operating temperature of fuel cells. However, the rationale for, and the effects of, changes are not clear. While the effects of changes may raise the operating temperature, it is difficult to judge the prospects for success.
- The proposed future work identifies the broad areas that should be addressed in this project. However, a clear plan is lacking. Statements like “broader range of backbone chemistry” are not especially informative.
- Not much progress was evident with the limited data presented on the membrane ASR of the proposed approach.

Project strengths:

- The PI seeks both to develop new materials and to understand the fundamental properties that control conductivity in this class of ionomers. The progress to date on polymer synthesis is reasonable for this project stage. Identifying challenges with the imide linking group and changing strategies is a positive pivot for the project.
- A few promising hydrocarbon PEM candidates were developed with BoS, and they promote decent proton conductivity at 120°C and 50% RH. The project team was able to satisfy their go/no-go milestone for BP 1, despite the no-cost extension. The proton conductivity of 0.08 ohm-cm^2 is good for 120°C and 50% RH.
- The multi-pronged approach makes it possible to discover materials that could otherwise not be accessed. The exploration of hydrocarbon materials is a strength.
- This is the only DOE-funded active project focusing on developing membranes with improved performance and durability at 120°C.
- There is an abundance of novel membrane chemistries proposed here.
- The team is experienced and understands what is needed.

Project weaknesses:

- The multi-pronged approach makes it difficult to identify the key developments or isolate factors that lead to improvements. The properties reported to screen and characterize the membranes are limited. For a project that aims to develop high-temperature materials, thermal–mechanical stability should be assessed as well. The synergy between the activities should be clarified better. The project could benefit from a better delineation of how the information flow will take place between tasks or materials (chemistry, processing, composite formation).

- The main weakness of the project is the selection of backbones studied. The styrene-type backbone in Nexar will probably not hold up to reactive oxygen species in a PEM fuel cell. The PAES backbone should fare better. The scope of work should include more detailed plans to assess durability for PEM fuel cell operation for HD vehicles.
- The PI reported that several polymers have been made, but there is little characterization presented. Overall organization could be improved. The role of M2FCT should be clarified. The plan for functionalized cerium nanoparticles (CeNPs) is unclear.
- The approach is unlikely to achieve the goals. The project uses a non-systematic approach (too much trial and error). No details of future plans were provided. Limited characterization data and analysis have been provided.
- Essentially no data on new membrane ASR was reported at target conditions.
- The cause and effect of changes is not clear.

Recommendations for additions/deletions to project scope:

- The project could benefit from collaboration with the ongoing HD vehicle membrane activities, including the use of existing membrane properties as a baseline for screening and comparisons. This could be followed by some MEA testing. More systematic and fundamental measurements of the materials are needed, especially because the chemistry and acidity are modified in these systems. Proposed future work on composites and durability should be kept—but with an explanation of the down-select process.
- There are a number of "knobs" that can be turned to achieve targets; the following are some that were not really addressed:
    - Air operating pressure: 50% RH, 120°C at high air pressure is a different animal as compared to low pressure; furthermore, counter flow gas feeds could help with membrane ASR for membranes with close-to-target performance.
    - Membrane thickness: One way to drive down ASR is to lower membrane thickness; in this project, the other system implications of this approach could be addressed later if membrane thickness could be driven to sub-10 µm effectively.
- There should be more focus on the relationship between key material properties such as water uptake, conductivity, and mechanical properties. Comparing these properties within the experimental membranes, but also with suitable baselines such as traditional sulfonated poly(ether ether ketone), will allow the reviewers and audience to see the advantages (or lack of advantages) of the new materials. M2FCT should be enlisted to conduct small-angle x-ray scattering or other techniques to investigate ion channel formation for the BoS systems compared to traditional hydrocarbons.
- The project should consider the following:
    - Share IEC and swelling data for all samples.
    - Show proof of ability to make thin films.
    - Report CeNP content.
    - Do mechanical testing (elongation to break, stiffness).

  Furthermore, ex situ conductivity measurement at 120°C and 50% RH (100°C dew point) is very difficult. Humidity is more easily controlled when doing in situ ASR measurement in a cell under increased pressure.
- Fuel cell membranes are complex and depend on having a number of properties in the electrolyte at the same time (e.g., ion conductivity, temporal stability, low adsorption on catalysts, and proper transport of hydrogen and oxygen). The team needs to make a better case for how changes in membrane components affect the properties (cause and effect) and prioritize accordingly.
- It is recommended that the project team perform accelerated stress testing of the most promising PEM variants in a fuel cell.

Project #FC-337: Cummins Proton Exchange Membrane Fuel Cell System for Heavy-Duty Applications

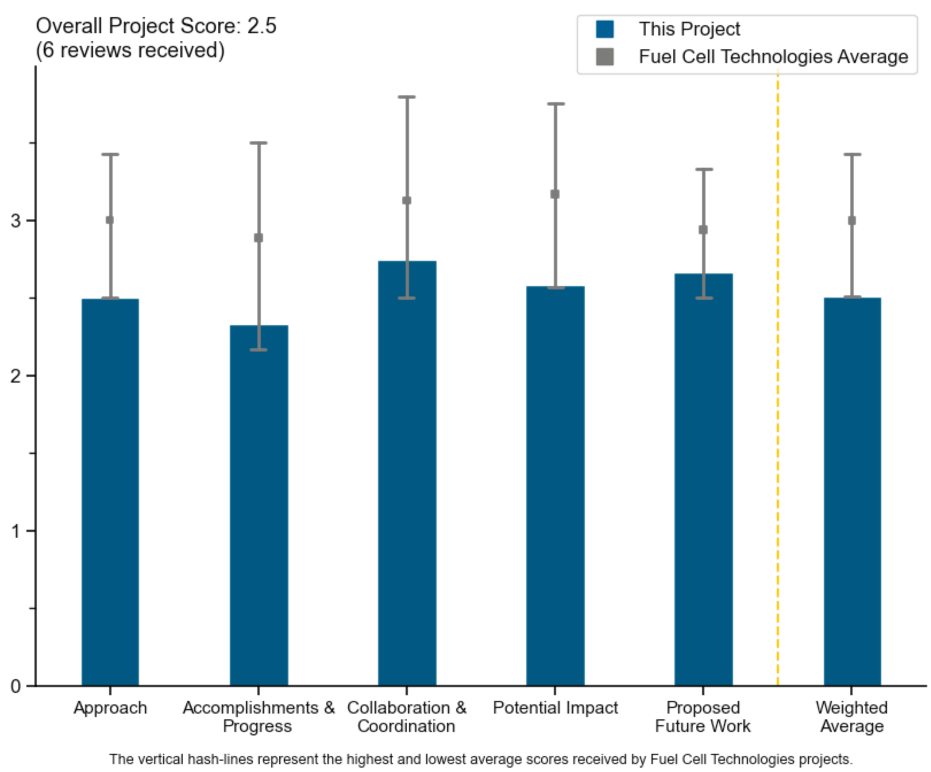
Jean St-Pierre, Cummins Inc.

DOE Contract #	DE-EE0009247
Start and End Dates	7/8/2021–7/31/2024
Partners/Collaborators	Cummins Accelera, Cummins Turbo Technologies, Dana Incorporated, W. L. Gore & Associates, Inc., Argonne National Laboratory, Million Mile Fuel Cell Truck (M2FCT) Consortium
Barriers Addressed	• Cost: \$80→\$60/kW fuel cell system cost enabled by a smaller radiator, high-volume manufactured bipolar plates, and a smaller, higher efficiency system

Project Goal and Brief Summary

The objective of this project is to develop and demonstrate a new standardized, modular, and scalable 100 kW proton exchange 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 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 a production volume of 100,000 units per year. 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 (comprised in part by Cummins' acquisition of Hydrogenics), Cummins Turbo Technologies, Argonne National Laboratory (ANL), W.L. Gore & Associates, Inc. (Gore), and Dana Incorporated (Dana).

Project Scoring



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.

- The high-level approach is reasonable, with MEA, system, and plate approaches. However, there are limited details on actual approaches, and therefore, the approach is difficult to assess. No details on MEA changes, plate flow field design, or e-turbo approaches are provided. The stack cost project is not planned until later in the project. Initial modeling should be presented to provide estimates of potential feasibility to meet cost targets. The cost review in Quarter 6 may provide some information; however, the details are not clear. The use of commercial-scale cells and stacks, as well as the 5,000-hour tests planned for later in the project, provide very relevant data and provide a good complement to other more fundamental projects. However, the lack of detail on the materials and design reduces the value of this work. The project team has stated that all data on MEA testing will be fed to ANL for model validation. This information will be an important aspect of the work to derive value from the testing. The statement of project objectives (SOPO) targets chosen are relatively low compared to DOE HD targets. The presenter was not able to provide any justification. Changes to highly accelerated stress test (HAST) conditions may have significant impacts on the stressors and mechanisms accelerated.
- Developing a PEMFC that operates at >100°C is very challenging, since state-of-the-art proton exchange membranes (PEMs) require water to work effectively, and most PEMFC degradation mechanisms are accelerated exponentially with temperature. Therefore, ideally, a breakthrough in PEM technology is needed, which is not the focus of this project. Although the activity losses can be reduced with higher temperature, this is typically offset by higher ohmic losses, especially at higher current densities when operating at higher temperatures is most advantageous since that is where high heat rejection rates are needed. Even if the goals can be achieved with conventional PEM materials, then the durability targets become far more challenging. However, since some new materials have been developed recently, it may be worth trying to develop a PEMFC system that is capable of >100°C operations.
- The project approach is to develop a novel fuel cell system suitable for HD fuel cell applications through a bottom-up design and/or selection of key components (bipolar plates, MEAs) from single cell to stack to system. The project will achieve this through integration of advanced high-temperature ionomer/ membranes, turbo compressors, and flow fields via improved compression molding. There are a few shortcomings. The project does not appear to be addressing one of the critical barriers, which is catalyst durability. Also, it is unclear whether the accelerated stress test (AST) durability protocols selected are representative of the known stressors for catalyst and ionomer. For example, it is unclear how the "50 acceleration factor" on slide 8 was determined.
- It was good to see the plan updated to run a 10 kW rather than a 1 kW stack, which would have been only one or two cells. The project does not use a representative durability test with known acceleration factors at the chosen high-temperature operating conditions. The project's target peak power density of 0.8 W/cm^2 at 0.3 mg Pt cm^2 is not very ambitious. Such a large (900 cm^2) active area will be very challenging, both to produce and to do stack assembly at high volumes. Cummins mentions they are already having trouble with compression molding. They have identified machining as an alternative, which will be much more expensive. It is unclear whether roll-to-roll MEA manufacturing will be demonstrated within this project.
- The approach provided as a set of milestones and deliverables just lists known tasks that are required to build a stack and test this in a lab. There are no specifics on how this project is addressing the critical barriers of improving (1) the high-temperature capability of the MEA, (2) stack cost vs. radiator cost for a 200–300 kW system, or (3) power density of the composite plates (not just the current density but the entire power density [kW/liter]) of the stack.
- Demonstrating a 1 kW stack in Budget Period (BP) 1 before building a 100 kW stack in BP 2 is a good approach. However, the go/no-go decision of only 0.3 A/cm^2 at 0.75 V is very low and needs to be made more stringent.

Question 2: Accomplishments and progress

This project was rated **2.3** for its accomplishments and progress toward overall project and DOE goals.

- The Gore-1 membrane was selected for a 10 kW short stack test. No work on bipolar plates or the turbo compressor was reported this year. Minor changes to the plate were introduced, but why they were introduced was not reported. A model was developed that predicts polarization curves at two different sets of conditions, both at 110°C. The project should confirm if the model is accurate at lower temperatures as well, where there may be liquid water present. Durability tests were run on two types of Gore membranes. The protocol was based on a General Motors HAST protocol but at higher temperature, which likely significantly reduced the mechanical stress by reducing the magnitude of the humidity cycles. The membranes had different thicknesses and stabilizers, so the researchers could not isolate what led to the increased durability of the Gore-1 membrane. There was no comparison of performance for the two Gore membranes. No catalyst analysis, such as electrochemical surface area or mass activity loss, was presented, nor were any mass transport or ohmic losses reported.
- No data was provided on bipolar plate design accomplishments in terms of pressure drop and ability to push the boundaries. Results presented in 2022 were all normalized, with limited information on the critical aspects that were stated as key project objectives, e.g., (1) Push the boundaries of compression molding technology with graphite/polymer composites; (2) Form fine flow field channels and achieve practical pressure drops at high pressures. At a minimum, results could be compared against literature or internal baselines (only channel-to-channel variability data was provided). The model fit seemed fine, but the presenter did not outline how this will be used to drive design. A significant number of potentiostatic ASTs were completed while monitoring H_2 crossover. The results on H_2 crossover over the 48-hour test duration seemed to be within noise, with no trends observed. They did not provide any indication of why the Gore-1 membrane is significantly more durable, and no analysis was done. The stack hardware design chosen was a traditional design. The design reviews would provide some benefit, but it would have been good to see some improvements in design as a result of the funding. MEA results exceed the SOPO target, but there was no indication of composition, and therefore, no learning was shared. The project used an implied acceleration factor of 50 to state a performance loss of 20 mV for 20,000 hours in the field. This is an incorrect assumption. A 500-hour AST test is a reasonable test duration but is not necessarily equivalent to 25,000 hours. Additionally, the test conditions were different from Million Mile Fuel Cell Truck (M2FCT) conditions.
- The project has not yet built the stack but does have a no-cost extension. The team has promising single-cell data, which (one hopes) can be reproduced in a stack. Only two sets of MEA durability data were shown. It is better to run shorter tests at this stage and run more of them to get some statistics, rather than just run one long test for >2,000 hours. Better to project out from fluoride release rate (FRR) and thickness change over, say, the first hundreds of hours at various conditions instead of running just one condition for >2,000 hours.
- The performance polarization curves indicate that the voltage is at 0.3 A/cm^2 and >1 W/cm^2. However, there is no mention of how these values are linked to the DOE target tables of 68% peak efficiency and 25,000-hour life. For the project-related goals of (1) demonstrating high-temperature-capable MEAs and (2) fine flow field channels to achieve practical pressure drops, there is no mention of the internal status before the project vs. what was accomplished throughout the project. The accomplishments feel more like re-testing Cummins' internal baseline(s).
- The primary accomplishments appear to be stack hardware design completion (few results shown), selection of the Gore-1 membrane for the 10 kW stack demonstration, model validation, and completion of a series of ASTs. Since these AST conditions are new and differ from existing protocols, it is unclear how relevant they are toward predicting durability under end-use conditions. Overall, the project appears to be behind schedule, but it is difficult to assess by how much.
- It is not clear why stack design is a major focus of this project, since higher-temperature operation should not have a major impact on the non-repeat parts, such as end plates and bus bars. Clarification is required if this is due to Cummins' not having yet established a robust stack design. The project appears to be significantly behind the proposed schedule, but no showstoppers have been identified.

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 addition of more input and assistance from the M2FCT team is good. The inclusion of the Pajarito Powder catalyst is also a nice addition, since catalyst durability is a major issue that warrants more attention here.
- There is very good collaboration with Gore, Dana, and M2FCT.
- The project has good interactions between original equipment manufacturer (OEM) and supplier, but this is not a true collaboration. It feels more like Gore and other sub-contractors are providing parts based on specifications from Cummins. Collaboration with M2FCT was mentioned, but no test plan or results were presented. The planned work to test MEAs through M2FCT and ANL data analysis of the stack would improve this score for the next review.
- Cummins is getting membranes from Gore, although they seem to be commercially available membranes, so it is not clear what Gore is doing other than providing materials. Dana will be providing the plates for the stacks. There is no evidence of contributions from ANL or M2FCT.
- Several partners are listed, but there is no indication of significant collaboration. The commercial partners are supplying materials only. The work with M2FCT is not outlined.
- It is unclear if there is significant collaboration with other institutions. Clarification is needed as to whether they are acting simply as suppliers or co-developers.

Question 4: Potential impact

This project was rated **2.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Building stacks and operating them under hot dry conditions will provide the Hydrogen Program (the Program) with excellent data toward HD application of fuel cells.
- Project goals are relevant and support targets for HD vehicles. Milestone targets are low and do not appear to push the envelope of capabilities.
- The project has potential for modest impact to advance against the barriers for HD fuel cells.
- If the project is successful and demonstrates membrane durability at a peak temperature of 110°C, that aligns with Program goals. If the project is successful in producing high-quality compression molded plates that meet cost targets, that would be valuable. Machining will not.
- The project is expected to address either efficiency (68%), durability (25,000 hours), or cost (80$/kW). It is unclear how any of the proposed work and the accomplishments listed so far are linked to these goals. It feels like this project is getting tunnel vision and focusing mainly on cost reduction through increased operating temperature. However, there is no analysis or data showing the impact of temperature on the cost of the fuel cell system. While it might help Cummins to reduce the cost of the radiator, it not a part of the fuel cell system and not included in the DOE targets table.
- The potential impact of this project is not clear, because it is not evident that the key benefits of a PEMFC that operates at >100°C have been sufficiently quantified. It is unclear what the savings are. The reduction of the radiator size in fuel cell electric vehicles (FCEVs) is clear, but the cost benefit of this is not substantial. Many FCEVs that operate at <100°C have been successfully demonstrated. In sum, this appears to be a high-risk, low-potential-impact project.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- The proposed work plan to build a 10 kW stack and share data and materials with M2FCT is excellent. This should help the Program.
- Proposed next steps are logical, based on this reviewer’s understanding of the project plan.

- The project plans appear to support progress toward project goals, but lack of detail provided on approaches make this question difficult to assess.
- The proposed future work is okay, but it is not clear why a 10 kW stack demonstration is warranted, unless small cells are demonstrating that the team's performance and durability metrics can be achieved. Presumably, the stack work is being prioritized here because one of Cummins' key objectives is to mature the company's stack design for any operational envelope.
- Future work needs to focus on identifying gaps to the project goals and specifically addressing those, not just a list of tasks to build and test a stack. It would be good to add the following for future work: (1) the impact of operating temperature on stack/compressor cost and durability, (2) the impact of key design features to improve power density of bipolar plates, and (3) a cost estimate and modeling of compression molded bipolar plates to pressed graphite plates.
- The project will conduct postmortem analysis of membranes from a durability test, including x-ray fluorescence (XRF) for stabilizer distribution, to determine failure modes. There is no plan to validate the claimed AST acceleration factor, and no future work on the turbo compressor is planned. Perhaps it is no longer part of the project. The team should prioritize addressing quality issues with the compression molded plates.

Project strengths:

- The project aims to integrate advanced flow field and turbo compressors to enable efficient operation at high pressure, a promising approach to meeting performance objectives.
- The team and principal investigator have a good deal of potential to make a meaningful impact and progress toward achieving the DOE goals toward HD fuel cell systems.
- Cummins' building fuel cell stacks for HD operations and sharing the data and materials with DOE is excellent for the Program.
- Strengths include the OEM, the project's operating at commercial-scale approaches, and the project's working with good suppliers and commercially relevant materials. The work is addressing high-temperature operation.
- The recent addition of more involvement by M2FCT should help establish better objectives (e.g., performance targets) and test methods (e.g., ASTs).
- Stack performance and durability data will be provided. Gore provides state-of-the-art membranes.

Project weaknesses:

- Crossover data during potentiostatic ASTs for the different membranes were not compared at the same conditions, making it difficult to make clean comparisons. Selected durability protocols have not been proven to include all membrane failure modes, especially stabilizer redistribution due to humidity gradients. The mitigation strategy for plate manufacturing of machining will not meet cost targets.
- The project lacks fundamentals, baselines, and sufficient material and/or design information to provide values to others. It is understandable that that some degree of normalization is required because of the commercial nature of designs. However, more attempts should be made to provide information in a format that will provide some value to others. Low targets have been set.
- The project does not have clear long-term objectives or targets. It is unclear what performance and durability measures are required to make a >100°C PEMFC viable.
- The project does not seem to be making significant efforts toward addressing the key barrier of HD fuel cell catalyst degradation, which would be expected to worsen substantially at the elevated temperatures this project appears to be targeting.
- The project team currently has tunnel vision, with a focus on enabling a cheaper radiator rather than trying to address the fuel cell system goals and barriers.
- More progress needs to be made with single-cell MEA durability testing.

Recommendations for additions/deletions to project scope:

- The project should report the FRR results, stoichs, and flow orientation for the HAST test. The performance model should be validated on the full active area cell over a wider range of conditions including lower temperatures at which liquid water may be present. Electrode analysis and diagnostics should be included.
- Any 100 kW stack or something bigger than a 10-cell stack should be removed from the project. This project is not a technology demonstration project. Rather, the focus should be on doing the following:
  - Use the polarization curve reported, along with the membrane crossover and compressor power data, to estimate peak efficiency.
  - Establish a plan to close the gap.
  - Conduct a cost estimate of the stack for various design options to demonstrate progress toward a $60/kW fuel cell system.
- The project should increase analysis of test results and provide conclusions. Data on baselines is needed, and real progress must be shown. Targets should be adjusted to better match DOE targets.
- Only two cells operating with different MEAs under a HAST-type test were shown. It would be good to expand this rapidly to other conditions. There is no real need to run 2,000-hour tests so early in the project when still selection is ongoing. It would be better to understand durability under various conditions.
- DOE should request that Strategic Analysis assess the impact of >100°C PEMFC systems, if this has not been done recently.

Project #FC-338: Domestically Manufactured Fuel Cells for Heavy-Duty Applications

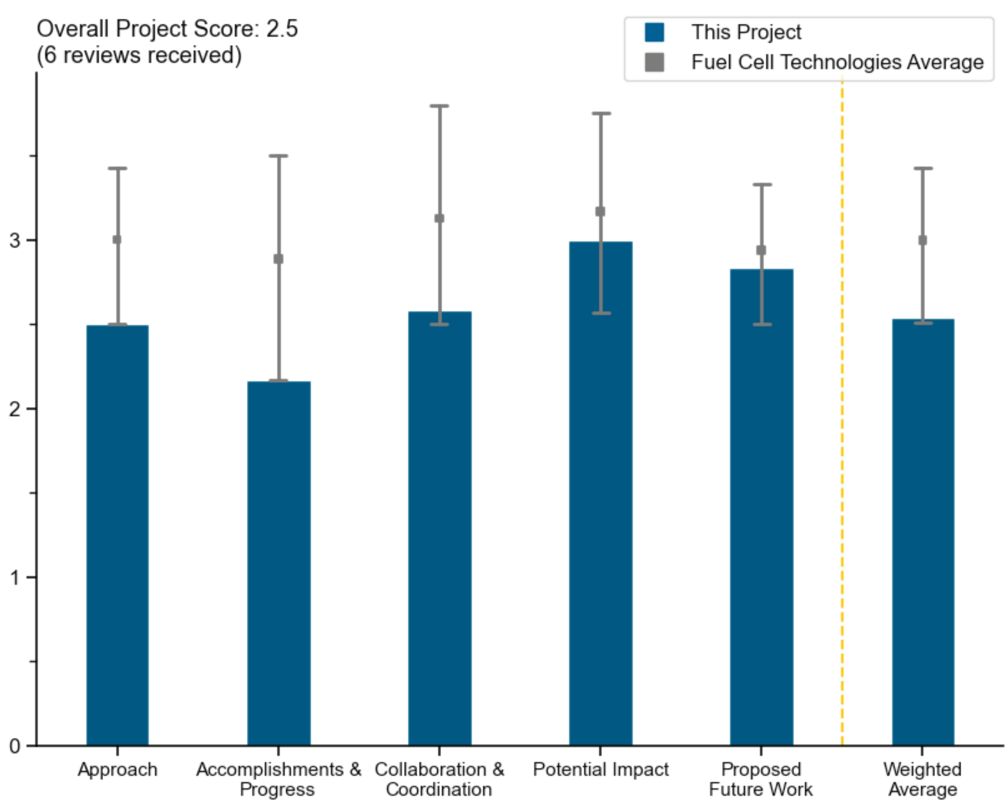
Karen Swider-Lyons, Plug Power Inc.

DOE Contract #	DE-EE0009248
Start and End Dates	10/1/2021–6/30/2024
Partners/Collaborators	Argonne National Laboratory, M2FCT
Barriers Addressed	• Performance: High catalyst activity, low mass transport resistance, low electronic resistance interfaces • Manufacturing: Supply chain, translate lab equipment to high-volume manufacturing

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.

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.

- The milestones in slides 7 and 8—especially the 840 mW/cm^2 power density at 0.769 V—are excellent and very aggressive. Building 5 kW and 100 kW stacks and sharing data with the Million Mile Fuel Cell Truck (M2FCT) consortium would help the DOE Hydrogen Program.
- The project overall seeks to develop high-performance, domestically manufactured fuel cells, via material screening (membrane electrode assembly [MEA] via accelerated stress tests [ASTs], BPPs, seal materials) and design and building of an automated stack assembly machine. The overall approach is largely experiment-driven, which is appropriate.
- The goal of using commercially available materials and high-volume manufacturing processes to produce heavy-duty vehicle (HDV) cell stacks is good since this is the most expeditious route to developing a viable product for potential HDV applications. However, what is currently being done by the team is not good. The project is running two very different test protocols on two different hardware platforms (single cells and short stacks), which makes comparisons of these apples-and-oranges results very difficult and is unlikely to result in learning anything really useful. It is unclear what running an AST protocol on short stacks would yield. The desired diagnostics are hard to do on stacks. One should do ASTs on single cells to determine whether the cell materials are prone to degradation due to the known proton exchange membrane fuel cell (PEMFC) decay mechanisms. The highly accelerated stress test (HAST) being done with the single cell is not the most appropriate AST to use, as was pointed out by one of the reviewers from General Motors who helped develop this HAST. The principal investigator's rationale for running a much milder AST on the short stacks was that the fuel cell community needs to show that PEMFCs can meet the HDV durability targets. It should be noted that multiple PEMFC-powered buses have now demonstrated >30,000 operating hours. What is really needed here is to show that Plug Power can build stacks (using the company's state-of-the-art, high-volume production processes) that can meet the HDV targets.
- The approach slide focuses on the validation of the ANL HD durability model. This looks like a reasonable approach and will provide value. The specific details that are to be shared are, however, not clear and may negate the actual value achieved. So far, there is little data on the types of materials used. Increased information will increase value of the project for others, including DOE, and will enable better guidance from reviewers and the research and industry communities. Several underpinning technologies are listed on slide 3. However, aside from the work on plate coatings, there is little in the project that addresses these. There is no information on what is being evaluated, i.e., which vendors, how many vendors, vendors of which components, etc. There is a reasonable amount of durability testing and diagnostics planned. These activities need to be complemented with end-of-life materials characterization and the data shared. The use of the HAST-type conditions for voltage degradation is not appropriate, as this was designed for membrane degradation. The very different conditions used for the single-cell vs. short-stack testing make comparisons difficult. Understanding differences between cell and stack durability testing when trying to make conditions as similar as possible would instead be a valuable approach.
- It is wonderful to see that this project is leveraging the high-volume production methods to provide stack-level data toward progressing HD truck DOE goals. However, there is no clear plan to establish the gaps toward any of the following HD goals: peak efficiency (68%), durability (25,000 hours), or cost. The approach feels like this project is trying to integrate various sources of catalyst, membrane, and other cell materials to see if progress can be made toward one of these goals. It is not clear where the team's state-of-the-art materials are compared to the DOE HD goals.
- While the general scope of work makes sense, there are not enough details on the materials and designs used and absolute results to assess the value of the approach. Plug Power is using an AST designed to accelerate membrane damage as a metric for performance loss. Also, for some unknown reason, the team used different lower current densities in the single-cell and stack tests, which, as expected, led to less degradation in the stacks.

Question 2: Accomplishments and progress

This project was rated **2.2** for its accomplishments and progress toward overall project and DOE goals.

- No power densities were reported. Plug Power claims potentiodynamic and potentiostatic corrosion tests were completed, but no results were reported. This is critical, especially with the claim that uncoated stainless has satisfied all requirements. If that is true, it is unclear why a more expensive titanium option was considered.
    - The resistance scorecard is difficult to follow. It is unclear whether it is new data that was generated as part of this project.
    - Also, reported catalyst coated membrane (CCM) resistances, which are typically of the same magnitude as the BPP–gas diffusion layer (GDL) resistance, are very low in this project.
    - The automated leak detection is the most intriguing work, with a demonstrated 14-second cycle time. It is not clear whether the tests are done at a cell or stack level or whether the cells are at the nominal stack compression levels during these tests.
    - Also, as Plug Power is ultimately getting MEAs from Johnson Matthey, one would assume Johnson Matthey has a pinhole/crossover spec on incoming MEAs.
    - Compression set is a function of stack materials, designs, assembly method, and operating conditions. It is unclear what Plug Power's approach is to reduce compression set. It is also unclear how the claimed reductions in compression set are affecting performance losses or durability.
    - Using different durability protocols between single-cell and short stacks severely limits the value of the comparisons.
    - ANL should be modeling the results of the durability tests to see whether the lab agrees with expected results. It is very surprising to see no performance loss in the stacks after 20% electrochemical surface area loss. It is unclear whether this is the expected result.
    - The stack MEAs do not appear to be fully broken in, whereas the single-cell MEAs do. It is unclear whether there are different break-in protocols on the two platforms.
- The work is said to include extensive screening of CCMs and GDLs; however, no data is shown. No actual data is shown for plate testing, and the data shown on slide 9 was not generated in this project. Leak detection in an automated system with a cycle time of 14 seconds is a good accomplishment. The low-compression set materials work is useful, but value to others is only achieved if additional information is shared, e.g., at least the material classes used (specific grades do not need to be revealed). The very different conditions in the cell vs. stack testing result in difficulty in comparing test conditions. There is good data mapping temperature and conditions of training stack. Sharing of fluorine data would have been useful.
- The results presented suggest a modest amount of work was completed over the past budget period in terms of the stack AST and stack/single-cell AST correlation work. Progress was made on high-speed MEA pinhole detection and metal BPPs.
- It is very good to see some stack-level data and the cells being tested on accelerated protocols. The test data being presented does take significant time and effort to plan, execute, and analyze. However, this significant amount of data has not necessarily translated to any significant accomplishment, which is likely because of a poor approach.
- It is unclear whether slides 10, 11, 12 and 13 show accomplishments from this project. Slides should be clearly marked with the specific progress on this project. It would have been helpful to see more data presented regarding the milestones.
- The team has already collected considerable data, but the data obtained to date is of limited value.

Question 3: Collaboration and coordination

This project was rated **2.6** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration with M2FCT and labs is excellent. It is unclear whether there is any collaboration with materials (catalyst/membrane/GDL) suppliers. It would be good to mention some of these, even if their names need to remain confidential based on agreements.
- ANL's role is in this project was not clearly communicated. Presumably, ANL models will be used to determine what the load profiles might be in different HDV applications. This is needed, but it is doubtful that Plug Power would use ANL's system model to project the stack load profiles, since one would assume that a fuel cell electric vehicle (FCEV) developer with Plug Power's experience would then have a superior idea of what the stack load profile might be (e.g., how the load is shared between the PEMFC and the batteries in a hybrid FCEV). In short, all ANL is providing is HDV load profiles. Slide 22 states that Plug Power's durability data will be integrated into ANL's model, but the value of this is not clear since Plug Power is not generating real-world data here and the AST results are not very helpful for ANL's system model. It is good to see M2FCT's durability team involved here, since Plug Power can use the consortium's help in establishing the appropriate AST protocols, comparing the company's results with AST results obtained by M2FCT, and using M2FCT's capabilities to examine post-test components that show evidence of significant degradation.
- It is expected that the collaboration with ANL and M2FCT will be relevant and useful, providing critical data to ANL for stack durability testing and providing significant MEA characterization by M2FCT to feed into that analysis. However, no specific information on M2FCT characterization is provided. No other partners are included.
- Plug Power, with its significant buying power, has the ability to bring in various international suppliers and vendors to develop an HD MEA that can simultaneously meet the efficiency, durability, and cost targets. While the project has listed some partners, the direct network of world-class material providers is a hidden benefit/collaboration that is key.
- All the work presented was done by Plug Power. ANL is a sub and could provide valuable modeling of performance and durability data, but this work has not started.
- It is unclear how significantly ANL and M2FCT have been involved with the project to date.

Question 4: Potential impact

This project was rated **3.0** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The intended impact of this project is well aligned with DOE goals. If the approach and execution is improved, then this project could be highly valuable, especially if Plug Power is willing to share the key findings, such as the performance losses observed and the results of teardown analysis.
- Developing stacks with state-of-the-art MEAs and evaluating their durability and sharing that data with the community will contribute to achieving DOE research and development goals and objectives. The project has the potential to lower manufacturing barriers.
- The approach to help ANL validate the HD model using Plug Power stack data is extremely valuable. The extent of details that will be shared will govern the extent of that value and is not currently clear. If successful, the project will enable Plug Power to meet goals and is likely to support supply chain advancements, e.g., stack leak testing equipment. The lack of information provided on materials and designs severely limits additional value.
- The project has the potential to help decrease the cost of domestic fuel cells by developing high-volume manufacturing for stacks comprising high-performance and durable MEAs.
- The project goals, if met, could have a significant impact toward meeting the DOE goals for HD trucks. This project has a correct goal and a good network; however, the approach needs to be modified to ensure that the potential impact can translate to actual, meaningful impact.

- It is unclear what is unique about this project for HD applications. At the end of the project, there will be a 100 kW stack, which is low power for HD. Cost benefits are not quantified. The automated leak testing is novel and potentially impactful. One hopes more details on how this is done will be provided.

Question 5: Proposed future work

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

- The plans for future work are reasonable, assuming Plug Power comes up with a stack test that accelerates voltage loss faster. Otherwise, the project team will not be able to forecast HD durability within the timeframe of the project. Plug Power should provide more details on the plate coating durability assessment. Plug Power should disclose some details about the MEA and plate materials used in the project. Other projects disclose much more (platinum group metal loading, plate materials, etc.).
- The project has proposed a good deal of work toward making a better MEA. However, the proposed future work does not clearly lay out what the gaps are and how the project team intends to close them. Perhaps the team already has a good idea on what the gaps are and a clear plan to close these gaps and simply has not clearly communicated that plan. Conversely, perhaps the team is still figuring out what the gaps are and how to close them. If the latter is the case, then the project needs to leverage either internal capability or ANL's capability to do a deep dive of the latest MEA results and pick apart the key factors contributing to the gaps in performance targets and lay out the MEA designs based on those.
- The proposed future work on slide 20 is all good, assuming that recommended modifications to the AST protocols and stack testing are implemented. More active engagement with the M2FCT team could help with making these needed changes.
- The next steps appear logical, based on work completed and the approach to Phase II.
- The work shown is planned in a logical manner. The lack of accelerated testing for the stack is a shortcoming.
- More details are needed on advanced MEAs and how the aggressive targets are going to be met.

Project strengths:

- The prime is a viable FCEV developer with extensive fuel cell manufacturing experience. This can help determine the status of PEMFC cells and stacks that are produced using commercially available materials and relatively high-volume manufacturing processes. The principal investigator appears to be open to constructive recommendations.
- Single-cell and short-stack testing and comparison of degradation effects will provide some value, although conditions could potentially be better chosen. Other strengths include testing of trends for MEAs when comparing ASTs, commercially relevant materials and designs, the high-volume automation approach, and equipment sourcing.
- The project has a good team and a wide network. Further, Plug Power brings in huge scale-up capability to have a meaningful, measurable impact toward zero-emission commercial vehicles.
- Strengths include a focus on an automated cell leak detection method and a plan to engage ANL for performance and durability modeling.
- Good progress has been made toward stack testing, considering the no-cost extension and the actual amount of money spent on this project. There is close collaboration with M2FCT and labs.
- The project is focused on addressing the key challenges with developing high-volume stack manufacturing.

Project weaknesses:

- Most of the results that were shared are well known and expected, such as an inlet-to-outlet temperature increase in a stack. Comparisons between short-stack and single-cell results are meaningless, as they use different protocols. Protocol comparisons should be done on the same platform. Platform comparisons should be done using the same protocol. The project team is using a membrane AST to study voltage loss, which is not accelerated in that protocol. Plug Power also modified the HAST protocol, increasing the lower current density to 0.1 A/cm^2, making it less stressful. No beginning-of-life performance comparisons were conducted between the single cells and short stacks. No details were provided about MEAs (Pt loading, membrane thickness) or plates (based materials, coatings, active area) used in stack tests.

- The stack AST testing may need to be assessed; it does not appear to be very accelerated (almost no decay after 500 hours). Considerations should be made to ensure that the stack protocol is capturing all relevant degradation modes (it seems to be going a bit easy on catalyst cycling).
- The approach is the biggest weakness. It feels like the researchers are trying to test all possible combinations, hoping to get lucky and find something that works. It would be better to leverage the project's very capable team, test capabilities, and production scale-up and direct resources to solving the gaps.
- The presentation could use more clarity on the project goals and the progress made toward those goals.
- A weakness is the current durability test plans.
- Limited material information and test data were provided. This makes it difficult to further assess approaches. A list of materials characterization tests to be completed is not included.

Recommendations for additions/deletions to project scope:

- The project is asked to:
    - Report absolute voltages from stack tests, noting that other stack projects are showing actual polarization curves rather than relative voltage loss.
    - Report details of plate corrosion tests, including test setup, protocols, and results.
    - Share details of the recovery protocol and report recoverable vs. non-recoverable performance losses.
    - Report fluoride release during durability tests.
    - Provide cell-to-cell performance variation in the stacks.
    - Conduct cost analysis, or at least provide enough details to Strategic Analysis so that they can quantify the benefits of this project.
- The team should develop an improved durability plan, which should ideally consist of the following: (1) using the new DOE AST for HDVs on single cells to determine whether their cell materials are robust (Plug Power's results can be compared to what M2FCT obtains on other cells using different materials and assembly methods), and (2) operating short stacks using a protocol that mimics the expected operation in an actual HDV application. When performance decay does occur, the team should consider using the simple polarization-change approach as a starting point to determine the type of degradation occurring (see M. L. Perry, R. Balliet, and R. Darling, "Experimental Diagnostics and Durability Testing Protocols," in *Modern Topics in Polymer Electrolyte Fuel Cell Degradation*, M. Mench, E. Kumbur, and T. Veziroglu, Editors; Elsevier, Denmark [2011]). Additionally, presenting delta-V (mV) vs. current density (A/cm^2) is preferable to plotting "percent voltage" vs. current density and still allows one not to show actual cell voltages (if that is considered proprietary).
- More information should be provided on materials used and data generated. It is not expected that specific grades would be shared, but some minimal information should be provided. There is a good set of durability test and diagnostics planned. These need to complement end-of-life materials characterization and the data shared. Cost projections for the stack and system should be included. Explanations are needed of how technology underpinnings on slide 3 are relevant to the project outcome. The results for single-cell vs. stack may provide value. It will be important to further analyze cycles and stressors (voltage, temperature, relative humidity, time, cycles) to draw correlations. The materials characterization will be very useful. Looking at the trends vs. MEAs will also provide useful information. Data on fluoride loss during degradation testing should also be provided.
- The project needs a clear plan for identifying and closing the gaps of state-of-the-art MEAs toward DOE goals. A simple waterfall chart to communicate the same will be helpful. Further, it is not clear if this team has leveraged ANL's capability toward modeling the degradation results from the tests conducted so far. Modeling the degradation would be helpful to provide additional pathways to close the gap toward durability and provide estimates for the acceleration factors for the project ASTs.

- The goal of the stack testing should not be to operate the stack in a benign condition to prove long lifetimes but to actually operate the stack under stressful conditions and then, using that degradation understanding, to extend lifetime either through materials improvements or system operating strategies.

Project #FC-339: M2FCT: Million Mile Fuel Cell Truck Consortium

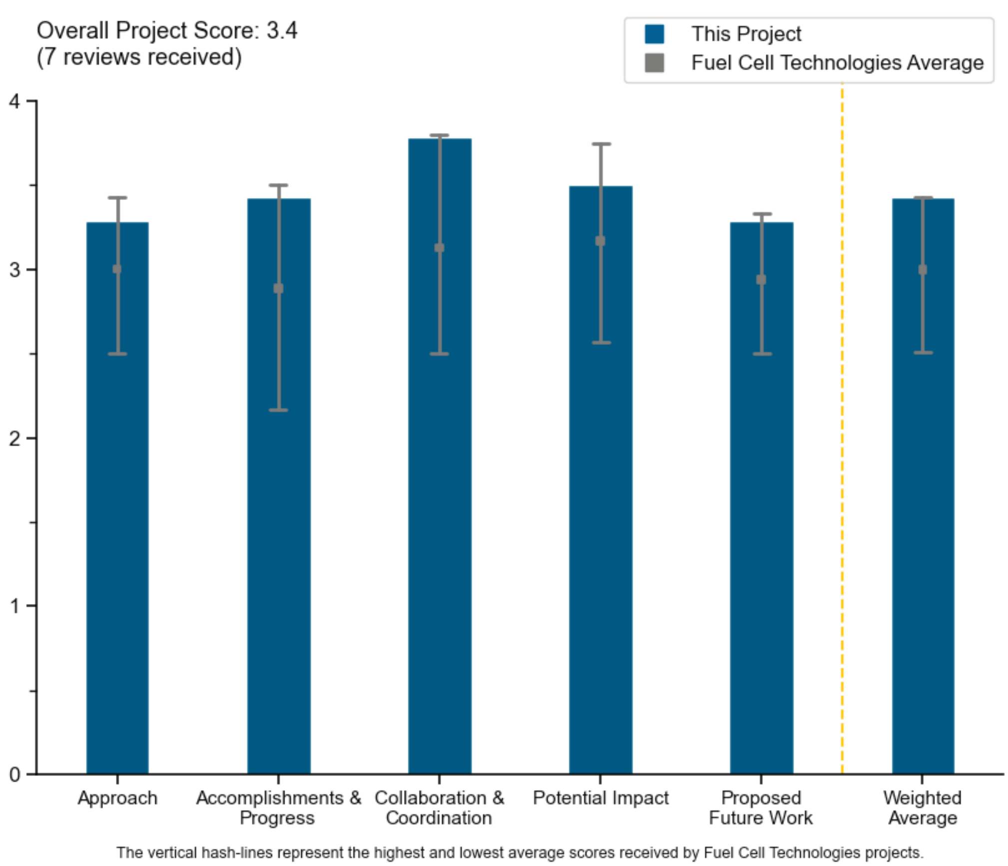
Rod Borup, Los Alamos National Laboratory, and Adam Weber, Lawrence Berkeley National Laboratory

DOE Contract #	WBS 1.5.0.402
Start and End Dates	10/1/2020–9/30/2025
Partners/Collaborators	General Motors, Nikola Corporation, Carnegie Mellon University, 3M, The Lubrizol Corporation, University of Tennessee, Knoxville, Cummins Inc., Plug Power Inc., Raytheon Technologies Corporation, NeoGraf Solutions, LLC, TreadStone Technologies, Inc., Caterpillar Inc., Eaton Corporation, R&D Dynamics Corporation, MAHLE Powertrain, LLC
Barriers Addressed	• Cell durability: 25,000 hours (2025), 30,000 hours (2030) • Peak efficiency: 68% (2025), 72% (2030) • Fuel cell system cost: \$80/kw (2025), \$60/kW (2030) • Overall target: 2.5 kW/g_{PGM} power – 750 mW/cm^2 (1.07 A/cm^2 current density at 0.7 V) – after 25,000-hour-equivalent accelerated durability test

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-equivalent accelerated durability test. The purpose is to create durable and efficient fuel cell designs suitable for adoption by the heavy-duty (HD) vehicle market.

Project Scoring



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 consortium totally covers development of key components/materials and system integrations (stack development and system modeling) for HD applications. It is very good to focus on key attributes for HD applications, efficiency, and durability. Here are some suggestions to consider additional study to reinforce the consortium.
  - Test Protocol Development for Stack Development: As mentioned, durability is an important attribute for HD application, and a proper validation method is critically imperative. The consortium now has a study to define accelerated stress tests (ASTs) at membrane electrode assembly (MEA) level with a subscale differential cell, which disengages the flow-field/bipolar plate effect. However, there is no test protocol to verify the stack design for durability. Obviously, stack conditions are different from subscale cells. For example, change of the membrane's hydration state is quite different between stack-level and subscale cells. A systematic approach to define test protocols for stack-level validation is necessary. This could be appropriate for national labs and universities to lead. It was shown that a stack project misquoted an MEA-level AST to use for durability validation with an unverified acieration factor (time factor). AST is the accelerated stress factor and not directly tied to chronological acceleration without validation.
  - Other Balance-of-Plant (BOP) Component Development: It is very good to have air management projects in the consortium. The air compressor is the largest peripheral power in the HD fuel cell system, and efficiency of the air compressor is critical. The hydrogen blower in the anode loop is also an important component, and the domestic supply is poor for HD application. Active recirculation of the anode loop is important for containing the hydrogen purge and improving the efficiency. It is highly recommended that projects be created for hydrogen blowers for HD application.
- This is a challenging presentation to review, given the broad scope for the Million Mile Fuel Cell Truck (M2FCT) consortium and impact on multiple projects. The current approach appears to have four main facets: (1) determining total cost of ownership (TCO) and the system's analysis with requirements, (2) setting standard protocols and baselines for comparison to new material/process development, (3) providing characterization and modeling support services to all DOE-funded projects, and (4) conducting independent research toward Hydrogen Program goals. In this regard, the approach is solid and meeting expectations; however, to meet the Hydrogen Program's goal of advancing commercialization, a fifth goal is recommended. Something lacking from most project summaries is an objective gap and risk analysis to advance the technology to higher technology readiness levels (TRLs) and hopefully reach a commercial readiness level. With the cumulative brainpower and experience level of the M2FCT, this would be an invaluable service to help project principal investigators (PIs) advance their projects in the right directions, strengthen their future plans, and if need be, pivot in strategy to make the most of DOE funds. This may not be the current mandate of the M2FCT, but it would be invaluable.
- Targets are clear and disseminated well to the community through the consortium site and other venues.
- Integrating with relevant partnerships and performing actual work for the partnerships are at the highest levels. The approach to report partners' achievements is duplicative and excessively detailed. Many approaches are presented as equally significant, which may not be true respective to risks and achieving the targets.
- Using a system analysis to determine what parameters have the biggest impacts on truck customer operating costs is an excellent approach. This helps guide what are the most relevant issues. The only negative was that some of the project work seems to be unrelated tangent projects in which the motivation was not so clear (i.e., studying exotic three-dimensional (3D) array membranes and zeolitic imidazolate frameworks [ZIF]-supported catalysts from constant voltage drop [CVD] methods).
- The technical approach based on the key issues of durability and cost is sound and reasonable.
- The proposed approach is well aligned with the scope and targets of the project.

- There are too many ASTs to rely on to understand whether 25,000 hours of durability can be achieved. There needs to a single model that is prioritized that can aggregate the different ASTs and deliver real-life durability estimates.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- The project helps advance the industry with at least three key accomplishments: disseminating HD cost models from the complex systems analysis; conducting detailed characterization of HD MEA degradation mechanisms; and establishing detailed ASTs for the industry and explaining how the group derived these ASTs.
- Significant progress has been achieved in the review period. The system modeling and analysis results were especially impressive and instrumental for the whole community.
- Great progress was reported in many areas of the presentation. It was great to see the breadth of work, ranging from material development to system strategy. It was great to see the systems analysis, TCO, and requirements/status spider plot set the stage for the rest of the presentation. It would be a challenge, but if there is any way to show the impact of these other projects, or the summation thereof, on the spider plot, it would be great to see. The following questions/comments highlight areas for greater clarity and potential recommendations for more hypotheses, gaps/risk analysis, and establishing a data quality metric for all concept evaluations.
    - Slide 21: It was unclear whether the number of cations in this evaluation was quantified. The effect was unexpected, as usually the inclusion of cations and heat treatment reduce water uptake and therefore reduce polymer swelling. It was unclear whether the team has a hypothesis for this. Further, it was unclear why the different dispersions were giving different conductivity when the chemistry and solvent composition are similar.
    - Slides 31/42: The project should state any expected challenges with the array electrode and co-axial nanowire electrode (CANE) concepts in keeping the structure intact after MEA processing and compression. It was unclear what the expected challenges are in scaling up this concept to high-volume manufacturing. It would be good to know what, if any, risks there are to membrane degradation with this kind of patterning. It was unclear if the team played with different aspect ratios to optimize the structure for performance and durability. It would be great to complete a gap and risk analysis for all concepts, taking into account TRL and key challenges to commercialization.
    - Slide 37: It is great the baseline evaluation was done, as many concepts will be compared against this data set. It was mentioned in the presentation that the data was repeated. For this particular data set, it is recommended that error bars be used to show the variation and data confidence so the value of other concepts can be clearly seen. Further, this would provide a good performance set so other labs could compare their own data sets in line with the new MEA AST. It is recommended that the project provide the same baseline set for the component ASTs.
    - Slide 58: Stabilizing antioxidants is an important challenge for achieving the HD durability targets. Based on this Ce retention, it is unclear if modeling will be done to understand the impact over longer time scales to show the crown ether is stable. Open-circuit voltage testing showed improvement over membrane durability; it was not clear whether any impact on performance is expected as Ce dissolves.
- As for the previous years, the results presented are numerous and of high quality. There is a good balance between prospective research for new materials, deep evaluation of existing materials, and development of relevant testing procedures. Regarding modeling, as there are several stack producers offering high-power stacks (+200 kW), it is unclear what the impact of using them would be, as it may lead to different BOP components and simplified architectures. It is surprising to see that operations and maintenance (O&M) costs are the same for diesel engines and fuel cells. Some bus operators claim that fuel cell O&M costs are much higher. Array electrode and CANE seem very promising. Evaluating industrial production and performing testing with increased surface areas (single cell of 50 cm^2) are encouraged. All the lab tests are performed using a classical serpentine design. As it differs significantly from current flow designs, it

should be investigated if the lab results reflect the performance/degradation in current stack designs. If not, a new design should be adopted, even if comparison with many years of data may be lost.

- Fuel Cell System Sizing Analysis: One of the remarkable accomplishments is system sizing analysis for capital expense and TCO benefit. It is expected that outcomes could update the design target for each project. Particularly, sizing is critical for air management projects. Ink Formation and Electrode Structure: Implications of catalyst layer cracks with performance and durability are unclear (no explanation of Method 1–5), and it is unclear whether it is specific for high-oxygen-permeable ionomer. Durability Analysis: Mechanism analysis on the resolution of Pt and PtCo alloy (or intermetallic) would be needed in order to understand the durability of the MEA, which can eliminate voltage clipping and improve the efficiency (high potential operation enabler).
- Progress to achieve targets through enhanced ionomers, membrane stabilization, and catalyst/electrode structure research is very good; however, a multiplicity of approaches to every MEA component brings chaos rather than structure and makes the roadmap confusing. Justification of new AST protocol is weak, and the degradation results in H_2–N_2 dominating over H_2–air are controversial and contradicting past experience by academia and industry. Monotonic degradation in AST justifies a shorter end of test than 500 hours using respective metrics. It is recommended that intermetallics be held at higher than 1 A/cm^2 current density for longer time and confirm they are not increasing electrode resistance. While the targets are specified at ~1 A/cm^2, the economics would be more attractive at higher-rated power densities.
- Excellent fundamental work is being conducted. Though the biphenyl sulphone: H Form (BPSH) work for membranes was a bit confusing because it is known BPSH will not last under truck operating conditions. It was difficult to understand how the PIs believe the 25,000-hour durability was met (Slide 19, spider chart).

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 structure of the project ensures an outstanding collaboration between the partners and with any additional relevant entity.
- The consortium has extensive and effective collaboration within the core lab teams and with a variety of external teams.
- The project has a strong and proper balance of members, industry, academia, and national labs.
- A top-notch set of collaborators are on this project.
- M2FCT is partnering with a broad group of national labs, universities, and industry.
- It was unclear which parts of the presentation were coordinated with which project, so it is difficult to assess the strength of coordination on each DOE project. Based on the data presented, it appears there was great support of several projects. It would create more value if M2FCT could have the mandate for a greater guidance role to drive technologies forward. This could be a voluntary ask from the various project PIs to audit their projects and strengthen their plans.
- Relation management with funded and non-funded parties is well organized and well presented. A consortium is an excellent tool for the industry and academia. Access to the specific consortium’s unique capabilities related to diagnostics, modeling, and the infrastructure could be enhanced and more transparent to the industry.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- From a fuel cell perspective, M2FCT is helping to address technology needs for fuel cell truck implementation, which is likely the first step toward wide-scale adoption of fuel cell vehicles. If wide-scale deployment of hydrogen refueling can be achieved in parallel, this project will have significant impact.
- HD fuel cell trucks are the first market entry point for large-scale renewable hydrogen. Developing highly efficient and affordable HD fuel cell trucks is the critical battle that the community has to win.

- The outcomes of this project have significant impact in achieving the cost, performance, and durability—ambitious targets.
- Hydrogen fuel cells for HD commercial vehicles are one of the most important areas for the Hydrogen Program. The consortium focuses on efficiency and durability of fuel cell systems and TCO benefits.
- M2FCT represents significant expertise and has broad impact on the hydrogen industry. This presentation highlights the current status and key challenges toward broader commercialization of fuel cells into the HD transport sector, and all work is relevant and working toward meeting these challenges. It would be good to provide an evaluation of the TRL and analysis of the gaps and risk on each concept to highlight the relative impact and value. This would have the added benefit of strengthening the path forward and where future DOE money would best be spent.
- The project is highly synergistic with the DOE objectives and has a high potential impact, advancing the project toward the DOE goals. However, there is still risk of concluding exotic and not scalable MEA structure that may not be accepted for the industry to scale up.
- Many good results and excellent fundamental approaches are included. To show achievement of key metrics, the project needs to think through how to aggregate those results to come up with something practical for the industry.

Question 5: Proposed future work

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

- The project's future work is reasonable, detailed, and well structured. It is also well aligned with the mid-term and final goals.
- Great detail was shown on the path forward for each segment. It would be valuable to understand the priority and importance of each area to better understand the impact and spread of resources toward low- vs. high-TRL concepts. Even a high, medium, or low ranking would help indicate where M2FCT sees the best bang for the buck.
- Very detailed plans for future work are outlined in the presentation and project plan. A better explanation is needed to justify further development of technologies that do not seem necessary or applicable for HD truck implementation, such as 3D array membranes and ZIF-supported catalysts from CVD methods.
- The project should prioritize a combination of practical concepts to achieve durability and cost targets.
- The future works presented (slides 62 and 63) are strongly supported. Here are some suggestions to consider for additional study to reinforce the consortium.
    - Test Protocol Development for Stack Development: As mentioned, durability is an important attribute for HD application, and a proper validation method is critically imperative. The consortium now has a study to define ASTs at MEA level with a subscale differential cell, which disengages the flow-field/bipolar plate effect. However, there is no test protocol to verify the stack design for durability. Obviously, stack condition is different from subscale cells. For example, change of the membrane's hydration state is quite different between stack-level and subscale cells. A systematic approach to define test protocols for stack-level validation is necessary. This could be proper for national labs and universities to lead. It was shown that a stack project misquoted an MEA-level AST to use for durability validation with an unverified acieration factor (time factor). AST is the accelerated stress factor and not directly tied to chronological acceleration without validation.
    - Other BOP Component Development: It is very good to have air management projects in the consortium. The air compressor is the largest peripheral power in the HD fuel cell system, and efficiency of the air compressor is critical. The hydrogen blower in the anode loop is also an important component, and the domestic supply is poor for HD application. Active recirculation of the anode loop is important for containing the hydrogen purge and improving the efficiency. It is highly recommended that projects be created for hydrogen blowers for HD application.
- The project should further focus on integrating the leading concepts in ionomers, catalysts, and structures on the MEA level and verify performance and degradation results as presented by the consortium through

industry testing and not only by the consortium. Short rainbow stack verification by the National Renewable Energy Laboratory could be duplicated by the industry partners.

- The project is encouraged to include real-life evaluation of aged components to develop robust AST protocols and assess the relevance of continuing to use conventional serpentine flow fields.

Project strengths:

- There has been great progress in the areas of (1) determining TCO and the system's analysis with requirements, (2) setting standard protocols and baselines for comparison to new material/process development, (3) providing characterization and modeling support services to all DOE-funded projects, and (4) conducting independent research toward Hydrogen Program goals. There is progress at varying TRLs, and some novel concepts are being explored. Further, it is excellent to see the support of diversity, equity, inclusion, and accountability goals into the various projects.
- The consortium project has clear objectives, excellent organization, strong teams, and effective communication and collaboration among the many lab teams. The project also shows a clear pathway to achieving DOE goals for HD fuel cell truck development.
- Access to the advanced and high-risk concept materials, implementing concept components into MEAs and electrodes by standard benchmarking techniques, is of high value to the industry. The consortium members' expertise is on top of the industry.
- The project leveraged modeling to determine the important factors in HD fuel cell truck system development. The project used detailed characterization and reasoning to develop new industry ASTs.
- The project is very well structured, based on a great team of experts and an excellent coordination of all the activities.
- A strength of the consortium is synergetic collaboration among capable members of industry and academia, including national labs.
- Strengths are teaming and access to tools for fundamental analysis.

Project weaknesses:

- There is great detail on the path forward for each segment. It would be valuable to understand the priority and importance of each area to better understand the impact and spread of resources toward low- versus high-TRL concepts. Even a high, medium, or low ranking would help indicate where the M2FCT sees the best bang for the buck. Further, something lacking from most project summaries is an objective gap and risk analysis to advance the technology to higher TRLs and hopefully reach a commercial readiness level. With the cumulative brainpower and experience level of M2FCT, this would be an invaluable service to help project PIs advance their projects in the right direction, strengthen their future plans, and if need be, pivot in strategy to make the most of DOE funds. This may not be the current mandate of the M2FCT, but it would be invaluable. This could be a voluntary ask from the various project PIs to audit their projects and strengthen their plans. This would be good to see for the M2FCT projects as well.
- The project has a very large scope and many participating PIs. Sometimes it may lose focus just because of the size and scope. Certain targets such as power output and PGM loadings are too safe, which may not be challenging enough to stimulate breakthrough and innovations.
- There is a multiplicity of high-risk concept materials under study. Hybridization approaches for the catalysts are lacking or were dismissed. High-risk electrode structures (CANE, etc.) are not verified for sensitivities to common electrode failure modes, such as flooding.
- Some of the work presented seemed to be unrelated side projects. A better explanation for the motivation or relevance of the advanced materials work would be beneficial.
- There are too many ASTs. There is too much focus on fundamentals and new concepts when the current need is an engineered solution that can compete with diesel trucks.
- Comparison with real-life aged components may be increased.
- No significant weakness has been seen.

Recommendations for additions/deletions to project scope:

- It is suggested that the project team deploy a systematic approach in identifying test protocols for durability validation for components to stack level. Durability is an important attribute for HD application, and a proper validation method is critically imperative. The consortium now has a study to define ASTs at MEA level with a subscale differential cell, which disengages the flow-field/bipolar plate effect. However, there is no test protocol to verify the stack design for durability. Obviously, stack condition is different from subscale cells. For example, change of the membrane's hydration state is quite different between stack-level and subscale cells. A systematic approach to define test protocols for stack-level validation is necessary. This could be proper for national labs and universities to lead. It was shown that a stack project misquoted an MEA-level AST to use for durability validation with an unverified acieration factor (time factor). AST is the accelerated stress factor and not directly tied to chronological acceleration without validation. For the air management project, it is suggested that the consortium define a common metric to measure efficiency. Currently, each project uses different metrics.
- It would be great if the consortium project could conduct a more thorough study on the heat rejection and management of the HD fuel cell system and take a more aggressive approach in improving existing or developing new materials that can increase the operation temperature of proton exchange membrane fuel cells. This is a major issue for HD truck design, which has not been sufficiently addressed in the project.
- In light of the polyfluoroalkyl substance (PFAS) regulatory discussions, it is recommended that the project look into perfluorosulfonic acid (PFSA) ionomer control and recycling strategies. The presented highlighted some work looking at hydrocarbon polymer materials; however, this technology is potentially decades away from being commercially viable. A more realistic approach to the PFAS regulation concerns is addressing control and recycling of these materials.
- It is recommended that the project further develop in-cell characterization highlighting MEA component deficiencies along degradation in ASTs (other than polarization curves, electrochemical surface area, and mass activity), specifically proton conductivity/mass transport in the cathodes. The team should develop explicit structure–property polarization curve relations for cathodes that remain true through the ASTs. Concepts should be weighed prior to disseminating.
- The project should attempt to verify the usefulness of the new ASTs in predicting real-world results. Collecting data from real-world demonstrations, even unsuccessful demonstrations, can help to confirm whether any stressors are present that the ASTs do not cover.

Project #FC-344: Low-Cost Corrosion-Resistant Coated Aluminum Bipolar Plates by Elevated Temperature Formation and Diffusion Bonding

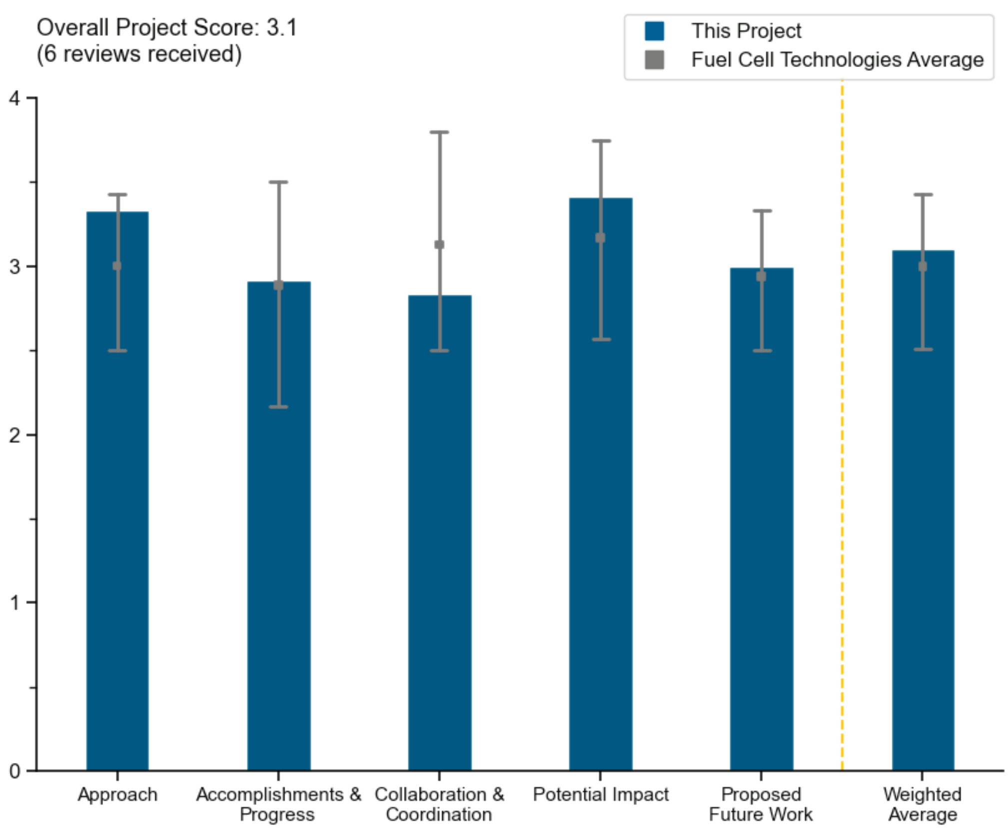
Tianli Zhu, Raytheon Technologies Research Center

DOE Contract #	DE-EE0009612
Start and End Dates	12/1/2021–11/30/2024
Partners/Collaborators	Pacific Northwest National Laboratory, TreadStone Technologies, Inc.
Barriers Addressed	• Targeted bipolar cost of $5/kW • Die design and forming process development for extremely small tolerances and complex geometries • Performance of the bipolar plate

Project Goal and Brief Summary

The project focuses on developing a defect-free coating process to fabricate low-cost corrosion-resistant coated aluminum bipolar plates (BPPs) for proton exchange membrane (PEM) fuel cells. BPPs are crucial in PEM fuel cell stacks, contributing to their weight, volume, and costs. The project utilizes elevated temperature forming and diffusion bonding and is developing a defect-free corrosion-resistant titanium coating, optimizing TreadStone Technologies' DOTS technology using carbon particles or gold to meet performance targets.

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 seeks to develop new technologies for manufacturing aluminum BPPs to improve functionality and reduce cost to meet the DOE target of $5/kW. More specifically, the team takes a different route of using high-temperature diffusion bonding to laminate aluminum substrate with Ti foil, eliminating coating defects and improving corrosion resistance. This strategy is combined with DOTS technology to ensure good electrical contact and electrical conductivity. The technical approaches of this project are appropriate and effective, covering all key aspects of aluminum BPP fabrication.
- The proposed approach is aligned with the scope and objectives of the project.
- The project approach seems reasonable. Adding the following studies is recommended:
    - Formability with thinner aluminum substrate plate: Use of aluminum is effective to the weight reduction of the fuel cell stack. However, thick aluminum plates reduce the effect and make the stack large. Using a thickness similar to state-of-the art stainless steel BPPs, e.g., 0.10 mm, is expected. Thinner plate makes stamping formability difficult. The currently used aluminum substrate with a thickness of 0.25 mm makes the fuel cell stack volume significantly larger. It is highly recommended that the project study formability with a significantly thinner aluminum plate, ideally 0.10 mm.
    - Aluminum leaching out: It is known that an aluminum ion is harmful to the PEM. It is recommended that the project check not only the corrosion current but also identify leaching out of metal ions.
    - Au DOTS: The project intends to use the Au DOTS technology to keep electrical conductivity on the BPP surface. Au is durable enough for normal operating conditions (normal fuel cell potential range) but not durable enough for high-potential conditions such as at the cell reversal condition (more than 1.2 V vs. dynamic hydrogen electrode [DHE]). The team should consider material/ coating selection for DOTS technology that is durable enough for anticipated conditions, including abnormal operations. Generally, Au is no longer used for the BPP coating of automotive fuel cells.
- Using Al as the main plate material should allow lower costs than steel- or Ti-based plates and could allow the project to meet cost targets. The use of elevated temperature should improve formability. The focus on formability in Year 1 is appropriate. The 25 µm Ti foil to be used for the coating seems thick, and a thicker coating could provide misleading information when it comes to formability issues and concerns about thinning/cracking of the coating during forming. The cost estimate uses 7 µm thick Ti (which is not available). Cost modeling should use Ti foil with a thickness that is currently available or show a sensitivity to Ti foil thickness (cost is not always proportional to thickness, especially as thickness decreases).
- The presentation indicates that the go/no-go decision relies on corrosion data from a Ti-coated Al plate without Au DOTS. Corrosion testing on the actual proposed structure/architecture should be repeated. Cost per kilowatt cannot be properly assessed without performance data, channel depth/width, landing fraction, etc. Capabilities should be assessed against metrics for optimum design/state of the art to ensure no performance is lost due to stamping capabilities.
- The team has established the proof of concept for the diffusion-bonded Al-Ti coupons and shown lower corrosion currents compared to Ti-Al and SS316. However, real-time application as a PEM fuel cell BPP is necessary to consider this technology to be a viable alternative for making BPPs in high volume.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and DOE goals.

- The team has made some progress in making diffusion-bonded coupons and carried out tests to evaluate their mechanical stability. It will be good to see how these diffusion-bonded bipolar plates work in 25 cm^2 and/or 50 cm^2 single cells.
- During the current period (Year 1), the project is planned to focus on elevated temperature forming and diffusion-bonded optimization to minimize forming time, die wear, and geometry reproducibility, as well

as the adhesion strength of diffusion bonding. Optimization efforts via design and modeling have been reported; however, experimental studies were delayed because of supply chain issues. Toward budget period 1 milestones, it is good to see the team has clarified a future path (thinner Ti foil, stacking, and reduced cycle time) to reach the $5/kW goal via techno-economic analysis. However, it is concerning that:

  - Samples for tensile tests were prepared with 25 µm Ti foil, not the 10 µm that was studied in the techno-economic analysis.
  - The flexural strength test result (one of the two important key performance indicators for mechanical strength) was not from this project (but rather from Pacific Northwest National Laboratory's [PNNL's] previous study), and a much thicker aluminum substrate (0.5 mm) was used in that study.

It could be difficult for the project to reach go/no-go milestones.

- The presented accomplishments are correct in terms of modeling the feasibility of different features of Al-based BPPs and the performance and cost. Some questions arise as to what the minimum thickness of the foils is and whether the diffusion-bonded process is acceptable for the high rates of production needed. Using only one Ti-coated side leads to lower cost, but it is unclear how the Al/Al welding and the long-term durability are affected. It is unclear how the stamped edges look. It is unclear whether Ti covered the Al foil, and if not, what the impact on the corrosion resistance would be. Carrying out evaluations of the BPPs in a real fuel cell is highly expected.
- With the use of finite element analysis simulation, it is good to achieve proper elongation with an aluminum plate. A thinner plate is expected to be used to contain the stack volume. It is expected that the formability study would be extended with a thinner plate, ideally similar in thickness to the state-of-the-art stainless steel BPP, e.g., 0.10 mm.
- The project should examine a cross-section of formed material to see whether there are any issues with Ti thinning or cracking during forming.
- Emphasis was made on strength and forming without showing adequate corrosion data.

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 team has established collaboration with a national lab and a small business.
- It is good to involve the national lab's capabilities in the project.
- Collaboration appears to be correct.
- All work in Year 1 was performed by the PNNL team, and there was no clear evidence showing how other research leads have been contributing to the project so far. Although this is likely just how the project was planned, it would be great to see closer collaboration between the project teams.
- There is good collaboration within the project team. The team should collaborate with the Million Mile Fuel Cell Truck (M2FCT) consortium for BPP testing. Collaboration with a stack manufacturer to ensure the forming is acceptable with the project BPP design would be beneficial.
- It would be useful to have an additional industrial partner with real-world experience designing metal plate geometries and fabricating metal plates that have been used in commercial products.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The proposed work will have great impact if the team successfully shows promising results in larger-area single cells and short stacks.
- The project is potentially high-impact work. The lower cost and weight of Ti-coated Al plates would provide significant benefits.
- Achieving low-cost and durable BPPs will contribute to lowering the stack cost to the targets.

- Metallic BPP technology is critical for heavy-duty (HD) fuel cell stacks, and domestic sources ensure stable supply chains for HD applications. Use of aluminum enables potentially reducing the stack weight compared with state-of-the-art metallic BPP technology, such as coated stainless steel plates (0.1 mm thickness). However, the project currently uses thick substrate plates (0.25 mm), which makes stack volume significantly larger, probably too large for HD applications. It is highly recommended that the project revise the approach and focus on substrate thickness and formability to make it more effective for the applications.
- The project seems to focus on cost at the substrate material level: forming the sheet. Forming plate halves and bonding them and the cost of that at production-level scale needs to be included. This is where costs could skyrocket and the project will become unfeasible, and this is where the project may not be completely aligned with DOE objectives. Risks seem to be weighted toward the negative side (the pareto chart indicates a higher chance of increasing costs) and a high risk of not meeting the DOE target.
- The project addresses an important challenge for PEM fuel cell development and the DOE target to reduce the cost of fuel cell stacks for HD vehicle applications. While Ti BPPs (the current state of the art) have superior advantages of light weight, good mechanical strength, and corrosion resistance, they are not economically feasible because of the high price and limited supply. Enabling low-cost, defect-free aluminum BPP manufacturing would be a game changer and significant breakthrough.

Question 5: Proposed future work

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

- The proposed future plan is reasonable for catching up some of the delays. Some testing may not need to be full-scale, such as corrosion and resistance tests, which may be pulled ahead in parallel. This may also help promote collaborations between the teams.
- Not enough emphasis was placed on material compatibility with fuel cells. Titanium is a well-known membrane poison; the possibility of titanium contamination of the membrane from the coating should be investigated as a potential showstopper early on, in case the lifetime requirement cannot be met.
- The project should look at joining, welding, and bonding in future work and include these in cost estimates. High temperatures used in elevated-temperature forming may increase oxide layer thickness and make joining more difficult.
- In addition to the proposed future work, it would be interesting for the overall evaluation of BPPs to include a life cycle assessment (LCA) and an assessment of recycling these coated BPPs.
- The team has proposed a significant amount of work to be carried out to meet the go/no-go criteria.

Project strengths:

- The project has a good concept and technical approach for obtaining defect-free aluminum BPPs. The project has a strong team, with strong leads and complementary expertise to achieve the goal.
- Finite element analysis has been used for stamping formability. This model-based engineering is one of the project strengths. Validation of the model is expected.
- This is a good project team. Al plates have high potential to meet cost targets if a defect-free corrosion-resistant coating can be applied.
- This project relies on an experienced team of experts.
- Strengths are an interesting concept and a well-rounded team.
- Involvement of a national lab is a strength.

Project weaknesses:

- The coating technology should be reconsidered. It is highly concerned with use of Au DOTS for automotive fuel cell conditions. Au is durable for normal operating conditions (normal fuel cell potential range) but does not have enough durability for high-potential conditions such as at the cell reversal condition (more than 1.2 V vs. DHE). The team should reconsider the material/coating selection for DOTS technology to make enough durability for anticipated conditions, including abnormal operations. Generally, Au is no longer used for the BPP coating of an automotive fuel cell.

- The focus is on detail; a high-level view of the impact in a commercial fuel cell is missing too many manufacturing steps and uses inherently expensive materials. There is no cost analysis beyond one for plate substrate material, and there is no early evaluation of fuel cell compatibility (particularly with the membrane).
- Progress was substantially slower than originally planned. Synergy among the project teams has not been demonstrated yet.
- The first validation of the new BPPs in a real fuel cell should be evaluated earlier in the project. LCA and recycling are not considered.
- The project needs fuel cell testing, at least in 50 cm^2 cells.
- The project needs to look at joining.

Recommendations for additions/deletions to project scope:

- This project is highly relevant to the goal of HD fuel cell development. Aluminum is a lightweight metal, and it potentially enables reduction of the stack weight. It is an important benefit for not only current HD applications but also aviation applications, in the future. Currently, the project uses a 0.25-mm-thick substrate, which reduces the benefit of weight reduction and makes the stack size significantly larger. State-of-the-art automotive fuel cell stacks use stainless steel or titanium substrate. Their substrate thickness is 0.10 mm, and the unit cell thickness is around 1.1–1.3 mm. If the substrate thickness was increased 0.10–0.25 mm, the unit cell thickness would be around 0.3 mm thicker. Usually, a stack consists of around 500 unit cells, which would make the stack 150 mm longer. It is highly recommended that the project focus on the substrate thickness and improve stamping formability with a thinner substrate. The second recommendation is to reconsider the Au DOTS technology on the surface. Au is stable for normal operation conditions (potential) but not durable at high potentials, which may happen at cell reversal conditions.
- Techno-economic analysis identified that reducing Ti foil thickness to 7 µm was necessary to meet the cost target. As such a thin foil is not commercially available, the model study needs to consider re-tooling cost for a Ti foil supplier to make this new product. The fuel cell stack market is typically too small for commodity manufacturers to change production lines; additional cost may be expected.
- The project should add additional in situ durability and performance testing and complete manufacturing cost (including stamping and welding, at high volume rates).
- LCA and recycling of these new BPPs could be considered, as it appears less obvious than stainless-steel-based BPPs.
- The project should collaborate with M2FCT consortium members to independently evaluate the BPPs in 50 cm^2 cells.
- The project should look at joining/welding of plates.

Project #FC-345: Development and Manufacturing for Precious-Metal-Free Metal Bipolar Plate Coatings for Proton Exchange Membrane Fuel Cells

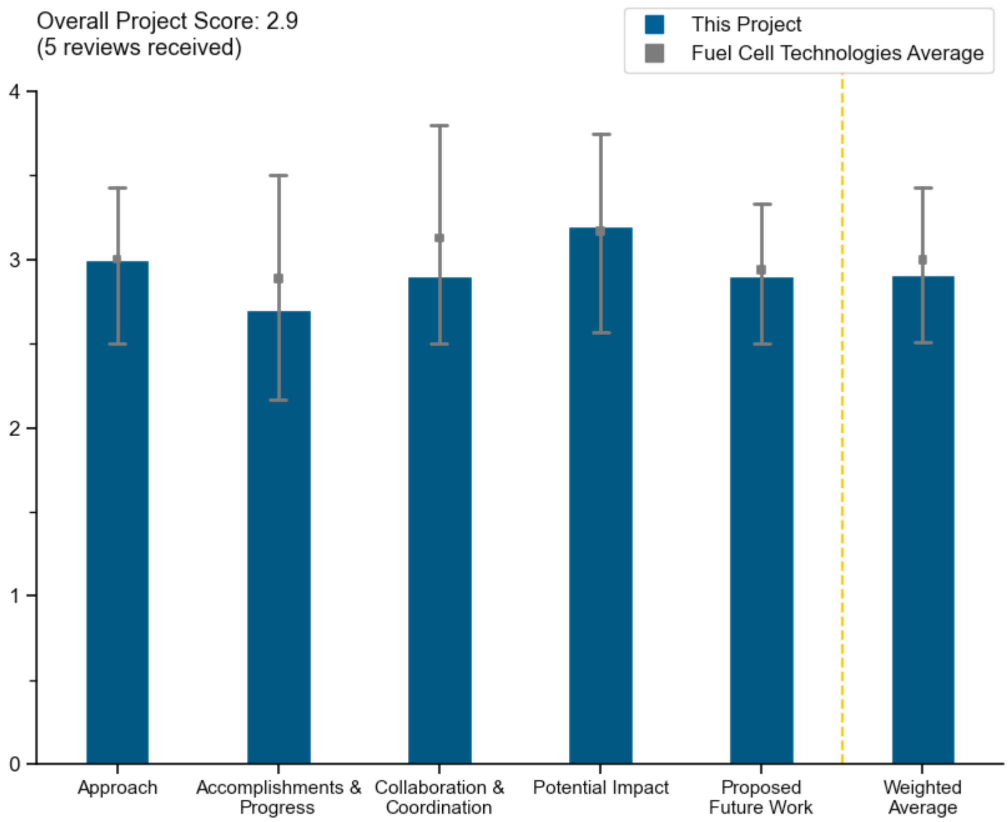
CH Wang, Treadstone Technologies, Inc.

DOE Contract #	DE-EE0009613
Start and End Dates	9/17/2021–3/31/2024
Partners/Collaborators	Los Alamos National Laboratory, Pacific Northwest National Laboratory, University of Tennessee, Knoxville, Austin Power
Barriers Addressed	Bipolar plate durability and cost: • Cost: <$5/kW (2025) • Resistivity <10 mΩ.cm^2 • Corrosion <1 x10-6 A/cm^2

Project Goal and Brief Summary

The project focuses on developing a cost-effective fabrication process for precious-metal-free doped titanium oxide (TiO_x) coatings on low-cost metal substrates (low-grade stainless steel [SS] and aluminum) for heavy-duty applications in proton exchange membrane fuel cells (PEMFCs) suitable for roll-to-roll manufacturing processes. Bipolar plates (BPPs) are the second-most expensive component in PEMFC stacks. The goals include reducing the manufacturing cost of metal BPPs to meet a cost target of approximately $5/kW, developing an accelerated stress test (AST) protocol for rapid evaluation of BPPs, and investigating the conductance mechanism of the TiO_x coating. Activities include demonstrating viability of diffusion-bonded titanium to aluminum, improving diffusion bonding cycle time, optimizing the TiO_x formation process on the Ti-Nb particle surface, demonstrating the TiO_x coated BPPs in PEMFC single-cell evaluation (including operation under AST conditions), and investigating performance degradation mechanisms of the TiO_x coating under PEMFC application conditions.

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 aims to develop manufacturable precious-metal-free BPPs for fuel cells, and it is halfway to its completion. The approach is utilizing Ti-based coating of SS to gain both the reduced manufacturing cost and improved durability. The approach seems to be relying on a well-thought-out process that built on the legacy established by participating partners in this project. The approach is well defined, well executed, and most importantly, well-grounded to the fundamentals that enable its feasibility.
- Combining low-cost substrate, diffusion bonding, and chemically inert particulate oxide coating is an adventurous but smart approach to reach multiple technical targets.
- The approach is a little confusing. The first slide addresses SS as substrate, while the rest of the presentation talks about aluminum. The approach is too focused on plate performance and cost without understanding the performance and cost in a complete fuel cell or system (for example, it is unclear whether the targeted performance is achievable with this kind of plate or whether more cells will need to be added to meet the required power). To avoid spending money on a dead-end path, the risk of using titanium in a fuel cell environment (which is a known membrane poison) needs to be addressed earlier.
- The main concern is that the approach of coating after stamping leads to coating cracking, which will expose the base metal surface (low-grade SS or aluminum), which subsequently leads to corrosion. Another significant concern is titanium stability during fuel cell operation. Platinum-group-metal-free coating is the right approach but is not unique to this project. Measuring Fe release during corrosion testing using inductively coupled plasma mass spectrometry (ICP-MS) is good; Treadstone Technologies, Inc.

(Treadstone) should also measure Al release for the Al plates and Ti release for all samples. The rough surface approach seems to help reduce contact resistance.

- Diffusion bonding of titanium to aluminum or SS substrates seem to be the only path investigated in this project. Although this project is focused on SS substrates, the approach is limited to using dibutyl phthalate (DBP). It would be better for the project to investigate other options for Ti bonding to SS to minimize risks and understand the techno-economic challenges better. Although the approach in this project uses Treadstone's DOTS technology for the TiOx surface coating, there is no effort to compare with other coating technologies. The recommendation is to do a techno-economic analysis of other state-of-the-art TiOx coating technologies, including mixed metal oxide coatings from thermal curing of appropriate precursors.

Question 2: Accomplishments and progress

This project was rated **2.7** for its accomplishments and progress toward overall project and DOE goals.

- Although the current progress toward the overall project goals is on track, a few gaps in the data need to be addressed to provide more clarity for the performance indicators.
  - The scale of the Ti layer on the Al substrate is not mentioned (on slide 7). This needs to be a key performance indicator (KPI) for the DBP cycle time and cost.
    - The cost or technical benefits for diffusion bonding at higher pressure and temperature need to be included in the cost analysis for feasibility (on slides 7 and 10).
  - It is not clear whether the corrosion current measurement procedure (on slide 8) is an American Society for Testing and Materials (ASTM)- or DOE-prescribed AST test method for this application. The corrosion current of <1 uA/cm^2 after approximately 90 hours is promising, but this test needs to be run for longer duration under relevant use case cycles, for example, under HD fuel cell truck load cycling conditions.
    - Cost analysis assumptions in slides 9 and 10 need clarification. Slide 9 suggests an 80 kW net fuel cell system, while slide 10 refers to 80 kW stacks. Moreover, slide 9 notes 1,150 mW/cm^2 at 0.663 V, 378 cells, and 328 cm^2 BPP, which works out to a 142 kW stack. At that size, an 80 kW_{net} system would mean that the stack is oversized for the system needs. However, in slide 10, an 80 kW stack is called out at the same power density and cell count. Clarification is requested.
    - The thickness of the BPP, 75 um SS409, should be confirmed for adequacy with a fuel cell original equipment manufacturer (OEM), as 75 um seems too thin. Cost analysis should be based on practical BPP thickness for the application.
  - It seems that the I_{corr} (corrosion current) in slide 12 may be for a 1 cm^2 active area. The I_{corr} needs to be reported at units relevant to the targets. Also, the E_{corr} (corrosion potential) is against the Ag/AgCl reference electrode. Hence, it will be ~200 mV higher against a standard hydrogen electrode.
  - There is a very nice effort to characterize the surface oxide by etching the substrate. For future efforts, a focused ion beam (FIB) analysis, followed by a cross-sectional analysis using transmission electron microscopy (TEM) and/or scanning electron microscopy (SEM) coupled with an energy-dispersive X-ray analysis (EDAX), might be an efficient way to characterize the surface oxides.
- The project is 50% on the way to its completion, and the comments here reflect reported outcomes. The SS and aluminum BPP coated by TiO_x and Nb-TiO_x were evaluated for corrosion, which showed an increase in corrosion rate by number of applied cycles (triangular cycles between 1 and 1.5 V, 80°C, 0.1 M sulfuric acid). While corrosion anodic tests are valuable input, it is expected that more accurate in-depth measurements would have also been accomplished. The project lists ICP-MS as an anticipated method for qualitative and quantitative measuring of corrosion rates. However, that remains to be accomplished, despite the advanced phase of this project. The usual turnaround of ICP-MS analyses is rather fast, and those results should be reported along with anodic corrosion tests. The microscopic structure was done by TEM, while surface composition was probed by x-ray photoelectron spectroscopy (XPS). Provided conclusions were aligned with well-known facts about techniques instead of data analysis, which cannot be

claimed under accomplishments and progress. A new method for surface–oxide analysis, the surface lift-off, is proposed. This method cannot be claimed as new; the project should be focused on method development, and hence, this outcome should not be reported under accomplishments and progress. The overall outcomes at 50% project completion should be at a more advanced stage. Rather simple, well-established analyses must be applied. These are rather simple systems to characterize.

- Treadstone has shown low contact resistance with the Ti alloy particle coatings. The project should report a direct comparison between the resistance with rough and smooth coatings on SS. Interface contact resistance (ICR) of Nb-TiO_x is impressive. Cost projections show potential to meet the DOE target. There is still no evidence that a 409SS plate that is coated with Ti before stamping will be durable. Details of the materials for the AST test results shown were not provided.
- The cost analysis is well justified and convincing. The approach is well articulated and partially proven on aluminum substrate. Demonstrated technical achievements decrease the risk of this project. The feasibility of forming a flow field structure is still to be demonstrated. The project lacks a physical and analytical explanation of the interfaces, i.e., "why it is working."
- Accomplishments are confusing. Corrosion and ICR results refer to aluminum base material, but the cost analysis is for SS. Ex situ ASTs are not enough to demonstrate durability. Interactions with other fuel cell components must be considered.

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 team is working with Los Alamos National Laboratory (LANL) on BPP ASTs. It is suggested that the researchers try to correlate AST results with in situ plate ICR loss and corrosion/iron release. Austin Power is doing cost analysis. There is nice collaboration with Pacific Northwest National Laboratory (PNNL) on Al BBPs, as well as nice collaboration with the University of Tennessee (UT), Knoxville, on developing methods to analyze plate surface.
- There is good contribution on the cost analysis and the original diffusion-bonding technology. However, there is a lack of contribution on the surface analysis and characterization.
- Collaborations and interactions with UT Knoxville are not very clear. LANL is better suited to work on the degradation mechanism based on AST protocols. The degradation/corrosion mechanism of TiO_x is relatively well understood; understanding the kinetics of corrosion under application-specific cycles should be the project focus. The project is based on the expertise and technologies of Treadstone (DOTS technology) and PNNL (DBP technology). However, it is not clear whether this is the right technology path to meet DOE targets. Austin Power should do a comparative cost analysis of current state-of-the-art BPP technology with the project approach/goals.
- Considering the partners involved in this project, the expected outcome should resonate well with the project goals, which would be challenging to claim here. Better coordination among participants is needed, which would enable maximal utilization of their own capabilities as well as execution of trivial structural, morphological, and chemical analyses.
- An industrial partner with real-world application experience would round out this project better.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- If successful, this project has great potential in addressing the second-most expensive component in fuel cells manufacturing.
- While there are significant concerns over the durability of the project approach, it does show strong potential to meet cost and performance targets.
- There are good indicators for meeting DOE goals for reduced cost and durable metal plate; some barriers (e.g., fuel cell durability) are not addressed adequately.

- The progress toward BPP targets is significant. The feasibility of in-cell integration is still to be proven.
- Project cost analysis done by Austin Power should include the lifetime of the capital, equipment, and tooling costs needed to implement this technology for rapid manufacturing and the rate of depreciation assumption for overall $/cell or $/kW calculations.

Question 5: Proposed future work

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

- The proposed future work will address some of the noted barriers.
- Future work includes single-cell fuel cell evaluation of the TiO_x-coated BPPs in PEMFCs, including operation under AST conditions. Using conditions other than start/stop ASTs is recommended. More details should be provided on plans to investigate performance degradation mechanisms of the TiO_x coating under PEMFC application conditions.
- Future work is logical. However, it is missing a backup plan in case formed flow fields show different corrosion currents or ICRs.
- Future work must address the missing analyses, and a more thorough list is needed. The three bullet points fail to comply with all complexities and associated uncertainties, which are directly related to material properties. More focused and precise work is necessary to provide answers to straightforward questions: actual morphology of films, Nb-TiO_x vs TiO_x, surface composition, microstructure, passivation mechanism, change of electrical conductivity, homogeneity and uniformity of coatings, chemical degradation based on ICP analysis, etc.
- Optimization of the TiO_x formation process and cost analysis should include other state-of-the-art methods of forming TiO_x. The reporting metric for corrosion and resistivity targets needs to be consistent with industry specifications for BPPs, at a realistic BPP thickness, high frequency resistance, contact resistance, or flatness as KPIs.

Project strengths:

- The primary strength is targeting cost-effective base material (SS409) that has previously been considered unsuitable. The mechanism of correlation between coating roughness and contact resistance is interesting. There is an opportunity for fundamental learning here.
- Strengths include the demonstration of very low ICR, inclusion of a cost analysis, and a plan to measure Fe release during corrosion testing and set an Fe release target.
- The approach, selection of materials, project goals, and team members should be recognized as strong.
- The project strength is in the approach, showing achieving baseline targets on the material level.
- There is good collaborations with PNNL and LANL. LANL expertise with BPP ASTs and the degradation mechanism needs to be leveraged more. The Austin Power cost analysis should be improved to consider all realistic design conditions for fuel cell system applications. Perhaps the project should use the Argonne National Laboratory’s model for fuel cell system sizing and cost analysis comparison.

Project weaknesses:

- The dependence of coating before stamping is a weakness, as it will lead to coating cracking. At the very least, Treadstone must provide evidence to the contrary. Ti coatings are expected to be unstable in a fuel cell environment. Start/stop ASTs are not relevant for OEMs that will use system mitigation to keep voltages low enough to prevent cathode carbo support corrosion.
- The collaboration with UT Knoxville is not clear. LANL is better suited to work on understanding degradation mechanisms along with the AST protocols. Cost analysis should be based on a realistic fuel cell system design for light-, medium-, and heavy-duty vehicles because the system size and lifetime vary with application.
- The concept remains on the flat coupons without mechanical forming. Surface analysis is lacking. ICR testing of half-cells would add value to the project.

- Weaknesses include the use of titanium, which is a known membrane poison, and the lack of a second industrial partner with real-world application experience (e.g., a truck OEM).
- The project does not deliver in-depth analysis of materials, aging, and processing conditions.

Recommendations for additions/deletions to project scope:

- The following are recommendations:
  - Report the thickness of Ti foils on all samples.
  - Include hydrofluoric acid in ex situ corrosion tests.
  - Conduct corrosion testing stamped sheets.
  - Report the ratio of solution volume to BPP area on corrosion tests. Clarify how the cut edges of the metal samples are protected.
  - Check for Nb oxidation.
  - Include measurements of Ti and Al, along with Fe, in corrosion solutions.
- It is recommended that UT Knoxville be deleted from the project partners. An addition would be to establish a project technical baseline for BPPs (with or without coating) and include current state-of-the-art TiO_x coatings to the cost analysis models. The project should include techno-economic analysis of Ti substrates or Ti on SS or Al based on other bonding technologies.
- ICR testing of half-cells would add value to the project. The team should focus on testing the flow fields and not flat coupons.
- The project scope is fine, while execution is falling behind.
- No additions or deletions are recommended.

Project #FC-346: Fully Unitized Fuel Cell Manufactured by a Continuous Process

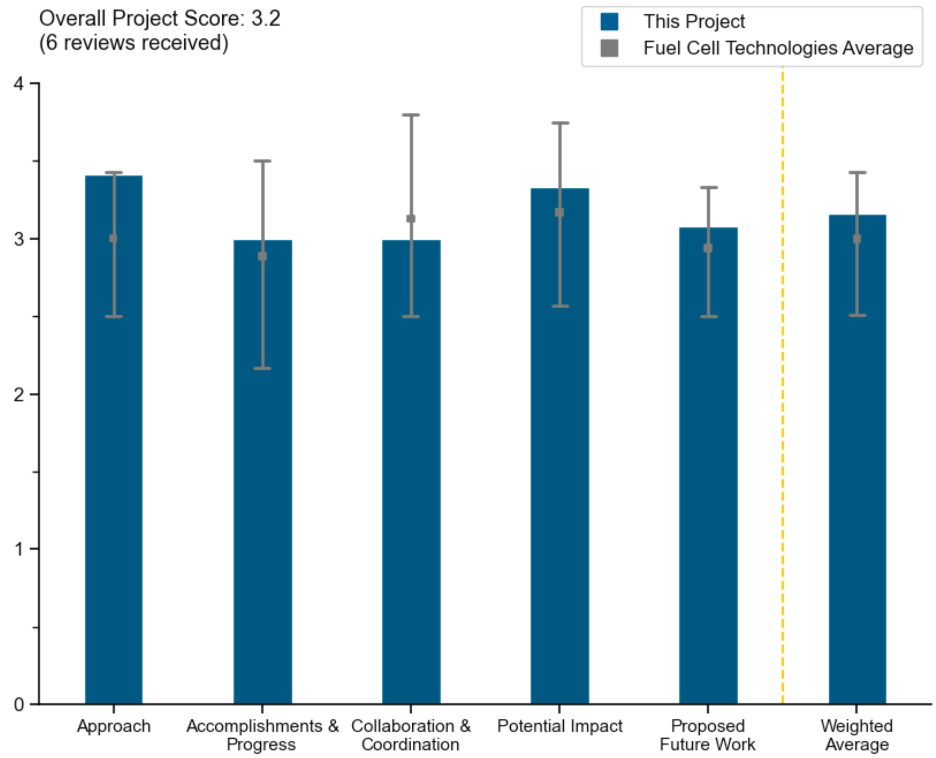
Jon Owejan, Plug Power Inc.

DOE Contract #	DE-EE0009614
Start and End Dates	2/1/2022–1/31/2025
Partners/Collaborators	University of Tennessee, Oak Ridge National Laboratory
Barriers Addressed	• Bipolar plate cost • Bipolar plate mass • Bipolar plate manufacturability

Project Goal and Brief Summary

The project aims to develop a fuel cell architecture for heavy-duty applications, specifically a proton exchange membrane fuel cell bipolar plate (BPP) utilizing flat foil metal separators with gas flow distribution through diffusion substrates' grooves, manufactured through continuous roll-to-roll (R2R) processing. Key outcomes include reducing BPP manufacturing cycle time fivefold, simplifying stack assembly, and reducing mass transport resistance. The research encompasses corrosion-resistant coatings, multiphase transport, modeling, validation, and new manufacturing methods. The projected targets involve a cost <$4/kW, a plate mass of <0.15 kg/kW, and durability of 25,000+ hours. Progress has been made in various areas, including the development of a wireless cell voltage monitor prototype, trials for coating development and characterization, and investigation of porous rib flow field geometries to enhance performance and reduce pressure loss. Additionally, techno-economic analysis (TEA) has been conducted, estimating BPP cost at $7.69/kW for stamped heavy-duty vehicle BPPs and $3.85/kW for the laminated concept, with part cycle time identified as the most influential cost parameter. The use of low-risk material (stainless steel foils) shows promise with an estimated mass of 0.16 kg/kW.

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 project concept overall is very innovative, including several potentially valuable advancements: flat plate flow design, high-throughput manufacturing, a wireless cell voltage monitor (CVM), and new coating approaches. The project may be considered high-risk, but with the high level of innovation involved, this is ideal for a publicly funded project. The project includes a strong scope of activities that are well chosen to meet the project goals, including a TEA.
- The project is focused on reducing cost and time to manufacture BPPs. There is proper selection of materials and coatings to complement the proposed R2R manufacturing method. Associated modeling suggests benefits to the proposed design vs. conventional BPPs.
- This is a well-thought-out and innovative approach to solving cost and manufacturing targets. Barriers are addressed at all integration levels (not just ex situ testing of single components but also in situ testing of integrated components).
- The project has an interesting out-of-the-box approach to fabricating unitized plates. The following are questions about the viability:
    - How the coolant mesh is held in place between the foils (i.e., the adhesion process).
    - What sealing mechanism is between the foils to prevent coolant leak.
    - Where the coolant inlet and outlet locations are on the plates when stacked together.
    - Whether the TiN coating on the plate is stable, i.e., protected from oxidization (recognizing that this is not a plate coating project).
    - What the limitations of channel flow geometry are—for example, how low channel and land width can be made using laser welding and what the effects on performance are.

  - What the sources are of the elevated high-frequency resistance (HFR) on slide 14.
  - Whether there is any fiber intrusion in the carbon fiber flow field.
- This project address barriers to high-speed, potentially low-cost plate/cell production, while introducing several new challenges. Whether these newly introduced challenges will be outweighed by the potential benefits remains to be seen. These challenges include:
  - Finding a supply for a grooved gas diffusion layer (GDL) at a reasonable cost.
  - Overcoming expected additional contact resistances between the metal films at the mesh for the coolant flow. It is unclear by what method Plug Power Inc. (Plug) will ensure robust film–mesh–film contact in the continuous R2R process.
  - Designing header ports to enable coolant flow into the metal mesh.
  - Maintaining seal and active area compression requirements with flat foil plates.
- Overall, this is a very good approach for meeting 10 million BPPs per year. The techno-economics to meet DOE cost and weight targets are dependent on the manufacturing feasibility and cycle time of the unitized BPP design. This should be the focus for budget period (BP) 2 to get an early understanding of the probability of success and cost of quality. Also, the number of 80 kW systems targeted per year should also be included in the TEA. From the TEA on slide 16, 10 million BPPs per year at a cost of $3.85/kW amounts to ~720,000 units per year.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- Good initial results have been demonstrated for most project tasks. Initial results look good for demonstrating the feasibility of the approach and down-selecting details. The project is still in an early phase, but planning and vision seem strong going forward.
- Accomplishments and progress are good, given the complexity of the concept.
- It is early in the project, but progress toward the first go/no-go decision is good.
- The project is on time to complete milestones going into the first go/no-go decision.
- The following points are unclear:
  - On slide 7, from the BPP requirements and material selection table, which key performance indicator (KPI) drives the down-selection process. There is no explanation of the definition of "+", "-", "0", etc. used to rank the materials and their characteristics.
  - On slide 8, what the parasitic loss is for the wireless CVM down the stack, as well as its requirements.
  - On slide 9, what the base material is for the "stamped channels" for cost comparison.
  - On slide10, what the scalability and feasibility is of open-air plasma treatment for BPP.
  - On slide 11, what the TiN paint thickness is and what the standard deviation at that scale is.
  - On slide 12, what the operating conditions were during the pressure drop measured between the two BPP channel depths. The sensitivity to operating conditions of temperature, relative humidity, and stoichiometry should be compared to understand boundary conditions for heavy-duty vehicle (HDV) and other applications.
  - On slide 16, whether a feasibility analysis been done for the R2R unitized BPP design to achieve 1 sec/BPP cycle time, as well as what the cost is of quality for the various cycle times. It would be good to understand or include it in the TEA.

  On slide 13, based on the downward trend of differential pressure for the porous rib vs. channel depth, it is suggested that the project try a porous rib with a 1.0 x 0.5 mm channel. The manufacturing feasibility of porous ribs also needs further clarification. Technical and cost barriers to the manufacturing of porous ribs need to be addressed early, before additional project funds are spent on the development of this concept. On slide 15, the University of Tennessee (UT) performance model is very detailed and provides a very good indication of the benefits of the porous ribs. Modeling the O_2 mass fraction as a function of channel dimensions should be focused in BP 2 prior to manufacturing pilot trials for this concept.

- N_2 plasma has been demonstrated to be capable of coating Ti-painted stainless films. There is no data for contact or corrosion resistance as of yet. Performance in porous rub cells shows benefits over solid cells at low oxygen stoichiometry results. The HFR is slightly higher than in the solid cell. Plug has demonstrated the project can meet the cathode pressure drop with GDLs with laser cut grooves, which is not representative of the final product. GDL channel prototypes have not been delivered.
- A wireless CVM has been produced, but accurate voltage reading has not yet been demonstrated.

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 collaboration and coordination are at an appropriate level. Having an industrial partner with real-world application experience as the principal investigator (PI) for this project is extremely valuable, ensuring that research and development value is also practical and targeted toward solving real problems.
- Collaboration between the partners is good. The contribution from Oak Ridge National Laboratory (ORNL) and UT is sufficient. External companies such as Smith Engineering and Limitless Design have been engaged well.
- All funded collaborators are contributing individual expertise to critical aspects of project. A number of non-funded collaborators were also mentioned in the presentation. In the next Annual Merit Review, it would be helpful to see, specifically, more information on options for manufacturing the grooved GDLs and the robustness of said GDLs when exposed to stressors experienced during fuel cell operation.
- The team members overall appear to be coordinated well to address the complex project goals. Tasks or project partners are well defined and clearly oriented toward the project goal. It is suggested that more iteration be conducted on the results from different team members in the coming budget periods.
- The collaboration with Smith Engineering, Limitless Design, and non-funded collaborators is unclear. The presentation did not mention whether Smith Engineering and Limitless Design are cost-sharing partners or vendors in the project. It would be helpful to know whether other CVM vendors were considered. If so, the PI should provide additional details on what the requirements were for this component and the supplier selection process. ORNL is developing the open-air plasma treatment and performing the interfacial contact resistance (ICR) and corrosion tests. However, it is not clear that these tests will be performed at the single-cell size for validation. The TiN-coated BPPs need to be tested for defects at beginning-of-life and at end-of-life (EOL)/end-of-transmission as well.
- This project really needs a GDL supplier as a partner capable of making grooved GDLs. UT has done some modeling, but it is unclear how it is driving the design. The model polarization curves are much lower than the data. ORNL did plate coating and surface analysis. The reviewer is looking forward to seeing the contact resistance and corrosion results. It was unclear who did the cost analysis (Plug or Smith Engineering).

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project appears very innovative, including several technologies that would all have significant impacts on advancing the DOE fuel cell program objectives. This type of high-risk but potentially high-impact work is ideal for publicly funded projects at the stack level. The flat plate BPP approach has high potential impact, as it can address manufacturing throughput challenges with BPP forming, as well as addressing issues with coating formed plates, simplifying manufacturing, and lowering stack weight and cost. Wireless CVMs and new coating approaches included in the project also have good potential impact.
- There are so many valuable aspects to this project (manufacturing, cost, diagnostic methods, materials development, performance, system efficiency) that this project has enormous potential to meet DOE goals.
- TEA projects that propose material selection and manufacturing methods will meet DOE targets for weight and cost when performed at scale. However, the proposed process is high-risk–high-reward, and the

proposed components need to be shown to be durable when exposed to fuel cell stressors, which is planned for after the first go/no-go decision.

- The impact of cost and manufacturing will be significant, if the project is successful.
- High-speed plate manufacturing is a key enabler to meeting fuel cell cost targets.
- It is unclear whether this is a new stack design or an incremental change to an existing design. Also, more information is requested on the current baseline cost, mass, or technical barrier that Plug is attempting to overcome in this project. It is hard to assess the approach and impact without understanding the current state-of-the-art challenges faced by Plug. Also, although ORNL is testing ICR and corrosion properties, the main technical barriers and the project objectives list only durability and mass targets. An EOL resistivity target needs to be specified to get full value from the development work and assess the long-term impact of the pursued technologies.

Question 5: Proposed future work

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

- Remaining milestones going into the first go/no-go decision, the proposed deliverables working toward the second go/no-go decision, and the finalization of the project are all clear and well-constructed—going from single-small-cell development, to full-size cell development, to short stack assembly and testing.
- Overall, the plan for the remainder of the project seems sound and well designed to achieve the goals for the full stack deliverable and durability testing. The project plans down-selects materials and steps up scale in a reasonable way. It is somewhat unclear whether all the proposed technologies will be integrated into the final stack or if alternative back-ups are being considered for risk mitigation.
- The proposed future work is well explained and laid out in enough detail (in the timeline slide). One area that might be overlooked (unclear) is whether development of materials requirements for the GDL will be done early enough. An open question is whether the GDL will suffer compression set over life, affecting geometry of the flow path and therefore performance and pressure drop.
- Overall proposed future work is good. However, prior to prototyping and demonstrating manufacturing at any large scale, a manufacturing feasibility study with all cost parameters need to be reviewed with DOE. It is recommended that a BPP accelerated stress test (AST) or unitized cell durability test be performed and EOL BPP properties (ICR, corrosion, etc.) be reviewed prior to scale-up or pilot stack manufacturing.
- Cost models should include GDL cost with supplier feedback. The project needs some focus on header design. It is unclear how the reactants and coolant will get into the cells. This project does not work without the grooved GDL. This needs to be a top priority. Plug should not make a stack with the dual GDL approach used in single cells. The plans for cell unitization and seal addition are unclear.
- Proposed future work has been identified, but demonstration of the idea as a stack will be crucial.

Project strengths:

- Overall, the project has a good approach and timeline, with appropriate go/no-go targets. Adding a resistivity target will only strengthen the project and help with understanding the risks to meeting manufacturing feasibility. Collaborations between Plug, UT, and ORNL are good. However, collaboration with Smith Engineering, Limitless Design, and non-funded collaborators is unclear. There has been good progress on porous rib design, and proposed future work to optimize the channel profile is good. Overall, progress is good, and the presentation by the PI was good. Plug has the right team assembled for the project.
- This is highly innovative work advancing fuel cell stack and BPP technology in several directions. The project appears to be well designed, and the team is generally well integrated to achieve project goals. Successful completion of all project goals would represent a major advancement in fuel cell stack technology that clearly supports the DOE objectives.
- The innovativeness and out-of-the-box thinking is a primary strength of this project, as well as the large assembled team. Projects driven by industrial partners (as this one is) can help ensure that research money is targeted toward current and actual problems.

- The project is exploring novel approaches to BPP manufacturing that, if proven successful, look to be game changers for making BPPs at scale.
- The project has an interesting concept and out-of-the-box thinking, as well as good collaborators. It is good to see Plug allowing room for such new ideas.
- This is a creative approach to high-speed plate manufacturing. The focus on wireless CVM is a strength.

Project weaknesses:

- R2R manufacturing limits compatible materials and specifications. The porous carbon-based GDL/gas channel must be shown to be durable compared to current graphite or stainless steel plates/channels. The project must show that water management does not become an issue as the stack ages and becomes more hydrophilic. The project also needs to show that the proposed corrosion-resistant nitride metal foils for Al (i.e., TiN) are stable in an oxidizing atmosphere and do not convert to an insulating TiO_2 layer.
- It is not clear whether the CVM and porous rib approaches are the only path investigated in this topic. If there is a down-selection process identified for these components, that needs to be published as well. Stack requirements for HDV systems, the KPIs that drive the down-selection process for the BPP material selection and processing, are not clear. The definitions of +, -, 0, etc. used to rank the materials and their characteristics need to be clarified.
- The project has no GDL supplier. For the coating, there is no evidence that the oxide layer has been effectively removed from the stainless in a continuous process. There is concern that the Ti will oxidize in an open-air plasma process. The plans for cell unitization and seal addition are unclear. The coolant mesh approach is expected to add resistive losses.
- The BPP coating technologies seem relatively early-stage and high-risk compared to the rest of the work. R2R application of BPP coatings does not seem to have a clear advantage over high-throughput batch processes. A potential risk of the thin flat plate design is the propagation of alignment or thickness errors through the stack, which should be carefully considered in the upcoming budget periods.
- This is an all-encompassing project, which can be seen as a strength but also might be a weakness if focus is diluted by trying to do everything all at once.
- Viability of the concept in a stack is yet to be demonstrated.

Recommendations for additions/deletions to project scope:

- It is recommended that a BPP AST or a unitized cell durability test be performed and that EOL BPP properties (ICR, corrosion, etc.) be reviewed prior to scale-up or pilot stack manufacturing. Also, short stack size for final performance and durability validation needs to be published. In addition, the final BPP deliverable to the Million Mile Fuel Cell Truck (M2FCT) should be at the beginning of BP 3 so that M2FCT labs can perform appropriate ASTs in parallel while Plug builds and tests the short stack. Finally, the duty cycle for the ≥1,000-hour durability test is not clear. It is recommended that Plug try to work with an HDV original equipment manufacturer to obtain an appropriate duty cycle for the durability tests and to project 25,000-hour durability feasibility.
- The project should report oxygen energy dispersive spectroscopy (EDS) or x-ray photoelectron spectroscopy (XPS) results of the plate surface after plasma treating. Plug may need a back-up plate-coating approach. Also, Plug needs to define the maximum anode overpressure requirement. The project needs to report how the seal is being introduced to the plate and how the membrane electrode assembly is being unitized with the plate. It needs to be determined whether the coolant mesh requires conductive coating. Compression effects on grooved GDLs need to be measured or modeled.
- The BPP coating approaches appear high-risk, and it would be good for the project to consider alternatives as a back-up plan for the final stack deliverable. The project should ensure that any concerns about the mechanical robustness of the alternative stack design are addressed.
- More detail is recommended around understanding the GDL material requirements for this concept.

Project #FC-347: Development of Low-Cost, Thin Flexible Graphite Bipolar Plates for Heavy-Duty Fuel Cell Applications

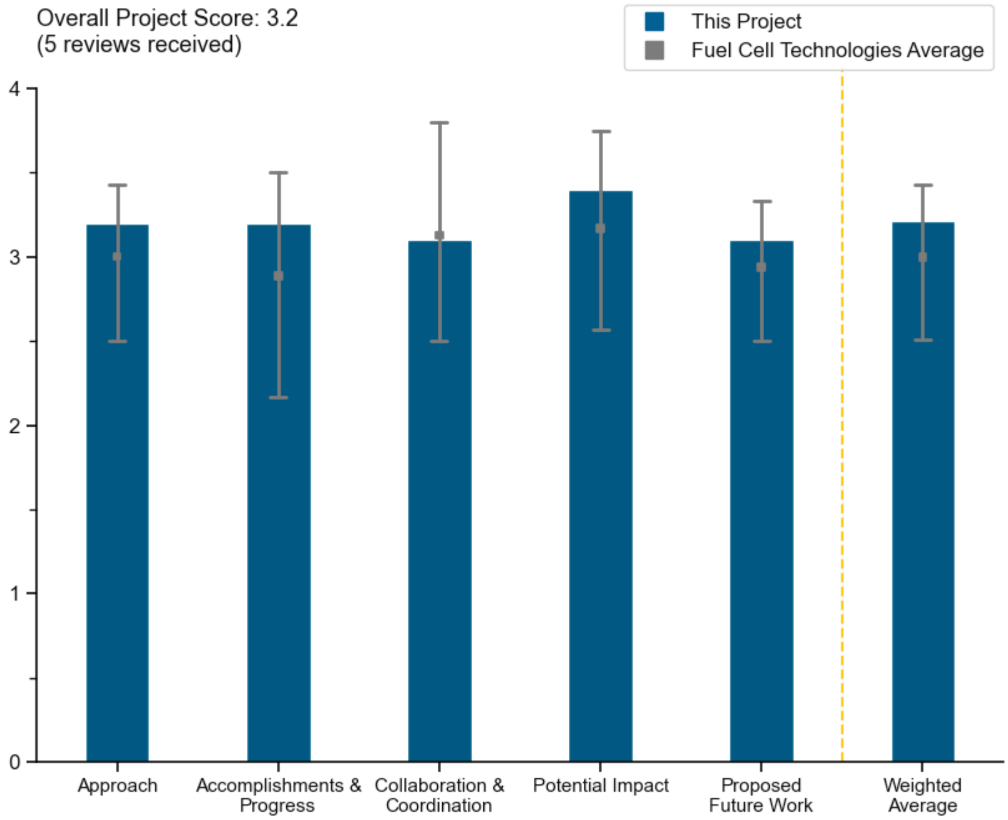
David Chadderdon, NeoGraf Solutions, LLC

DOE Contract #	DE-EE0009615
Start and End Dates	5/1/2022–5/31/2025
Partners/Collaborators	Ballard Power Systems, Strategic Analysis, Inc., Norley Carbon & Graphite Consultants, LLC
Barriers Addressed	• Bipolar plate assembly cost

Project Goal and Brief Summary

The project aims to reduce the cost of bipolar plate assembly (BPA) graphite by approximately 90% to enable a BPA cost of $5/kW for next-generation heavy-duty fuel cell applications. The project addresses the technical barrier of leak failure due to inclusions in the graphite and proposes various approaches to eliminate the impurities and evaluate their impact on BPA performance. The cost reduction will be achieved through the development of thin (from approximately 1.7 mm to 1.4 mm) and durable flexible graphite plate assemblies with low graphite basis weight (from approximately 600 g/m^2 to 340 g/m^2) and minimal leak-causing impurities (from approximately 17% to <5% leak failure rate due to inclusions in thin plates). Reducing the BPA thickness and impurity content will contribute to higher volumetric cell and stack power densities. Milestones include producing flexible graphite from alternative feedstocks, implementing an ash separation process, and evaluating the effectiveness of a clean furnace sealing material. Future work includes testing alternative graphite feedstocks, optimizing the graphite expansion process, and conducting short stack testing to demonstrate BPA performance.

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 project uses a simple but effective approach. It uses a proven technology for the production of bipolar plates (BPPs) and targets reducing the amount of material that is used by decreasing plate thickness. The challenge that this pathway creates is the inclusion of foreign particles in the plate. For certain particle size to plate thickness ratios, defective plates may be manufactured. The challenges seem to be understood and are being addressed through improvement of the production process.
- A proposed approach is based on modification and cleaning of natural graphite flakes, which is very viable, scalable, and controllable. Proposed methods for the removal of natural and/or artificial impurities are well described and sound reasonable.
- A metric reflecting ash content was shown, including removing particles >200 microns and bringing down the ash content to a range of 6–22 parts per million (ppm). More information is needed on this metric and the confidence level that reducing ash to this level will be sufficient related to cation/impurity release and BPP gas leakage. Also, it seems this metric is important to the final limitations related to how thin the plates can be. It seems part of this metric should include what the ash content is. For example, SiO_x is probably completely inert, whereas FeO_x could be problematic. It would be nice if the approach would include a comparison of theoretical power density between composite plates and metal plates. In addition, as some original equipment manufacturer (OEM)/stack developers are working on relatively high-temperature operation, the project should examine the plate/resin materials to evaluate higher-temperature operation, such as 100° to 105°C, and the durability. The resin materials might have to be specifically chosen depending upon the OEM operating temperature. Furthermore, Advent presented a new membrane

electrode assembly (MEA) manufacturing line with an operating temperature of 180° to 200°C. Finally, the stated goal seems to be reducing the plate thickness from 1.7 mm to 1.4 mm. It is not clear that this reaches power density and volumetric density goals of most OEMs.

- The project is addressing the cost of the bipolar plates for heavy-duty fuel cell systems. The project is not addressing either the durability (25,000 hours) or the efficiency (68%) target. The material choice for bipolar plate may not have a significant impact on the fuel cell system's peak efficiency. However, the stack durability could be significantly affected by the bipolar plate-to-membrane interactions. To improve membrane durability, it would be good to understand the level of iron contamination for these expanded graphite materials and add some tasks to reduce iron contamination if preliminary analysis shows >5 ppm of iron.
- In general, the approach is good. It is recommended that the project assess whether process or material is the more significant source of inclusions. Then the approach could be more targeted.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The project is only 10% spent to date, so accomplishments reflect that amount of spending. A Design for Manufacture and Assembly (DFMA) analysis reading of $4.5/kW is a positive result for the potential of these materials. Additional information on the prior plates, which operated for millions of miles—the operating conditions and overall results of those plates—and the differences between those materials and the project materials would be valuable.
- Accomplishments demonstrated to date are in good agreement with proposed work scope. Planned milestones were achieved.
- Significant progress has been made toward demonstrating lower-basis-weight plates. Achieving <5% rejection of thin plates is a key criterion that needs to be demonstrated quickly, per Milestone 14.
- The project is in early stages, but a significant amount of progress has been made.
- According to the plan, the project is on schedule. Foreign particles in the BPPs have been significantly reduced, showing that progress is being made. However, given that a larger-than-Six-Sigma production environment is required for the production of BPPs, stacks can be built adhering to Six Sigma principles, as Six Sigma translates into 3.4 errors in one million parts. With a base failure rate of 17% in the team's assessment, the target should essentially be much better than 0.00034%.
- It is somewhat unclear whether inline quality control is available that can prevent faulty BPP from being assembled in a stack. It is also unclear if a certain number of faulty parts (i.e., the yield of usable BPPs) is considered in the cost analysis.

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.

- Ballard Power Systems and Strategic Analysis, Inc., are valuable partners for this project, and the project team covers the materials, plate formation, cost analysis, and an OEM. The Cummins project (not part of this project) presented machined graphite plates. This project should initiate an additional collaboration with projects like that one (as obviously using machined graphite plates is not a long-term approach, and that is currently the rate-limiting step for that project).
- This is a good mix of industry (customer, manufacturer, and material supplier) and research and cost engineering. All project partners seem to be effectively engaged and contributing.
- The team has shown good collaborative effort, including a coordination with the Million Mile Fuel Cell Truck (M2FCT) consortium.
- All project partners are collaborating well. However, there is no interaction with any university or national lab. While the plate leak check is a good way to catch issues before stack build, it may not translate to 100% leak-free plates in the stack after testing and during 25,000-hour durability. Therefore, it is critical to

develop methods for detecting any inclusions and particles >100 microns in the graphite roll before the plates are formed/pressed. Perhaps the project can leverage the M2FCT consortium or other entities to estimate iron contamination and develop a nondestructive plate quality check to detect inclusions in the plate.

- The team includes industry, analysis, and national laboratories (through M2FCT).

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project addresses the cost reduction of bipolar plate assemblies to meet the DOE target of $5/kW. Graphite is the largest cost driver for high production volumes of BPPs. This project targets the reduction of graphite material used while maintaining all other requirements on the BPPs. The challenge of material inclusions that cause leaks and weak points in the plates is addressed. The project is well structured in logical and sensible tasks. The overall approach is well described and makes a good deal of sense.
- A direct comparison between these composite graphite plates and metal plates is inevitable. There should be OEM input on mass manufacturing and evaluation on the Strategic Analysis, Inc., cost analysis; it seems only a few OEMs are exploring graphite plates. Most OEMs seem to be exploring metal/coated metal BPPs. Assuming these materials can reach the cost target (as modeled) and can have similar volumetric and mass power densities, this is a valuable technology to pursue.
- It is important to continue developing cost models and manufacturing improvements for carbon-based plate materials, as they have a better potential for meeting all DOE research goals (including durability).
- This project can have a significant impact on stack durability and cost, if executed per the plan and additional quality control methods for particle detection are implemented.
- If successful, the project will substantially effect a price decrease of BPPs for fuel cells and potentially other applications.

Question 5: Proposed future work

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

- The team proposed future work based on the project milestones and go/no-go design points, which correlates with a final deliverable.
- Future work is planned in a logical manner, and milestones are appropriate.
- Future work seems to be laid out relatively well. Discussions with other OEMs (beyond Ballard Power Systems) to verify that applicability of the materials is widespread could be valuable.
- Future work is reasonable. The team should have some interaction with a university, a national lab, or the M2FCT consortium for iron-level analysis and defect detection.
- The project focuses on the BPP production part entirely. The team is talking about reduction of leak rates, but in terms of plates leaking, the question is what the effect of leaking BPPs is on the durability of the MEAs in the stack. Several questions need to be answered: how much H_2 or O_2 is leaking, what efficiency is lost through these leaks, what the implications are of leaks on durability—in other words, what these leaks mean.

Project strengths:

- The project builds upon working BPPs that are employed in the field. Cost analysis is used to show that cost targets can be reached at target production volume.
- The project has a well-defined and well-thought-out approach on making expanded graphite particles (“worms”), followed by carbon sheet manufacturing.
- This is a good team that covers the needed technical areas. This is the only DOE-funded BPP project exploring carbon composite plates. It seems like that is the minimum that should occur (the number of projects should not be zero).

- The project has good collaboration and materials for development. The topic is important.
- The project has a good team and a good approach.

Project weaknesses:

- One weakness is the potential omission of supply chain evaluation for new sources of feedstock material. It would be helpful to know where the sources are located, whether the supply is limited, and whether there are any logistical or price issues.
- The understanding of what particle inclusion can be tolerated is based solely on leak rates. The actual impacts on performance, efficiency, and degradation are missing. This information is required to understand what type of particle inclusions may be acceptable and which ones should result in rejection of a plate.
- The project could use more work on understanding where some of the metrics originate and whether those metrics are appropriate.
- There should be more collaboration with national labs to better characterize the nature and origin of impurities.
- Lack of coordination with M2FCT is a weakness.

Recommendations for additions/deletions to project scope:

- Some studies should be added on (1) the efficiency and durability effects of the leaks (e.g., tolerated leak rates) and (2) on-line quality control that allows separation of plates with particle inclusions prior to stack assembly.
- The project should add (1) quantification of iron levels and (2) in-line/roll-to-roll defect detection for finding >100-micron particles in the graphite roll.
- There should be outreach to other OEMs to make the technology as widely applicable as possible.
- It would be good to add some supply chain analysis.

Project #FC-348: Fuel Cell Bipolar Plate Technology Development for Heavy-Duty Applications

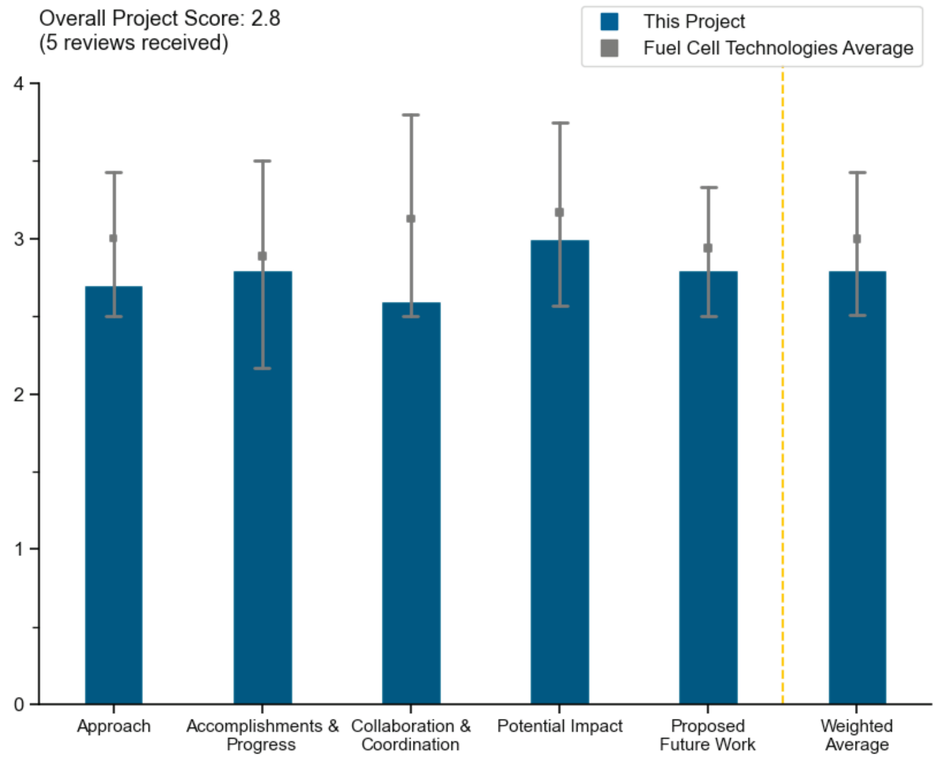
Siguang Xu, General Motors LLC

DOE Contract #	DE-EE0009616
Start and End Dates	1/1/2022–6/30/2025
Partners/Collaborators	The Pennsylvania State University, Northern Illinois University
Barriers Addressed	• >40% equivalent elongation for ferritic stainless steel • Low-cost and durable coating • Fast laser welding (90 m/min)

Project Goal and Brief Summary

The goal of the project is to develop a bipolar plate (BPP) manufacturing solution that achieves a BPP durability of 25,000 hours and a weight of 0.18 kg/kW for 100,000 units per year. In the fundamental technology development phase, the project is developing thin coil stamping technology (to achieve >40% equivalent elongation), low-cost post-stamping coating technology (to meet 25,000-hour durability and high conductivity), and fast BPP laser welding technology (to meet 100,000 units per year through-put with less than 2% scrap rate). The next phase involves integrating the developed technologies into the design, manufacturing, and testing process of a small BPP (50 cm^2 active area) for feasibility and scalability studies. The project has attained the target for equivalent elongation in low-cost ferritic stainless steel through channel-forming trials, developed microgrid technology for thin-sheet formability testing, identified humping as a major defect in high-speed BPP laser welding, and made progress in coating optimization trials. Future work includes completing material characterization and failure strain measurement, additional stamping simulations and testing, optimization trials for coating, further laser weld testing, and improving numerical simulation capabilities.

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 **2.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project aims to develop a stamping technology that enables the production of BPPs from low-cost ferritic steel. Part one is looking at various production approaches, such as single-step versus multi-step; part two is looking at the development of required coatings for use as BPPs in fuel cell systems; and part three is enhancing laser welding technology for the assembly of these plates into BPP assemblies (BPAs). The approach is sound and logical with regard to fundamental aspects and the development of a method to create such plates. Understanding how well the coatings may hold up in the harsh conditions of a fuel cell stack and how this could result in contamination processes is not yet addressed.
- Emphasis appears to be on the forming/stamping/manufacturing of the BPPs. Material and coating development is coming later. The comparison between atomic layer deposition (ALD) and physical vapor deposition (PVD) coatings will be interesting. ALD will likely be the cheaper long-term alternative. The project will develop stamping/laser welding and coating methods for ferritic BPPs. This should be a substantial cost savings over Ti plates.
- The approach is generally good—in particular, the fundamental understanding for forming and welding failures and the replication of those failures in simulation and modeling. However, the approach for coating seems weak or was not given enough attention. It does not look like the coatings are on track to meet the conductivity performance target, no corrosion data is available yet, and more details around the cost–manufacturing assessment are expected.
- The approach to the work is to form BPPs at high speed and then coat and weld them. There seems to be a disconnect between the project approach and the project goals, which are focused around making 100,000 units/year, and also a disconnect with the broader DOE goals to make 20,000 fuel cells per year, which requires on the order of 6 million BPPs per year. There is little explanation of how the project will

meet the go/no-go goals. It is not clear how electrical conductivity and iron release will be measured. Coatings work is shown, but the resistance reported in this presentation (the lowest is 0.015 ohm cm^{-2}) exceeds the project goals. It is not clear how the resistance will be lowered.

- The proposed approach was neither well described nor well presented. The approach workflow was unclear and not structured. The challenges to address were not stressed.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- According to the plan laid out, the project is on schedule, and very good progress has been made with regard to understanding various stamping, coating, and welding processes. The project has well-communicated basic research elements whose results are useful to the entire industry. Some results, such as the reason one laser power strategy works better than another, should be looked at from a theoretical direction in addition to the empirical approach that was presented. This may save time in optimizing the process and making it available for other materials and/or plate thicknesses.
- This project is in its early stages, so progress is reasonable, especially given significant delays in material procurement, etc.
- The project is only 3% to 4% spent to date, so it is just starting, with limited accomplishments at this point. It seems like the project needs to ramp up. Two-step forming seems like a more expensive methodology. ICR appears to need improvement, especially considering this is beginning-of-life.
- Progress is difficult to evaluate for this project. The spending is somewhat low, so it appears to be early in the project. It would have been helpful if the presentation had worked through the technoeconomic analysis and required manufacturing speed; the reviewer had to go through the numbers in the presentation and calculate the required welding speeds, etc. One challenge with this project is that it was awarded with the goal of 100,000 units per year, but DOE has already moved on to a goal of 2,400 units per hour (see Funding Opportunity Announcement 2922), or approximately 6 to 10 million units per year. The resistance of the plates is presently too high to meet the go/no-go criteria. Clarification is needed on how it will be lowered to meet the goals. There was no mention of Fe emissions from the plates, particularly over time toward the 25,000-hour goal for the Million Mile Fuel Cell Truck (M2FCT) consortium. For the project review next year, the presentation should be more explicit about the DOE M2FCT goals and project goals and how the research is progressing toward those goals.
- Despite several accomplishments presented, it was not emphasized how they effect the achievements of the project's final goals.

Question 3: Collaboration and coordination

This project was rated **2.6** for its engagement with and coordination of project partners and interaction with other entities.

- There appears to be a good level of collaboration between partners.
- Penn State is doing the imaging of the laser welding at Argonne National Laboratory (ANL), presumably using the Advanced Photon Source (APS), but the APS is closed for a significant time. It is not clear where future imagining will take place. The project includes General Motors (GM, a primary original equipment manufacturer), plus two universities (Penn State and Northern Illinois University).
- The team has industry and university contributions. It is unclear whether this project is collaborating with the M2FCT consortium. With regard to basic understanding of the degradation of the coatings that are developed here, this may be beneficial.
- The presentation was not very clear about how GM was coordinating with the partners. The Penn State logo was included on several slides, but specific accomplishments were not clear. The accomplishments of Northern Illinois University are also not clear. GM appears to be collaborating with ANL, on imaging and it would be helpful to clarify the lab's role on the collaboration slide.
- There was no collaboration with external institutions, especially coordination with M2FCT consortium.

Question 4: Potential impact

This project was rated **3.0** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project addresses the cost reduction of BPAs to meet the DOE target of $5/kW. Graphite is the largest cost driver for high production volumes of BPPs. This project aims to create thin-sheet BPAs that are welded together and use low-cost steel coated with a protective layer.
- In particular, the understanding and simulation of high-speed welding defects are very important and have large potential (positive) impacts.
- The project is aimed at lower-cost materials and processes to meet the DOE BPP targets. The project is examining the stamping processes, which few other DOE projects have done.
- If successful, the project can result in decreasing the price of BPPs and increasing the fabrication rate.
- The progress on rapid welding is very good and could have a high impact. The impact of this project is not clear, as its goal is 100,000 plates per year, while a more realistic goal should have been 6 million per year. While the contract was likely negotiated at 100,000 per year, GM and DOE need to figure out whether they should change the goals for this project. If the goals do not change, it seems like much of the work will be low-impact because it will not be able to meet the speed requirements for modern fuel cell manufacturing. The cost impact of the methods chosen is also not clear in terms of the M2FCT goals of $80/kW per system.

Question 5: Proposed future work

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

- The project just started, so the majority of the project is the future work. Coating development (TiC by ALD and/or PVD) appears not to have started yet. This is listed as trials being complete by the end of Fiscal Year 2023, which seems like an important portion of the project. The material evaluation plan related to corrosion testing seems undefined at this time. The project should include a cost comparison between ALD and PVD coatings. The overall cost analysis of the BPPs, other than the DOE cost target, does not seem to be mentioned. This project should include a cost analysis.
- Risks were not identified; mitigations were not proposed. The decision point comes almost at the end of the project. Given that the coating includes Ti (a known membrane poison), future work should include not only an understanding of the durability of the coating but also the durability of other fuel cell components in the presence of that coating.
- Future work is included on slide 8. The activities are relevant to meeting the Phase I goals for the project, but there is no specific mention around meeting the go/no-go criteria for durability measurements (i.e., Fe dissolution) and plate resistivity. There is also no mention of meeting goals for speed (100,000 plates per year) or scrap rate.
- Future work should include studies on the lifetime of the plate coatings, potential contamination of cell components, and quality control (QC) aspects, such as surface roughness and flatness of the created BPPs.
- The team presented future work based on the project milestones and go/no-go plan.

Project strengths:

- High-speed welding of BPPs is a tremendous challenge for the fuel cell industry. Others seem to have met the required speed goals by using adhesives, but a welded BPP would clearly be superior. Also, it would be highly beneficial to have BPPs made from lower-grade steel. GM and the team are doing a nice job using advanced imaging methods to evaluate welding work. ALD and PVD seem like promising methods to make robust coatings.
- The project covers the entire stamping/welding processes, plus different coating processes to meet the DOE cost target.
- The project has a sound approach and development concept that creates basic knowledge that may be useful in other fields and industries.

- The team has significant plate and simulation expertise. Welding investigation is important.
- The project offers a potential increase in welding and production rates.

Project weaknesses:

- The project goals seem out of alignment with DOE goals to make 6 to 10 million BPPs per year. There is little techno-economic analysis showing how the innovations in this presentation lead to the project goals, for instance, whether ALD and PVD coatings meet cost and speed requirements. The principal investigator should correlate the welding speed (m/sec) and coating method speeds to BPP manufacturing rate and cost.
- Coating investigation seems to be given lesser priority; the impact of coating on durability of other fuel cell components has not been considered.
- If the coatings do not last, then the whole development will not be useful for fuel cell systems. The lifetime of coatings, contamination in cells, and QC are missing.
- It is unclear whether the processes defined in this project will be made available to the wider community or if this is going to be available only to GM.
- The workflow lacks structure.

Recommendations for additions/deletions to project scope:

- This project is still in early stages. For next year, the team should consider evaluating a more rigorous techno-economic analysis showing how the path that GM has chosen will meet DOE cost and speed goals. At a broader level, DOE and GM need to consider whether it is worthwhile to pursue a method for 100,000 BPPs per year (enough to make 167 stacks with 300 cells and 600 BPPs per stack). It seems that 167 stacks per year is far from the volume needed for a successful product.
- A presentation or report should clearly state challenges and how the project approach will resolve these challenges. The results and accomplishments should be clearly structured, correlated with milestones, and represent progress toward final goals.
- Earlier in situ evaluation of coating performance and durability in a fuel cell environment is recommended.
- Inclusion of a material vendor related to the plate materials and stamping process could be valuable.
- Studies should be added on lifetime of coatings, contamination in cells, and QC of plates.

Project #FC-349: Foil-Bearing-Supported Compressor–Expander

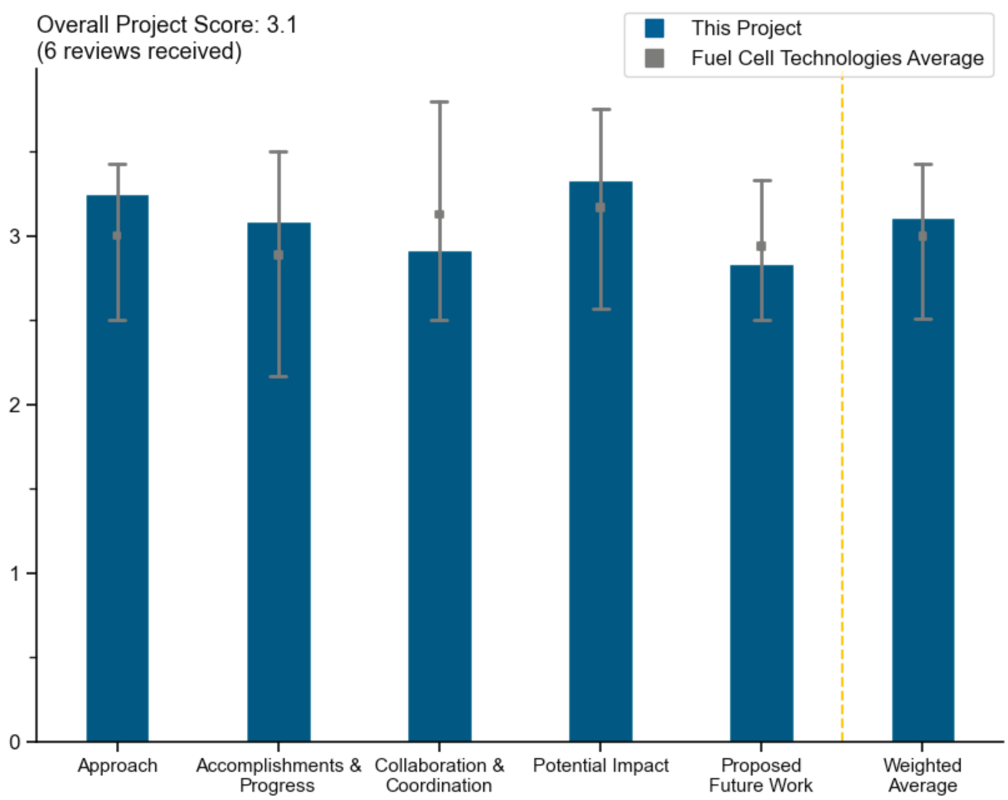
Giri Agrawal, R&D Dynamics Corporation

DOE Contract #	DE-EE0009617
Start and End Dates	5/1/2022–11/1/2024
Partners/Collaborators	Loop Energy, University of Texas – Dallas
Barriers Addressed	• Meeting the efficiency for the compressor expander at the required pressure ratio

Project Goal and Brief Summary

The project focuses on developing a fuel cell system compressor–expander (CE) for heavy-duty (HD) vehicle applications. The approach involves the development of a high-speed centrifugal CE supported on oil-free foil air–gas bearings, incorporating surge bypass, variable turbine nozzles, a permanent magnet motor, and a motor drive with SiC switches.

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.

- R&D Dynamics Corporation highlighted the company's partnership with Loop Energy in helping to address the critical barriers of efficiency, mass, and cost in fuel cell system CE expander development. The project team has demonstrated excellent progress toward meeting or exceeding the stated efficiency goals for CE, turbine, motor, and drive efficiency. The project also has an excellent pathway toward meeting weight and volume targets. However, the team is waiting for quotes to state the projected CE cost. An estimate on projected CE costs should be known, as the project is close to 50% completion. There was also a question on noise from the reviewer panel that may not have been fully addressed. CE cost and noise could be addressed during the next Hydrogen Program review.

- The approach of the team is good and has identified critical enabling capabilities for the air-handling system for a fuel cell system. Targets on efficiency, cost, and durability have been identified. Performance was substantially discussed. Cost and durability received less communication at this early stage but could have been addressed a bit more in the discussion of the design stage to ensure targets are met.
- This work demonstrated the technology enablers to meet DOE air machine efficiency, package, and weight targets, including high-speed centrifugal wheel design, air foil bearing, motor driver with SiC, etc. More supporting evidence to demonstrate 25,000-hour durability is needed.
- The project focuses on efficiency and durability. These attributes are the most important for the fuel cell system for HD applications.
- A trade study to understand the engineering balance of cost, efficiency, and reliability, which are the three primary project objectives, would be appreciated. Going into what decisions have been made with the planned prototype hardware would be appreciated. For example, slide 4 lists advantages, but nowhere else were the disadvantages or challenges of the selected sub-components and designs readily apparent.
- It is unclear whether the minimum rotation will be sufficient to ensure that an air lift will be achieved to minimize friction and maximize efficiency at the anticipated fuel cell idle flow.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- Achievements include a planned air machine using compact aerodynamics that enables package volume and weight that appears to be competitive. Company experience with air bearings is a plus. Regarding opportunities, the project would benefit from aero maps for the compressor and turbine. Aero efficiency is not quite reaching the project target, and it appears there is an external air feed that should be called out, as it leads to overall air machine efficiency impact. Also, it would be good to see a more detailed validation test plan that includes water injection testing of the expander. Perhaps accelerated testing could be conducted to look into damage modes to this air machine. It would also be good to test at module level with Loop Energy once component tests are completed (or in parallel, if time is an issue); it was not clear whether such a test was planned.
- The project largely completed design in the period, as per the plan. This work is progressing well. Several critical design elements were identified as having been complete but were not addressed in the Annual Merit Review (AMR) materials; two that may be expected to be difficult to resolve are (1) balancing of thrust forces and (2) internal motor heating due to integrated power electronic switching at high speeds. One of the stated critical capabilities was the need for air foil bearings to eliminate oil contamination. This was not addressed with detail in the AMR material, so it is difficult to understand progress on this with respect to expected capability and durability.
- R&D Dynamics Corporation has shown excellent progress toward addressing the critical barriers of efficiency, mass, and cost in fuel cell system CE development. The project is exceeding many of the performance targets in CE efficiency, mass, and volume. Cost metrics are pending. Also, the total power of the fuel cell system air CE does not seem to be noted.
- There has been good progress in meeting or showing evidence in meeting air machine efficiency, package, and weight targets. Supporting data or testing plans to meet the 25,000-hour durability target are requested.
- The basic design has been completed. It would be helpful to see the model of efficiency and the performance diagram and intended operation points for HD fuel cell system applications, as well as the design verification test plan.
- Three milestones originally scheduled for January and May 2023 were not completed. An explanation for the delay and a mitigation strategy to either avoid a reoccurrence or accelerate progress were not provided.

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.

- R&D Dynamics Corporation seems to be in good engagement with project partners. Discussion with Loop Energy on addressing CE efficiency was highlighted during the review. Discussions with the University of Texas – Dallas (UT Dallas) on CE drive and control software design were highlighted in the presentation. R&D Dynamics Corporation is encouraged to summarize specific accomplishments from each partner in future presentations.
- The project demonstrated good collaboration between the fuel cell system developer, component developer, and academic partner.
- While it is still early in the project, it would be good to know how much collaboration has been done at this point. System mechanization of the air delivery system should be included because that plays a foundational role in how the component is selected. The inverter–controller with high-frequency SiC metal–oxide–semiconductor field-effect transistors (MOSFETs) and the algorithm/software comprise a large portion of the component cost; therefore, more detail should be provided.
- Preliminary design and fabrication of drive electronics and software were completed (perhaps by UT Dallas, although that was not clear), but results were not presented.
- Project collaboration is being clearly and effectively leveraged.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project being led by R&D Dynamics Corporation is providing excellent support toward advancing DOE objectives in fuel cell air delivery systems. If successful, R&D Dynamics Corporation will have developed a fuel cell system air CE expander that could transition to industry. The total impact of a fuel cell system air CE expander on the overall DOE fuel cell system is more challenging to address at this point of the project.
- A highly efficient, durable, small, and low-cost air machine is one of the key enablers for fuel cell technology adoption and commercialization to reduce CO_2 emissions. This project demonstrated the potential path to meet DOE research, development, and demonstration goals and objectives.
- Outcomes (particularly the proper size of an air compressor for HD fuel cell systems) would be highly impactful on the domestic supply chain for HD fuel cell system development.
- The stated goals and execution toward those goals are important to the success of fuel cell electric vehicles in application.
- Efficiency is close to the target. However, understanding accurate volume production costs and long-term durability, especially with liquid and vapor water exposure, will be critical.
- Several performance targets appear to have been achieved, and several others are yet to be defined. These targets are yet to be demonstrated with a prototype. Anticipated system weight and volume are significantly below targets. It would have been useful to show performance maps for both the compressor and expander.

Question 5: Proposed future work

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

- R&D Dynamics Corporation's presented milestones provide good effectiveness to address project management. The project has one go/no-go decision point in November 2023, which will allow DOE monitors to appropriately address project risk. A point of clarification to address is how much of the CE will be manufactured and tested by the November 2023 go/no-go decision point. CE testing should be completed before November; the presentation summary states "end of the year."
- The proposed work is a logical sequence. However, it is unclear how durability over 25,000 hours will be assessed. An accelerated stress test is perceived as necessary. R&D Dynamics Corporation is a foil bearing

pioneer. However, performance data for other applications were not reported, which could support an assessment of the risk level of the proposed work.

- It is suggested that the project provide more detailed plans in durability protocol developments, including accelerated durability testing protocols with various failure mode stressors.
- It is suggested that the project clarify test protocols for design verification, particularly efficiency and durability.
- The plan by which durability will be validated in 2024 was not clear. It is not clear whether there is an accelerated test procedure that can extrapolate to the required end of expected life for the application.
- Future work is not well outlined, nor are any potential headwinds.

Project strengths:

- The project strengths include R&D Dynamics Corporation's technical knowledge of turbo machinery. The partnership with Loop Energy, an industry leader in fuel cell system development, is also a strength. The communication between Loop Energy and R&D Dynamics Corporation is appropriate for this effort.
- Strengths include R&D Dynamics Corporation's expertise in foil bearings and air machinery and the inclusion of a fuel cell developer.
- The team has strong expertise and experience in compressor and expander development.
- The solutioning approach, technology experts, and collaboration are all good.
- The project will provide good evidence to meet air machine DOE targets in efficiency, weight, and package.
- Size and mass are strengths.

Project weaknesses:

- There is no significant project weakness at this point of execution. Clarification is needed as to when a fuel cell system CE could be available. If one could be available prior to the November go/no-go, there is no issue. If after the November go/no-go, perhaps the go/no-go decision point should be moved. Per discussions at the AMR, R&D Dynamics Corporation should state the power level, address cost, state the approach to the accelerated stress test, and provide estimates on noise of the fuel cell system CE in future project updates.
- Time in the AMR to address the details of the critical design decisions was limited, so it is difficult to say whether requirements are being met with a robust technology. The team has stated the requirements' importance, so it would appear that they are being addressed. Some concise evidence of completion could have been helpful.
- Weaknesses include a justification for the inclusion of UT Dallas, progress delay, the unknown match between fuel cell idle and foil bearing airlift, and missing relevant information in several areas.
- The project should provide more supporting analysis and/or data to meet the durability target.
- A project plan to demonstrate reliability and estimated costs has yet to be seen.

Recommendations for additions/deletions to project scope:

- The project schedule and scope are appropriate.
- The project team should seek to interact with academia and/or national labs to pursue the modeling; study of materials compatibilities, particularly for durability; development of test protocols; and design verification plan.
- The reviewer has no additions or deletion to the current project scope.

Project #FC-350: High-Efficiency and Transient Air Systems for Affordable Load-Following Heavy-Duty Truck Fuel Cells

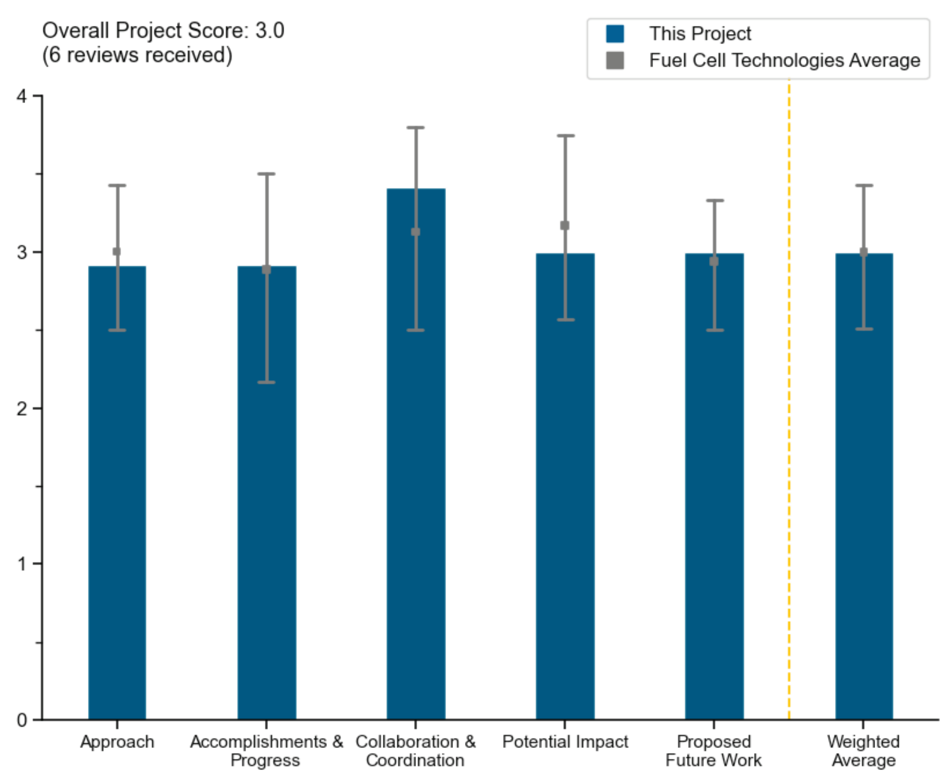
Doug Hughes, Eaton Corporation

DOE Contract #	DE-EE0009618
Start and End Dates	9/1/2022–11/30/2024
Partners/Collaborators	Ballard Power Systems, National Renewable Energy Laboratory
Barriers Addressed	• Air system power consumption targets • 27.9 kW at 100% flow • 10.8 kW at 50% flow • 0.32 kW at idle • Response time target: 2 seconds • Turndown ratio target: 20

Project Goal and Brief Summary

The goal of the project is to develop a highly efficient and responsive air system for on-highway commercial vehicle fuel cells by using positive-displacement Roots machines, maximizing waste energy recovery, and managing water to enhance performance. The project aims to achieve ~50% improvement in air system power consumption, leading to improved reliability, durability, and affordability. Existing fuel cell air systems are a significant source of parasitic power loss and limit system durability and reliability. The proposed system innovation can potentially reduce power consumption by 50%, equivalent to a 9% improvement in fuel cell output. The project's approach involves optimizing the proposed system through modeling and simulation, designing and building a subscale test system, and conducting design studies to establish component specifications.

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

- Eaton has clearly identified the critical performance barriers being addressed by its project. The project is well defined and feasible. Teaming with Ballard Power Systems (Ballard) and the National Renewable Energy Laboratory (NREL) makes for a good approach to performing the work. NREL's task on air system modeling and simulation seems to be the most developed task of the project. It was not exactly clear how much work has been completed at Eaton, as approximately 15% of the funds are reported to have been spent and the project is over 40% complete. The execution of the proposed work may need more clarification. It was unclear if a no-cost extension was requested, as it was not easily found in the documentation reviewed.
- The approach of the team is good. It has identified critical enabling capabilities for the air-handling system for a fuel cell system through the application of a Roots machine to deliver performance and efficiency. The project stated targets of 50% improvement in power consumption and a path to improve reliability, durability, and affordability. Performance was substantially discussed. Cost and durability received less communication, and a clear path to address these in the project is needed against the project goals.
- It is good for the project's approach to use model-based engineering to validate the prototype. It is supposed to show the design specification of air flow and pressure—perhaps full and partial power points for heavy-duty (HD) application. A value of 260 g/s at 2.33 bara seems to be too small for HD application (per the Million Mile Fuel Cell Truck [M2FCT] reference fuel cell system). It is suggested that the project reconcile design requirements and specifications.
- The project outline seems to be well communicated. Challenges and mitigation factors have been provided, although some could be unsolvable within this project scope.
- This work used a system modeling approach to define fuel cell system architecture and conducted design studies to establish component requirements to meet system targets. The project should provide more supporting data to address high-risk barriers, including meeting air machine efficiency, package, and durability targets and oil contamination concern.
- The selected compressor type may not achieve the intended efficiency target, and durability is expected to be compromised by the injection of water, leading to corrosion.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and DOE goals.

- The project has made good progress.
- In terms of accomplishments, the potential for reliability seems suited for permanent grease-type roller bearings as long as sealing can be guaranteed. It would be clearer to understand directly what compressor/expander/motor efficiencies are compared to the funding opportunity announcement target, rather than baking everything together as a power number. This could further highlight the strengths and weaknesses of the sub-components that make up the air machine. A testing plan to include water is a plus; however, it is focused on a compressor inlet based on system architecture decisions and not so much on an expander inlet, which is normally the point of concern. In terms of opportunities, cost, mass, and volume are not well covered. Expander inlet water testing is not addressed. Further explanation is needed regarding what can be done to make a Roots expander more feasible. Using a recuperator is interesting from an efficiency perspective but may lose value because of water evaporative cooling upstream, and freeze is a real concern. It is not convincing that adequate humidification is achievable with the water introduction location, plus having two heat exchangers before the stack.
- Eaton has presented current estimates on fuel cell air delivery system power consumption, which are on track to meet the project objectives. The execution of the proposed work may need more clarification. A go/no-go gate is scheduled for November 2023. Some of the estimates for power consumption are expected to be validated with hardware. This might not be possible with the state of effort discussed during the review. This was also not completely clarified during the question-and-answer session at the merit review.
- Good progress was made in system modeling and design studies. The presenter should provide more supporting data to meet air machine efficiency, to meet package and durability targets, and to mitigate oil

contamination risk. For example, it is unclear what the design options are to close the power consumption gap at 50% flow.

- The project largely executed design and analysis tasks in the period, as per plan. From the material presented, it is difficult to assess whether the project is proceeding per schedule. The project stated a go/no-go before November 2023.
- Only progress toward energy consumption targets is mentioned, leaving many other targets undefined, such as weight, volume, and cost.

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.

- Eaton seems to be in good engagement with project partners. It is getting input from Ballard on fuel cell system requirements and working with NREL on modeling. The presentation highlighted the programmatic accomplishments led by NREL.
- The project demonstrates excellent collaboration between industry and academia, particularly in model-based engineering. The project is expected to clarify the design requirements for HD applications from the M2FCT reference fuel cell system for Class 8 HD trucks led by Argonne National Laboratory, rather than Ballard.
- The project demonstrated good collaboration between the fuel cell system developer, component developer, and NREL.
- There appear to be good links with Ballard and NREL, and work has been shown.
- Collaboration with technology partners appears excellent. Several questions during the Annual Merit Review (AMR) were answered by an assumed partner from the audience. It was difficult to track the answers, as they were given off-mic and off-camera.
- Although a fuel cell system duty cycle is useful (M2FCT), it is unclear how such a cycle would be applied to derive a compressor–expander accelerated stress test to rapidly evaluate durability.

Question 4: Potential impact

This project was rated **3.0** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- A highly efficient, durable, small, and low-cost air machine is one of the key enablers for fuel cell technology adoption and commercialization to reduce CO_2 emissions. This project demonstrated the potential to meet DOE research, development, and demonstration goals and objectives; more supporting data are needed to overcome high-risk barriers in meeting air machine efficiency, package, and durability targets and mitigating oil contamination risk.
- Eaton can provide excellent support toward advancing the DOE objectives in fuel cell air delivery systems. If successful, Eaton will have developed a fuel cell air delivery system that is “transitioned to industry,” i.e., Eaton can mass manufacture the proposed fuel cell air delivery systems.
- The project is highly expected to impact the domestic supply chain in the air management system for HD fuel cell system applications.
- The stated goals and execution toward those goals are important to the success of fuel cell electric vehicles in application.
- The power consumption at 50% load is still significantly higher than the target. The lower-speed machinery impact on durability and reliability is compromised by the water injection, which is expected to lead to corrosion. Projections for several important metrics have not yet been quantified (weight, volume, cost). The risk of air contamination by lubrication oil is not discussed.
- Three main pillars of the project are cost, durability, and efficiency. Cost so far is missing. Durability has potential but is yet to be seen, and a productive accelerated durability test would be fruitful. Efficiency for the 50% power point seems far off target.

Question 5: Proposed future work

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

- The project summarized the remaining challenges and action items, which is an excellent approach.
- The project did a good job being forthcoming with challenges on Slide 11.
- The project sequence is reasonable, but significant risks remain, such as the presence of corrosion, air contamination by oil, and operation under subfreezing conditions.
- Eaton presented milestones providing a good effectiveness to address project management. The project has one go/no-go decision point in November 2023, which will allow the DOE monitors to appropriately address project risk. This might need clarification or review.
- The development of the pathway to improved durability and affordability was not clear. An accelerated test procedure that can be extrapolated to the required end of expected life for the application should be performed. It was unclear whether cost vs. payback is being evaluated against a baseline.
- More supporting data is needed to close the efficiency gap, mitigate oil contamination risk, develop a durability protocol, and provide test planning and execution.

Project strengths:

- The project presents a good technology opportunity and has an aggressive performance improvement goal. Good technology expertise and collaborative partners are also strengths.
- The project strength is use of a system modeling approach and design studies to define system architecture and component requirements.
- The project's strengths are leadership: an industry leader in vehicle air machinery and a world leader in fuel cell system design and manufacturing.
- A strength is team composition, with the inclusion of a major original equipment manufacturer and fuel cell system subject matter expert.
- Strengths are strong capabilities in Roots compressor–expander design and development and strong collaboration to pursue model-based engineering to design.
- Durability is a strength.

Project weaknesses:

- Limited time was available in the AMR to address the details of the critical design decisions, so it is difficult to say whether requirements are being met with a robust technology. The team has stated their importance, so it would appear that they are being addressed. Some concise evidence of completion could have been helpful on affordability and durability.
- The main project weakness is in execution as presently reviewed. If the fuel cell air delivery system is not on test by November, a no-cost extension should be considered. Per reviewer comments, understanding the impact of water injection into the fuel cell air delivery system is crucial to assessing viability.
- The project should show more supporting data/analysis to address high-risk barriers in meeting air machine efficiency, durability, and package targets and mitigation of oil contamination risk.
- Weaknesses are undefined machinery accelerated stress test, corrosion, air contamination, and subfreezing risks, as well as missing projections for several important metrics (efficiency, weight, volume, cost).
- Cost (unknown) and size/weight are not addressed.

Recommendations for additions/deletions to project scope:

- This project is to develop an air management system with a positive displacement compressor and expander. It is suggested that the team clarify advantages and disadvantages vs. a centrifugal compressor and expander for HD applications, including effectivity of the Roots expander for partial power. A value of 260 g/s at 2.33 bara seems too small for HD application (per the M2FCT reference fuel cell system). It is suggested that the project reconcile design requirements and specifications.
- Corrosion, subfreezing, and air contamination activities to assess risks should be included.

- The project schedule and scope are appropriate.
- No additions or deletions to the current project scope are recommended.

Project #FC-351: Durable and Efficient Centrifugal Compressor-Based Filtered Air Management System and Optimized Balance of Plant

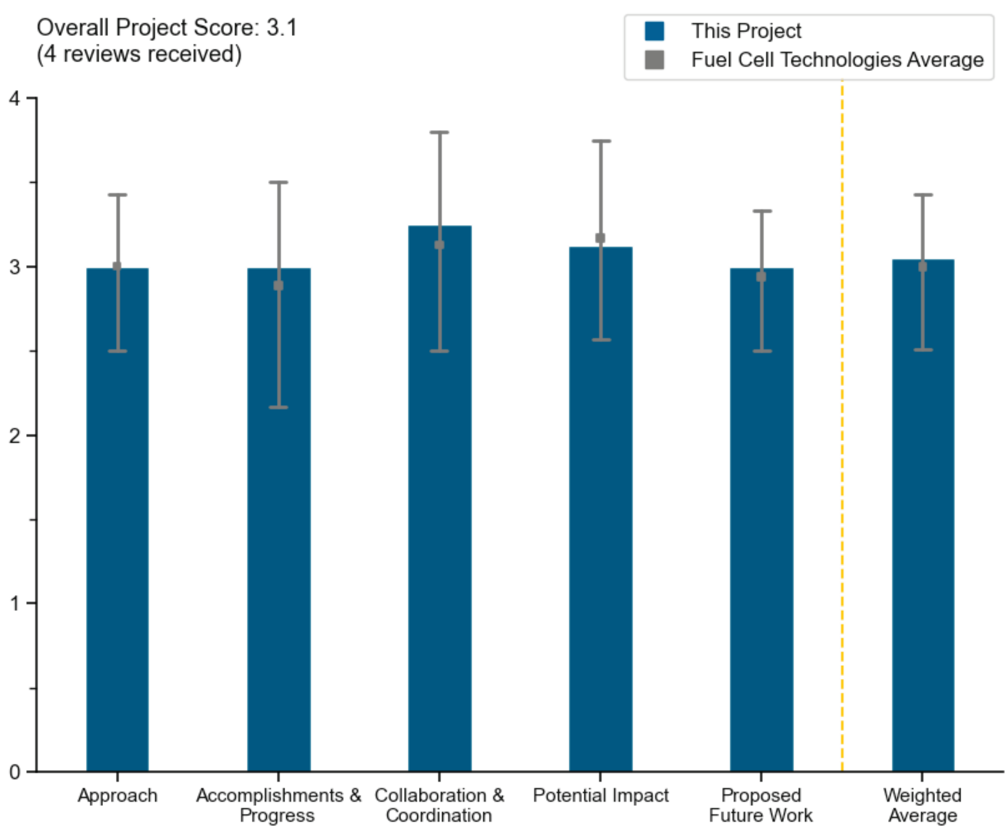
Mike Bunce, MAHLE Powertrain, LLC

DOE Contract #	DE-EE0009619
Start and End Dates	10/1/2022–1/1/2025
Partners/Collaborators	BMTS Technology, MAHLE Filter Systems, Oak Ridge National Laboratory, General Motors Global Propulsion Systems
Barriers Addressed	• Durability of air management system • High parasitic losses leading to increased fuel use

Project Goal and Brief Summary

The project's goal is to develop a low-cost ($12/kW), high-reliability (25,000-hour) air management system for heavy-duty fuel cell vehicles. The approach involves optimizing compressor and expander designs, utilizing novel compressor bearings for increased durability and reliability, and implementing primary and catalytic air filters to enhance the durability of the fuel cell stack. The project will use a quasi-empirical one-dimensional fuel cell system model for optimization, right-sizing, and interface control, along with prototyping controllers and hardware-in-the-loop test benches. Achievements include the completion of the initial model, the selection of compressor and turbine geometry, and the definition of the air cleaner size and geometry. Future work includes individual component design activities, fuel cell system control strategy development, integration with experimental setups, and high-fidelity component performance degradation and stack poisoning modeling.

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.

- MAHLE Powertrain, LLC (MAHLE) has clearly identified and addressed the critical performance barriers of the project. The project is well defined and feasible. Teaming with BMTS Technology (BMTS) on compressor–expander design was important on this project. MAHLE has presented a well-designed project to meet the objectives. The company is also integrating the efforts between Oak Ridge National Laboratory (ORNL), BMTS, and General Motors (GM) Global Propulsion Systems well.
- The project objectives are clearly identified:
    - Optimizing the compressor–expander and bearings.
    - Developing primary air filters with adsorption.
    - Incorporating a secondary filter to remove chemical impurities in air.

  The project approach includes an aerodynamically optimized compressor wheel and housing for high efficiency, a coated aluminum variable geometry turbine for a low-enthalpy environment, and a novel "3D" bearing for tighter clearances and faster compressor speeds that is water-lubricated to prevent oil leakage.
- Water-lubricated appears to mean ethylene-glycol–water-lubricated. Ethylene glycol will be problematic for the catalysts if there is any leakage into the fuel cell. It is not clear there would be any advantage to ethylene-glycol–water lubrication over an oil-lubricated bearing, as both ethylene glycol and oil leakage into the fuel cell will cause similar issues. The redundant air filtration system should improve reliability. The presence of Pt in the "catalytic" filter could be problematic from a critical materials and cost perspective. Approaches without precious metals should be prioritized, and cost needs to be considered for the filter. Two of the three systems being investigated contain Pt, but the amount of Pt in the filter is not discussed. The project does not address the motor controller, which is a major cost contributor to the air management system.
- The inclusion of a secondary air filter is expected to increase durability and reliability. However, water–glycol for lubrication is likely to lead to corrosion, even if subfreezing temperatures are averted.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- MAHLE is on track to meet project objectives for the development of the catalytic air filter for the fuel cell air system. The company is also on track with BMTS support to meet the DOE fuel cell air system goals stated during the review, and the team is hitting virtually all the stated metrics with an un-optimized system. Programmatic milestones may not have been shared during the Annual Merit Review (AMR). These would have helped give a better picture of project status. As discussed in previous AMRs, funding expenditure seems lower than expected. Clarification on spend rates should be discussed at the next programmatic review.
- The project has made good progress in the first six months. Only the progress made in the first quarter was mentioned. The team has developed an initial simulation model for the air system and component models to project the performance relative to the end-of-project targets. The team has determined the air cleaner size, geometry, and pressure drops. The team has selected catalytic materials for the secondary air filter.
- The project is still early in development. Good progress has been made on compressor designs to date.
- A milestone schedule was not provided, so it was not possible to assess progress against deliverables. Progress includes air compression, system simulation, and primary and secondary filters. Several important weight, volume, and cost targets were not addressed.

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.

- This is a strong team with several original equipment manufacturers (OEMs) that cover all major elements of the proposed air subsystem including powertrain, compressor–expander, and air filters. Contributions from national laboratories and support from other fuel cell manufacturers (e.g., Ballard Power Systems and Hyzon Motors Inc.) are also included.
- The project has a strong team, with BMTS and ORNL as subcontractors and GM as an industry advisor.
- MAHLE has a strong team for addressing fuel cell air subsystems. The contributions from BMTS were well highlighted. The work from GM and ORNL could be better highlighted. Per text and AMR discussion, MAHLE has received input from GM, Hyzon Motors Inc., and Ballard Power Systems. This might be better highlighted or tabulated in future AMRs.
- There appears to be good collaboration to date. Additional collaboration is needed to determine the filter requirements and specs for air coming out of the filter (i.e., acceptable contaminant levels).

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- MAHLE has a strong team that can provide excellent support toward advancing the DOE objectives in fuel cell air delivery systems. The partnership with BMTS provided a good pathway to commercialization of MAHLE's product. There were some reviewer questions regarding corrosion from leakage of the BMTS compressor–expander machinery. This concern should be addressed.
- Air management equipment is very relevant. Air handling is a major cost contributor and can be a significant parasitic loss to system efficiency.
- The project goals are mostly consistent with the funding opportunity announcement targets.
- Several targets (e.g., weight, volume, cost, and durability) cannot be evaluated because they are seemingly not included in planned activities. More specifically, it is unclear whether an accelerated stress test will be used to obtain compressor–expander durability within a relatively short period (<<25,000 hours). Activities are ongoing to establish primary and secondary filter maintenance needs. The impact of a Pt catalyst for the secondary filter on cost has not yet been determined and increases constraints on this element availability for fuel cell manufacturing.

Question 5: Proposed future work

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

- The proposed work follows a reasonable sequence. It is unlikely that stack poisoning relationships will be successfully developed, because a relevant air mixture needs to be defined and realistic concentrations would lead to a slow degradation that will be difficult to separate from other degradation modes. More specifically, the inclusion of only SO_2, H_2S, NO, NO_2, and NH_3 is too limited and does not reflect the presence of other contaminants.
- Plans for Pt-based catalytic filters for the species identified seem misguided. These appear to be more accurately described as chemical traps, and more cost-effective options than Pt should be available.
- The project needs additional collaboration and input to determine filter performance requirements.
- MAHLE may have not included (or adequately discussed) project milestones during the AMR or in the documentation submitted. A go/no-go milestone is discussed, but the date is omitted. Assuming a date of November 2023, MAHLE should be able to demonstrate sufficient progress to clear this go/no-go gate. With respect to work in 2024, more details on fuel cell stack poisoning could be useful.
- The proposed future work is consistent with the barriers and challenges identified to date.

Project strengths:

- Project strengths include an extensive team of OEMs and national laboratories, collaboration activities, and the inclusion of a secondary filter.
- The compressor is based on a known reliable design with relevant previous data and acquired experience. The design would suggest the project can come close to performance targets.
- The project's partnerships are its greatest strength toward meeting the DOE goals for developing an advanced fuel cell air system.
- Project strengths include a strong team and relevant experience.

Project weaknesses:

- There are no glaring weaknesses in the execution of this project as presently reviewed. Per reviewer comments during the AMR, an understanding of glycol leakage from the compressor, an understanding of possible corrosion from the glycol leakage, and an understanding of the impact to the fuel cell catalyst should be presented at the next programmatic review.
- The project's weaknesses involve several targets not being discussed (e.g., weight, volume, cost), the corrosion risk (i.e., water–glycol lubrication), a few unreadable illustrations, an unclear development schedule (i.e., milestone tracking) that makes gauging progress difficult, and difficulty in establishing practical poisoning relationships.
- The project fails to address motor controllers. The use of Pt in the catalytic air filters and the presence of ethylene glycol in the bearing lubricant are also weaknesses.
- The project is not yet addressing the cost and weight targets. It has no plans to develop the motor and motor/controller, even though these components are known to be the most significant contributors to cost.

Recommendations for additions/deletions to project scope:

- Use of noble metals, such as Pt, as coatings for the secondary filter should be discouraged. The project should add a subtask to develop low-cost motor and motor/controller.
- Recommendations include adding activities to quantify the corrosion risk and reconsidering and revising contamination activities.
- Pt-based catalytic filter work should be removed or decreased.
- The reviewer has no additions or deletion to the current project scope.

Project #FC-352: Leveraging Internal Combustion Engine Air System Technology for Fuel Cell System Cost Reduction

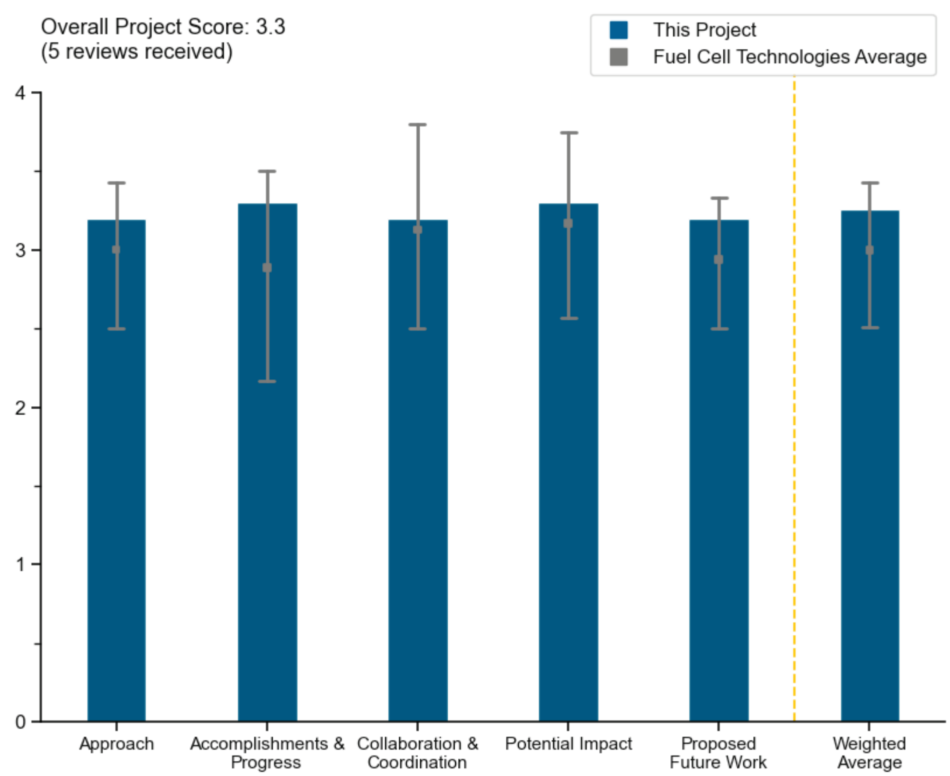
Paul Wang, Caterpillar Inc.

DOE Contract #	DE-EE0009620
Start and End Dates	8/1/2022–7/31/2025
Partners/Collaborators	BorgWarner Emissions, Ballard Power Systems
Barriers Addressed	• Zero-leak seal validation for oil-lubricated bearings • Turbine wheel optimization and validation for low-temperature/high-humidity conditions

Project Goal and Brief Summary

The project aims to research, develop, and demonstrate a high-efficiency air boosting system for proton exchange membrane fuel cells (PEMFCs) in heavy-duty applications, including enabling a lower-cost PEMFC system. The project utilizes Pugh analysis, simulation studies, and component design to assess various air system architectures and technologies, leading to an informed down-selection. The balance-of-plant components, especially air system components, have a significant impact on the performance and reliability of fuel cell systems. The project addresses this by developing an air system that consumes a lower percentage of fuel cell power output, reduces system cost, and minimizes system downtime. The project's approach includes system simulation, component development, adaption of proven technologies, and extensive bench testing to validate the developed air system. Accomplishments and progress include literature review, steady-state system modeling, analysis of candidate technologies, and down-selecting the optimum solution.

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 project goal is clearly stated as developing a high-efficiency air boosting system that will form the basis for larger 350 kW to 1,000 kW fuel cell systems for heavy-duty construction machines. The approach is well laid out but not novel. The project plans to use off-the-shelf compressors and expanders, down-select available bearing options (rolling element, fluid film, and air foil), and design a new electric motor.
- The approach of the team is good and has identified critical enabling capabilities for the air-handling system for a fuel cell system. Stated targets on efficiency, cost, and durability and critical barriers were identified. All were substantially discussed and addressed in the design phase of this project, as appropriate.
- Caterpillar has clearly identified the critical performance barriers being addressed by its project. The project is well defined and feasible. Teaming with BorgWarner Emissions (BorgWarner) and Ballard Power Systems (Ballard) are project strengths. The proposed approach is pragmatic for delivering a fuel cell air system.
- A technology-agnostic and comprehensive approach is used to identify the best option for the air system. An alternate design (oil lubrication) minimizes risks if the main down-selected solution is inappropriate.
- Rolling-element-bearing-type machines are used mainly in screw-type compressors, not e-compressors. Caterpillar lists some disadvantages, but there are more, including:
    - Limited load capacity. In a fuel cell compressor, the impeller rotation and aerodynamic forces generate significant radial and axial force.
    - Sensitivity to contaminants critical to a fuel cell.
    - High start–stop wear.
    - Speed limitation. In a fuel cell application, the rotational speeds can be demanding and lead to heat generation, fatigue, noise, and reduced bearing lifespan.
    - Ball bearings that require more frequent maintenance than other bearing types.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- Caterpillar is on track to meet, or ahead of meeting, the programmatic schedule. The status toward addressing the critical barriers to the DOE goals of motor and controller efficiencies, compressor and turbine efficiencies, reliability, noise, packaging, and cost is summarized and on track for success. Accomplishments to date are focused on compressor–expander, bearing selection, and motor. Spending might be low compared to reported milestone progress.
- All milestones scheduled before the Annual Merit Review (AMR) were completed. Additionally, significant progress was achieved for five other milestones spread over the three budget periods (50%–100% completion).
- The project has made good progress in the first year. It has down-selected the compressor, expander, bearings, seals, motor, and power electronics.
- Thorough review of the approach to select critical technologies is mindful of efficiency, durability, and cost.
- Cost and efficiency were reported for the various options considered. No analysis was shared to indicate the potential to meet durability or sealing targets. The team claims a Pugh analysis of candidate technologies was completed, but it was not shared.

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 has a strong team, with Caterpillar as prime; BorgWarner as a subrecipient for air system design, fabrication, and testing; and Ballard as sub-recipient for PEMFC system.
- Caterpillar has a strong team for addressing fuel cell air subsystems. Coordination between the team members seems appropriate for a successful project.
- The project includes an effective team composed of fuel cell and compressor manufacturers led by a heavy-duty vehicle manufacturer.
- The collaboration on the project is being clearly and effectively leveraged.
- There seems to be a good coordination between Caterpillar and Borg Warner on the air machine design, selection, and test plan. Ballard's contributions are unclear. Presumably, it will provide stack/system models to quantify system performance benefits.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Caterpillar has proposed a pragmatic approach to addressing the DOE goals for fuel cell air system development. The Caterpillar team comprises partners with strong manufacturing ties. As presented in the AMR summary, the project seems appropriate to the DOE Hydrogen Program goals.
- This is the only funding opportunity announcement project funded by the Hydrogen and Fuel Cell Technologies Office that is targeting air systems for 350–1,000 kW fuel cells for heavy-duty applications.
- Low-cost, high-efficiency, high-power air systems are essential to enabling heavy-duty fuel cell commercialization.
- The stated goals and execution toward those goals are important to the success of fuel cell electric vehicles in application.
- Most targets are projected to be met. Although a durability test is included in the approach, it is unclear how this will be ascertained—for example, whether bearing liftoff will be achieved at fuel cell idle condition to reduce erosion; or whether an accelerated stress test will be used to determine, in a short amount of time, whether the device will last 25,000 hours. It is not clear whether a method been selected or devised to assess oil leakage from the prototype.

Question 5: Proposed future work

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

- The proposed future work is consistent with the barriers and challenges identified to date.
- The proposed future work is appropriate and logical.
- Caterpillar has effectively planned its project to address the DOE fuel cell air system goals. The milestones and go/no-go decision points are well established. Per a reviewer's comment during the AMR, cost may need to be reviewed. The DOE goal for the fuel cell air system is $12/kW; Caterpillar is stating it is at $8.8/kW. This seems better than the DOE goal, but there was a question as to how the cost was calculated. This may need to be reviewed.
- Testing should include start–stop tolerance. The sealing validation plan was not shared. The project should test for turbine robustness to liquid water. It would be great to see Caterpillar work with Argonne National Laboratory (ANL) to run system analysis against a known benchmark.
- The plan by which durability will be validated in 2023 was less clear. It was unclear whether there is an accelerated test procedure that can extrapolate to the required end of expected life for the application.

Project strengths:

- The project's partnerships with industrial partners are its greatest strength toward meeting the DOE goals for developing an advanced fuel cell air system. Another significant strength is the pragmatic approach to keeping the fuel cell air system as simple as possible.
- The project is addressing all the DOE targets for component efficiencies, volume, weight, and cost.

- Strengths include a good solutioning approach, good technology experts, and good collaboration.
- The project has a strong team appropriately focusing on cost and efficiency.
- Strengths are a strong comprehensive approach and team and rapid progress.

Project weaknesses:

- There are no glaring weaknesses in the execution of this project as presently reviewed. There is a concern (not a weakness) about air system costing. Perhaps Caterpillar's estimate of $8.8/kW for the fuel cell air system could be discussed at the next programmatic review.
- No significant weaknesses were detected. Durability evidence against an accelerated protocol is a perceived challenge.
- This has the appearance of a developmental project relying on existing expertise in turbomachinery. The only criticism is that it is not very innovative.
- It is unclear whether/how the selected design can meet sealing and durability requirements. Test plans were not shared.
- Durability demonstration approaches are unclear.

Recommendations for additions/deletions to project scope:

- The project should test against the DOE target of 50,000 start–stops. The project should report the voltage operating range for the selected machine. Compressor–expander performance maps should be shared with ANL (Million Mile Fuel Cell Truck [M2FCT]) to compare system efficiencies with other air machine technology being developed through DOE projects.
- No additions or deletions to the current project scope are recommended.
- Project schedule and scope are appropriate.

Project #FC-353: Fuel Cell Cost and Performance Analysis

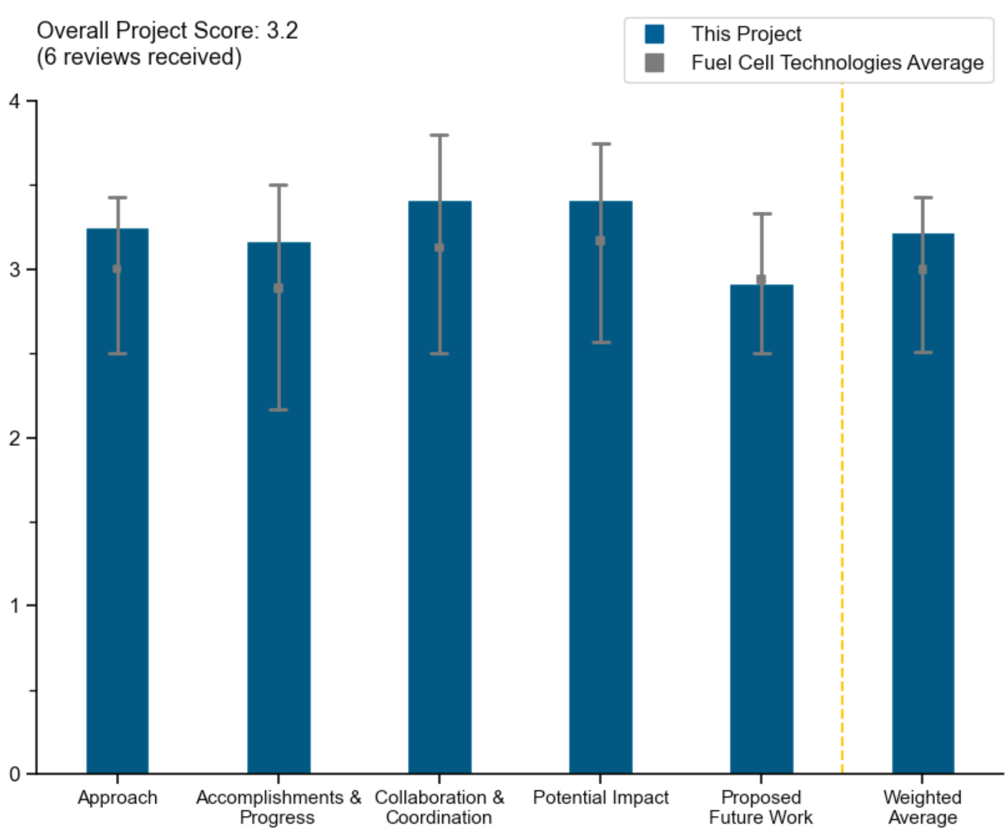
Brian James, Strategic Analysis, Inc.

DOE Contract #	DE-EE0009628
Start and End Dates	10/1/2021–09/30/2025
Partners/Collaborators	National Renewable Energy Laboratory, Argonne National Laboratory
Barriers Addressed	• System cost: Realistic, process-based system costs, need for realistic values for current and future cost targets • Demonstration of impact of technical targets and barriers on system cost: Balance-of-plant components, materials of construction, system size and capacity (weight and volume)

Project Goal and Brief Summary

This project's primary goal is to develop fuel-cell-centric techno-economic analysis models based on Design for Manufacture and Assembly (DMFA), an engineering methodology geared toward reducing time-to-market and production costs by simplifying manufacture and assembly in the early design phases of the product lifecycle. This methodology will be employed in an effort to understand the state-of-the-art fuel cell technology for low-, medium-, and high-duty (LD, MD, HD) vehicles; project the cost of future fuel cell systems; and measure and track the cost impact of technological improvements in these systems. The project will highlight cost drivers to facilitate Hydrogen and Fuel Cell Technologies Office programmatic decisions. The information gained from these initiatives will be disseminated to the fuel cell industry through comprehensive reports.

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 Strategic Analysis team members use their DFMA approach to set cost targets for MD and HD fuel cell vehicles. They have optimized their model for years and work with vendors to constantly update prices/costs. The work of the Strategic Analysis team is generally well regarded, and they are recognized for setting the key performance indicators for DOE, and effectively the world, in fuel cells.
- It is excellent to keep to a consistent DFMA approach for cost analysis. The collaboration with Argonne National Laboratory (ANL) on system analysis is a good approach to specifying the system architecture and performance as a basic assumption of cost analysis. It seems to be good to expand the cost analysis to other than the HD applications. Clarification is needed on how the fuel cell system information is being obtained to pursue the cost analysis for train and marine applications.
- The proposed approach is well aligned with the scope of the project.
- The project team members have demonstrated that they are very good at cost analysis of fuel cell systems and components. This was very well suited for a research and development (R&D) project focused on LD fuel cell systems where lowering capital costs was the top priority. However, there is concern that this approach is too narrow to provide the most value for HD systems, where capital costs are secondary to total cost of ownership (TCO). It appears that the project is targeted to minimizing capital costs under some semi-arbitrary constraints on durability, efficiency, and other application requirements. This is fine for cost benchmarking, but for strategizing R&D, it would be better for the analysis to look at which HD fuel cell system minimizes TCO and then identify fuel cell R&D priorities based on the answer.
- There is a good approach for LD, MD, and HD systems with prioritized timelines. Rather than application-specific analysis (for example, HD vehicles vs. rail or marine), it may be helpful to have cost as a function of only power level (e.g., the cost for 100 kW, 200 kW, 300 kW) since such fuel cell packages may be interchangeable in different applications with slight packaging variations. Also, it may be helpful to keep the power level of LD and MD vehicles the same to drive some complexity out of cost modeling and allow a focus on underlying cost drivers due to higher durability requirements. Some additional background or references on balance-of-plant (BOP) cost drivers to meet durability would help. It would be helpful to know whether there is any relation between cost and usage (i.e., whether the same MD vehicles with bigger batteries have an impact on fuel cell cost).
- It is difficult to quantify HD vehicle costs when it is not clear whether 25,000-hour durability is possible with the current material set and systems approach. It would be more valuable if the predictions were bounded between a high and low. With the current material set, it is difficult to see stacks lasting 25,000 hours. Perhaps the team should also be looking at a stack replacement in the 2025 numbers. It just seems unrealistic that the numbers being predicted with a single original set are likely.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The Strategic Analysis team responded to original equipment manufacturer (OEM) concerns and decreased the power loss of the stacks over their lifetime by introducing “voltage clipping,” which is a standard method used by controls engineers to not over-oxide platinum and platinum alloy catalysts. The team also looked more carefully at the impact of battery hybridization for sizing the fuel cell, another common practice now, especially as the cost of batteries has decreased. In this way, the project is able to provide guidance on how to lower costs and improve durability.
- There are good outcomes from the new Million Mile Fuel Cell Truck (M2FCT) reference system (275 kW) cost analysis.
- The project progress is clear, with regular accomplishments being reported. Focusing efforts on MD and HD road vehicles (rather than rail) appears to have been a good choice, as the level of application-specific detail required for a systematic analysis is significant. This limits the number of applications that can be effectively investigated with this approach. However, given the wide range of fuel cell applications that are

of interest, it may be worthwhile for the project researchers to consider whether they could apply an alternative “breadth first” approach to provide some useful information on a broader variety of applications quickly without a complete detailed analysis. Specific results of the project are generally well communicated in terms of understanding the reasoning and basis for the analysis, although there could be some improvement in making the high-level results more digestible, especially considering the complex tradeoffs and constraints for HD fuel cells.

- Regarding accomplishments and progress for MD vehicles:
    - On the table for Battery Energy on slide 8, it is not clear whether the peak is in kilowatts or kilowatt-hours. Also, since the battery is a key enabler for MD, it would be helpful to provide some estimate of the cost of this battery.
    - It is not clear why fuel cell “key-on” time is 14.5 hours versus 25,000 vehicle hours, nor is it clear whether the target of 25,000 is for vehicle hours or fuel cell system hours.
    - The project has a good approach for the cost walk between LD and MD. Since the main difference between these applications is durability (not power), a cost walk of associated durability enablers will help readers correlate cost−benefit, or “bang for their buck.”
    - The rational for an additional $35 for changes to BOP is unclear, as the size (kilowatts) is similar to LD. It is not clear whether it is for more durable components or whether that is factored into the replacement cost—or whether there is some double-counting.
    - Since BOP cost is a significant cost driver (almost half of the cost increase), a detailed component-by-component breakdown would be helpful. Also, any insights into which components will need to be replaced will help with those designing and packaging the fuel cell systems.
    - It is not clear whether the need for active area-oversizing to meet durability considers the benefits of hybridization to help enable durability in the ANL analysis.

  Clarification is needed on the peak power of the battery in the HD study on slide 13. Insight into the tradeoff between battery size and battery cost for both MD and HD vehicles would be helpful, as would any insight or key references on usage (i.e., battery charge−discharge cycling) of its durability. The reviewer is looking forward to future updates on this side study.
- As usual, accomplishments correspond to the foreseen work plan. It is not clear whether using a cost target for 100,000 systems per year for HD vehicles is relevant, as this number refers to a unique system producer. Perhaps 30,000 systems per year is more appropriate. In the cost breakdown comparing LD and HD vehicles, the impact of the different duty cycles should be taken into account. HD vehicles have fewer dynamic duty cycles, which should have a positive impact on lowering the degradation of some bipolar plate components compared to the corresponding components used in LD vehicles. As some stack suppliers are now providing high-power stacks over 200 kW or even 300 kW, it would be helpful to know the impact of the system modeling and the overall cost.
- It is not clear whether the numbers have been verified with OEMs.

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 Strategic Analysis team appears to be effectively integrated with the project partners at ANL and the National Renewable Energy Laboratory (NREL) to improve understanding of fuel cell technologies, model system development, manufacturing considerations, and durability concerns. The feedback and information from industry partners appears to be effectively collected and used by the project.
- The Strategic Analysis team does an outstanding job gathering information from the fuel cell industry to make accurate models. The team also works with ANL on a vehicle model and supports the techno-economic analysis at NREL. The team does an excellent job at not “leaking” information from any of the fuel cell sources to retain the company’s trusted status in the industry.
- In addition to collaboration with the systems analysis led by ANL, the project demonstrates good communication with industry partners to obtain the information.

- There is good collaboration with ANL on the performance and durability modeling.
- There might be value in looking at cost savings possible by standardization. Also, OEMs should be involved in validating the approach and numbers.
- The collaboration seems adequate, but close discussions with HD vehicle manufacturers and users could be strengthened.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project provides essential information to the DOE Hydrogen Program (the Program) and fuel cell community to understand fuel cell costs as well as considerations of manufacturing and system integration. Much of this information is typically proprietary and therefore inaccessible to the broader community, but the model systems developed and analyzed within this project, with industry input, effectively convey necessary lessons in a non-proprietary format. This provides key strategic guidance for the Program and broader fuel cell community to maximize the effectiveness of R&D efforts.
- Cost is always an important attribute for commercialization. Analyzing M2FCT reference system design (275 kW) and providing feedback for the next design iteration has high impact potential for HD applications.
- The outcomes of this project may facilitate final investment decisions of several projects and convince new adopters to shift to hydrogen mobility, in particular for HD vehicles.
- Cost reduction is a key enabler for wide acceptance, and this team is helping break down the cost drivers and helping with projections into the future.
- The potential impact of this work is very high.
- It might be worthwhile to relook at carbon plates if SS316 is $3/kW. (Ballard Power Systems is recently claiming a large reduction in costs due to an improved manufacturing process.)

Question 5: Proposed future work

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

- The proposed future work is to add rail and marine system analyses and then return to update the analysis for the various system types. This is a reasonable approach following the project's current focus. However, there is concern that the analysis is not fully embracing a consideration of TCO concerns to the extent required for effective analysis of HD fuel cell systems. It is suggested that the project incorporate this into all of the analysis going forward (or at a minimum, that the project have side studies looking at how system choice affects TCO). For example, the project could consider how stack oversizing, degradation rates, and replacement times affect TCO, or the project could consider what kind of system design maximizes overall efficiency and whether this justifies potentially higher capital costs. The planned future side studies of hybridization, battery and power electronics costs, and comparisons of stack replacement strategies are all good topics.
- The future work appears to be correct, with some additional proposals. The project should assess the sensitivity of the battery costs (which depend not only on their size but also on the type of battery energy/power and the chemistry chosen). The impact of using non-polyfluoroalkyl substance (non-PFAS) membranes should also be assessed. The project should compare the fuel cells with hydrogen combustion engines for HD vehicles. The project should also include a TCO approach, which is an important factor used for selecting HD vehicles.
- The team is planning to conduct cost studies for the battery and its impact on overall system cost. Strategic Analysis should continue to collaborate with the analysis teams (i.e., ANL) to study optimal MD/HD system battery size that minimizes overall TCO for different applications (e.g., MD and HD vehicles vs. rail vs. marine).
- The proposed work by the Strategic Analysis team is fairly incremental, following on existing work. The team does not have any plans for how to capture the changes in hydrogen costs and battery electric vehicles

in the fuel cell industry. The models should also include the impact of platinum group metal (PGM) recycling, even at a minimum of recuperating 20% of the Pt value, and then showing the impact of recovering higher values.

- The priority on rail or marine system cost analysis does not match. The fuel cell system design should be created and agreed upon first. The project should prioritize the HD system analysis, particularly by updating the M2FCT reference system (275 kW net), and provide feedback for the next design iteration (system analysis) to reduce the cost.
- The approach and numbers should be validated before any more applications are modeled.

Project strengths:

- A project strength is the very high-quality work on core cost analysis and model system development. There is good integration between project team members and industry partners. There is high value and potential impact from the project efforts.
- One of the strengths of the project is the accumulated knowledge of DFMA cost analysis approaches, particularly the detailed level of the stack, unit cell, membrane electrode assembly, and bipolar plate. The project shows a strong connection with industries to obtain cost information.
- The Strategic Analysis team members make improvements to their models yearly, and their guidance is used throughout the fuel cell industry to set costs and performance goals.
- There is sound, rigorous analysis from both a technology and a business perspective (e.g., the impact of horizontal integration).
- This project relies on many years of development and on a strong, skilled team of experts.
- A strength is the diligence in collecting cost data.

Project weaknesses:

- The impact of stack parameters on cost and degradation seems to be mature. However, it is unclear whether BOP durability and replacement projections are mature. It is suggested that the project conduct some analysis on transfer functions between vehicle usage to fuel cell system usage (with battery buffer) and then to component usage (with some assumption of underlying controls and operating strategies). Also, references for basic physics of stressors for each of these components would help with understanding cost impacts.
- The models consider a relatively low outdoor maximum temperature of 40°C. U.S. military standard MIL-STD-810 is for 49°C, and this seems like a better, more proven temperature to use. The Strategic Analysis team’s models do not reflect major changes in the hydrogen fuel cell market, such as the impact of the decreasing cost of hydrogen on vehicle ownership. The models are not validated because they are based on high-volume manufacturing, which does not exist yet for fuel cells.
- The project consideration of TCO for HD applications is lacking. It seems as though the constraints on the project scope and use of fuel cell specifications from national lab consortium partners may limit the project from providing the best strategic guidance on HD fuel cell R&D priorities.
- A multi-year approach with numerous types of transport vehicles may lead to not being able to deepen enough different potential system architectures.
- The presentation did not provide a detailed level of the DFMA approach for BOP components.
- A project weakness is the unvalidated data/approach.

Recommendations for additions/deletions to project scope:

- The Strategic Analysis team began to examine the impact of PGM recycling on costs in some of the company’s prior work, and the team should continue this work. It might make more sense to use higher Pt loadings for higher performance, coupled with recycling, rather than using a lower Pt loading and oversizing the fuel cell stack. The Strategic Analysis team has a “bottoms up” approach with its DFMA model. It would be interesting to compare the cost targets for fuel cells versus projections for battery electric vehicles (and for hydrogen internal combustion engines), especially as the cost of hydrogen is projected to fall. As awards are made by DOE in 2024 for high-volume fuel cell manufacturing, DOE and the Strategic Analysis team should consider how to validate their models with real data.

- It is highly suggested that the project should pursue the TCO analysis for HD applications as a side study. For HD applications, customers are conscious of TCO rather than capital expenditures (system cost). It will be good to identify implications of TCO with system efficiency and durability. In addition, the cost analysis is expected to expand to include the recycling of previous materials in the cost model. Finally, the BOP cost analysis should be updated with ongoing project information, such as the air management system (centrifugal and positive displacement) as a side study.
- The project should expand to incorporate TCO into its cost analysis or begin working closely with other projects focused on TCO analysis to make use of their findings. It would be good for the project to consider alternative system designs, for example, a very high-efficiency system. An investigation into hybridization strategies is a good step in this direction.
- The project should assess the sensitivity of the battery costs (which depends not only on their size but also on the type of battery energy/power and the chemistry chosen). The impact of using non-polyfluoroalkyl substance (non-PFAS) membranes should also be assessed. The project should compare the fuel cells with hydrogen combustion engines for HD vehicles. The project should also include a TCO approach, which is an important factor used for selecting HD vehicles.
- The scope seems correctly prioritized, with initial focus on HD vehicles and then on other applications.
- Validation and consultations with OEMs should be added.

Project #FC-363: Advanced Fuel Cell Vehicle DC-DC Converter Development

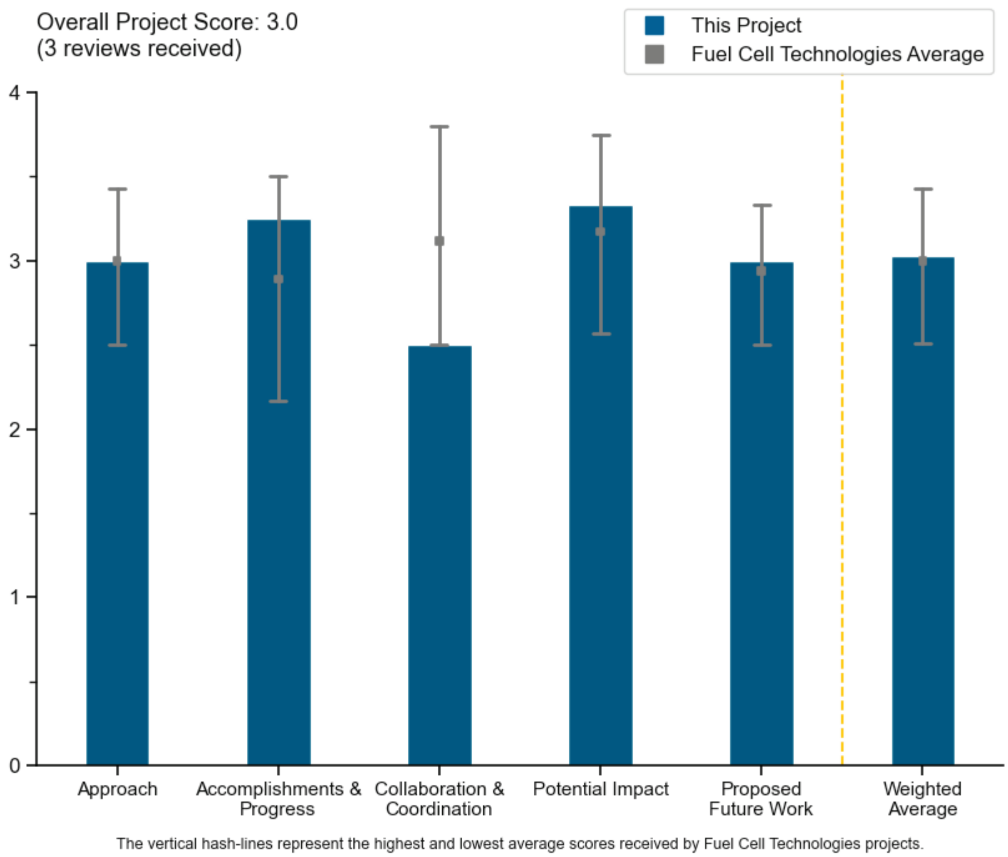
Vivek Sujan, Oak Ridge National Laboratory

DOE Contract #	WBS 1.4.0.650
Start and End Dates	4/1/2023–3/31/2026
Partners/Collaborators	Million Mile Fuel Cell Truck Consortium (M2FCT)
Barriers Addressed	• Safety • System efficiency • Durability

Project Goal and Brief Summary

The goal of the project is to develop a high-frequency power electronic direct current (DC)-DC converter architecture for fuel cell electric vehicles (FCEVs) to enhance safety and durability while achieving high-power and high-efficiency targets. The project aims to create a flexible and scalable platform approach that meets or exceeds system isolation requirements for fuel cell power levels aligned with heavy-duty (HD) truck requirements. The project follows a platform approach, starting with safety and then developing a fuel cell DC-DC converter platform (100–400 kW). The design considerations include isolation levels, input/output current and voltage characteristics, parallel/series fuel cell stacks, current leakage pathways, operating efficiency, thermal management, and single/bi-directional power flow. The project proceeds through system modeling, detailed electrical system design, and component validation to optimize efficiency, cost, and durability. The project leverages the knowledge, characterization, and modeling capabilities of national laboratories to develop a scalable platform that supports the Million Mile Fuel Cell Truck (M2FCT) consortium. The project outcomes will contribute to pre-competitive system analysis, design optimization, and critical component characteristics, accelerating technology development for at-scale production.

Project Scoring



Note: This is a new project in 2023. 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.

- The project appears to be considering overall system cost and tradeoffs between the fuel cell stack and DC-DC converter in the optimization, not just DC-DC converter costs and efficiency, which is appropriate. Project targets (i.e., cost, efficiency) are not defined, and milestones do not contain DC-DC converter or fuel cell system performance metrics. The approach seems to be trying to cover a broad space and appears to be attempting to design a flexible DC-DC converter architecture that would be applicable to a wide range of architectures, applications, and power levels. The low end of the proposed power range (100 kW) does not match current Hydrogen and Fuel Cell Technology Office (HFTO) priorities. A focus on higher power levels of ~250–400 kW, current fuel cell vehicle system architectures, and HD vehicles would better match current HFTO priorities and allow for quicker identification of requirements and design optimization.
- The approach is clearly spelled out, but there are some holes that need to be filled. There are several approach drawbacks. (1) Cost receives some mention, but it should be a key consideration listed on slide 5. (2) The presentation mentions targets but then fails to list numerical values. Slide 7 lists a target of >94%, but that seems a low and not particularly ambitious target. (3) In terms of clarity, the team speaks of architectures but not of circuit design/material selections. It is not stated what basis material set (metal-oxide semiconductor field-effect transistor [MOSFET] vs. insulated-gate bipolar transistor [IGBT]) is being considered.

- This project seems well organized; barriers are identified, and objectives are clear. More effort should be placed on leveraging existing knowledge. For instance, rather than developing some of the models required for Phase 1 (powertrain resistance and performance models), existing models should be adapted and improved.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- This is a brand new project; planning and background material are at an appropriate level for this stage of the project.
- The project has just started, so there are no results yet.
- The project just got started.

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.

- Collaboration with M2FCT is good and provides the project with access to a range of companies conducting FCEV development. The project also lists "consultancy" with three companies, one stack/system/vehicle developer, one stack/system developer, and one coolant fluid developer. This provides the project with good input on the system-level issues. Electronics/DC-DC converter companies are not listed. Oak Ridge National Laboratory (ORNL) has substantial internal knowledge, but consultation with actual companies developing DC-DC converters would strengthen the team.
- Currently, no collaborations exist. The project team expects to collaborate with M2FCT in the future. This project would benefit from collaboration with fuel cell stack and fuel cell truck original equipment manufacturers (OEMs), (Cummins, Plug Power Inc., Nikola Motor, Hyzon Motors Inc., etc.), especially during initial phases when requirements are being defined and in the validation activities.
- Planned collaboration with industry partners and leveraging ORNL power electronic expertise will improve the likelihood of success.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The DC-DC converter and the power electronic architecture considerations involved with it have been historically overlooked by the community and DOE. This project will take a large step in correcting this.
- This is an important component in the fuel cell system that drives weight, cost, and efficiency and is under-studied. This project could significantly impact DOE targets and goals for FCEVs.
- The project aligns with DOE objectives to improve efficiency and reduce costs of HD fuel cell vehicles. The DC-DC converter does not appear to be a major contributor to overall system cost, and efficiencies are already fairly high (~95%–98%). While improvements would be beneficial, the expected impact of this project on achieving overall fuel cell system cost or efficiency targets is not expected to be large.

Question 5: Proposed future work

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

- As this project is just starting, all of its work is proposed future work. The approach is good, so the future work is also good.
- Planning and milestones are logical. Targets are very ambitious; the team should make use of existing models wherever possible and lean on industry partners.
- The planned work is logical.

Project strengths:

- Work on power electronics for FCEVs is overdue, and this project is a step in the correct direction. The project starts with architecture studies and ends with a hardware demonstration. That is a good approach. Coordination with M2FCT is a must-have. ORNL is a well-experienced, knowledgeable team appropriate to take on this project.
- ORNL expertise in power electronics and vehicle electrification is a strength.
- Strong collaboration partners are a strength.

Project weaknesses:

- The project does not have numerical metrics for the milestones and go/no-go criteria. The project does not have a collaboration or consultancy with an actual electronics manufacturer for that particular perspective.
- The project lacks existing collaborations with fuel cell vehicle OEMs and defined requirements and performance targets for the DC-DC converter.
- The project might be too ambitious. The range of applications and use cases might prohibit a truly scalable DC-DC.

Recommendations for additions/deletions to project scope:

- Numerical targets should be added to milestones and go/no-go criteria. Cost and total cost of ownership should be incorporated earlier in the project (included in budget period 1). The team should consult with a volume manufacturer of DC-DC converters. Current DOE/M2FCT plans assume only a low of 0.7 V/cell at peak power (at the end of life). But current FCEVs can dip to 0.6 V/cell. This potentially changes the required ratio for the DC-DC converter. This lower voltage should be considered in the project. Mention is made of different coolant fluids and types. In addition, Chemours is included as a consultancy. Specific assessment should be made of the impact of colder refrigeration fluid temperature on the efficiency/performance of the DC-DC converter.
- Collaborations with fuel cell truck OEMs would be beneficial.

Systems Development and Integration – 2023

Systems Development and Integration Subprogram Overview

Introduction

The Systems Development and Integration (SDI) subprogram aligns with priorities in the *U.S. National Clean Hydrogen Strategy and Roadmap* and aims to enable the H2@Scale vision and support the Hydrogen Energy Earthshot (Hydrogen Shot) through targeted hydrogen and fuel cell system integration and demonstration activities. To achieve this mission, the SDI subprogram focuses on:

- Identifying hydrogen applications and system configurations that can provide affordable and reliable clean energy.
- Validating and testing first-of-a-kind integrated energy systems.
- Bridging the gaps between component-level research, development, and demonstration (RD&D) and commercialization by integrating technologies into functional systems, reducing costs, and overcoming barriers to deployment.

Demonstrations conducted during verification and validation activities provide valuable data and feedback to research and development (R&D) conducted through the U.S. Department of Energy (DOE) Hydrogen Program. The data are also used in techno-economic assessments of various market scenarios to provide essential information regarding market readiness to manufacturers, investors, and potential end users.

The SDI subprogram focuses its activities on key emerging markets and technology applications based on preliminary findings of the Analysis, Codes and Standards 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 SDI subprogram is currently focused on three technology application areas:

- Grid energy storage and power generation applications, with a focus on grid integration and direct coupled renewable and nuclear hybrid systems, as well as distributed and backup power generation. Projects are designed to produce low-cost clean 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. Within this application area, the subprogram also supports manufacturing RD&D to develop techniques to produce advanced hydrogen system components and sub-systems at high production volumes.
- Chemical and industrial processes, with a focus on decarbonizing hard-to-decarbonize industrial sectors through integration of hydrogen technologies. These end uses include industrial processes, such as iron ore reduction needed for steelmaking, and chemical applications such as ammonia, synthetic fuel, and chemical production, among others. The integration of clean hydrogen will reduce greenhouse gas emissions, preserve and support jobs, and support environmental justice by helping build a clean economy.
- Transportation, which includes medium- and heavy-duty trucks, maritime, rail, off-road equipment, and other heavy-duty applications requiring significant power, range, and up-time. The focus for heavy-duty transportation applications is to demonstrate and validate fuel cell durability and performance under real-world conditions. Projects will also demonstrate and validate high-flow hydrogen fueling to support these transportation modes. Analysis will be conducted to determine total cost of ownership and future targets needed to compete with incumbent technologies.

Goals

The overarching goals of the SDI subprogram are to identify and demonstrate new and promising integrated hydrogen production and end uses, expedite private-sector commercialization of hydrogen and fuel cell systems, validate the performance of these systems, and achieve economies of scale as envisioned in the H2@Scale initiative.

Key Milestones

Key milestones for the SDI 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 directly integrated with nuclear and renewable power sources with the goal of achieving clean hydrogen production at <$1/kg.
- Validate 90% efficiency (based on high heating value of hydrogen) for high-temperature electrolysis systems operating at nuclear plants utilizing onsite waste thermal energy.
- Validate an integrated distributed and backup power generation system in real-world operations for power demands at a megawatt scale.
- Demonstrate integrated electrolyzer systems at the megawatt level using multiple electrical sources and targeting hydrogen end uses across transportation, industrial/chemical processing, and power generation.

Chemical and Industrial Processes

- Verify clean hydrogen system cost and technical performance comparable with incumbent technologies for metals production.
- Demonstrate approaches to integrate clean hydrogen to decarbonize iron/steelmaking at a scale of at least 1 tonne/week, with a path to capacities of at least 5,000 tonnes/day to meet the requirements of existing steel mills.
- Integrate emerging concepts with industrial processes for production of synthetic fuels and chemicals; verify costs and validate technical performance.
- Initiate transition to clean hydrogen for hard-to-decarbonize industrial applications and identify specific locations for potential scale-up (e.g., ammonia, refineries, steel).

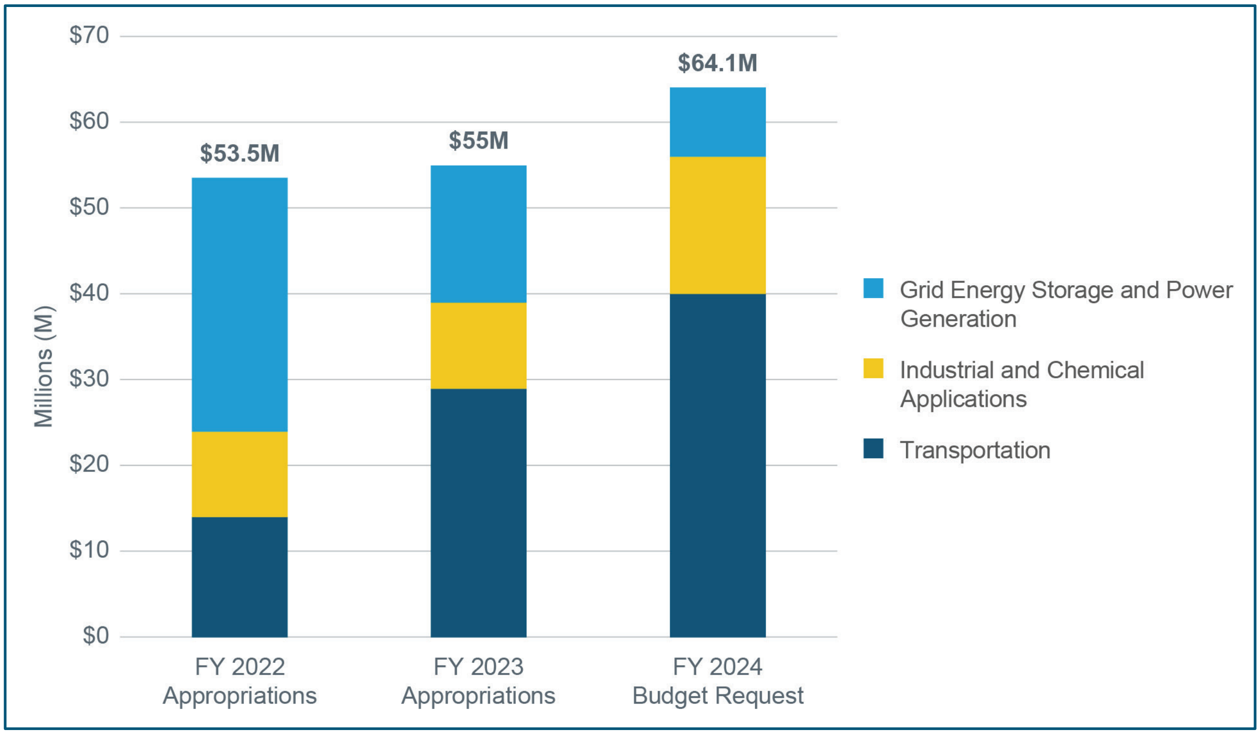
Transportation

- Develop and demonstrate fuel cell systems capable of achieving 25,000-hour durability and 68% peak efficiency for heavy-duty truck applications.
- Demonstrate how a substantial reduction (75% or greater relative to diesel-equivalent trucks) in greenhouse gases and local pollutant emissions from moving goods in trucks can be achieved in a way that is economical and scalable.
- Develop and demonstrate fuel cell systems capable of achieving a 30,000-hour lifetime and a cost of $60/kW for ultra-heavy-duty applications (e.g., ferries, rail, mining).
- Validate technical and economic potential of hydrogen and fuel cells for off-road applications.
- Deploy scalable hydrogen fueling stations to support early fleet markets, such as heavy-duty trucks and buses capable of 10 kg H_2/min (average) fueling.

Budget

The Fiscal Year (FY) 2023 appropriation for the SDI subprogram was $55 million. Additionally, the subprogram is collaborating with the Office of Clean Energy Demonstrations and the Hydrogen Program to allocate $8 billion, funded through the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law), for Regional Clean Hydrogen Hubs.

The FY 2024 budget request is $64.1 million to continue accelerating efforts to demonstrate and validate low-cost hydrogen production integrated with various hydrogen end uses to enable decarbonization, support the H2@Scale vision, and align with priorities in the *U.S. National Clean Hydrogen Strategy and Roadmap*.



Annual Merit Review Results

During the 2023 Annual Merit Review, 34 projects funded by the SDI subprogram were presented, and 25 were reviewed (a breakdown by budget category is shown on the right). The reviewed projects received scores ranging from 2.9 to 3.7, with an average score of 3.3. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Following are reports for the 25 reviewed projects. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Number of Projects Reviewed by Budget Category	
Grid Energy Storage and Power Generation	11
Industrial and Chemical Applications	3
Transportation	11

Project #SDI-001: Integrated Modeling, Techno-Economic Analysis, and Reference Design for Renewable Hydrogen to Green Steel and Ammonia

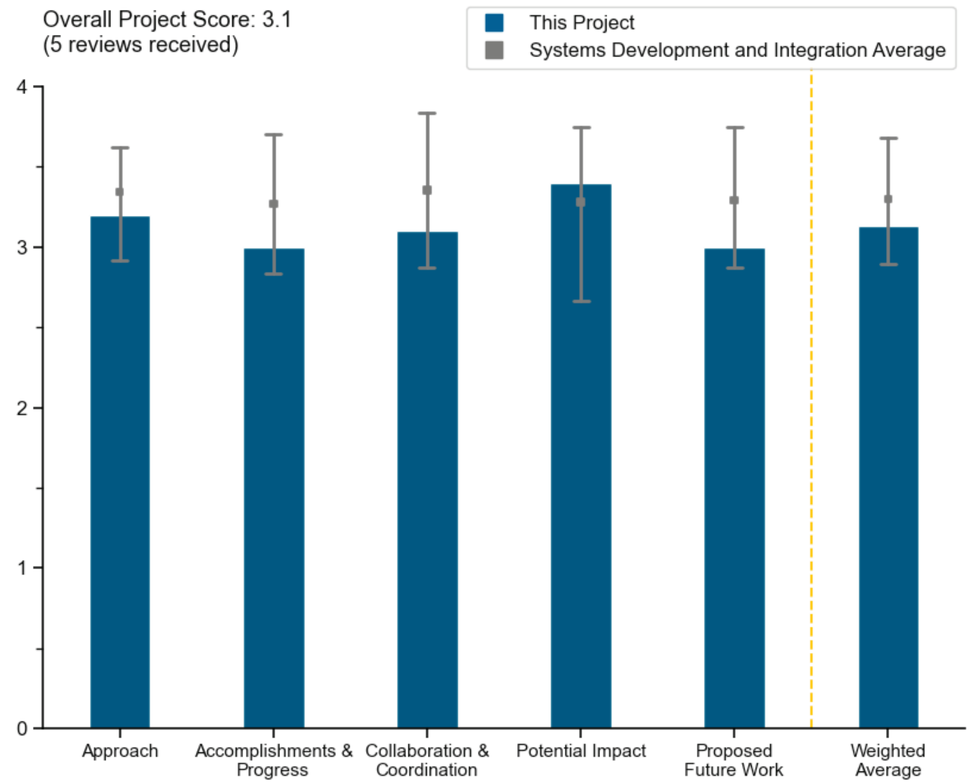
Steve Hammond, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.23
Start and End Dates	8/1/2022
Partners/Collaborators	Lawrence Berkeley National Laboratory, Argonne National Laboratory, Sandia National Laboratories, Oak Ridge National Laboratory
Barriers Addressed	• Design and analyze shared components across renewable power, hydrogen, and steel/ammonia • Integrate tools developed in isolation for individual technologies into one framework to exploit synergies across technologies • Targeting systems that reduce costs 10%–20+% due to tight-coupling and co-locating technologies

Project Goal and Brief Summary

The project aims to develop a national roadmap, integrate component-level modeling tools, and develop reference designs for gigawatt-scale, off-grid, tightly coupled hybrid energy systems specifically designed for green hydrogen production. The project's goal is to accelerate the decarbonization process for hard-to-abate industries, with a focus on lowering costs for green steel and green ammonia production. The project involves designing and analyzing tightly coupled systems with cost projections, comparing them to steam methane reforming and grid-connected designs, and calculating life cycle greenhouse gas emissions. The research aims to demonstrate the viability, cost-effectiveness, and rapid deployment of integrated hydrogen systems, providing a more sustainable alternative to fossil fuel-based methods.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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.

- Project objectives are clearly identified as analyzing reference designs for gigawatt-scale, off-grid energy systems utilizing green hydrogen production. The approach uses a combination of use case hydrogen production configurations in close proximity or co-located with industry end uses. It is good that the work is building on other modeling work that already exists and is integrating those models to explore this area. The approach for the bulk storage component regarding the use cases is not described well (e.g., the types of storage that were considered in locations where salt caverns are not available).
- Green hydrogen for ammonia production is an important area for research, given the large amount of hydrogen used in this industrial sector. Hence, the project is well targeted, as an analysis-type project, perhaps leading to actual field trials/real-world deployment-type projects.
- The approach aligns well with the project goals. Case studies and regions selected for assessment support the development of a national roadmap for green hydrogen production for industrial use.
- The budget does not make sense. The presentation states a Fiscal Year (FY) 2022 budget of $2.5 million and an FY 2023 budget of $3 million for a total budget received of $2.5 million. It is not clear why the total budget is not $5.5 million. This is an extremely well-funded project for a market analysis. There are very limited locations that have both excellent wind and solar that are not already being developed.
- This project does not have list of tasks and milestones, despite having such a large budget. It is hard to know what it aims to achieve quarterly and ultimately. It is also not clear how the project acquired data and analyzed data. For example, it was not clear what model was used for data analysis. In addition, the project did not disclose the names of steel and NH_3 plants. It would be more convincing if the steel and NH_3 players could be shared. Finally, the project selected five locations, but Wyoming location information is missing.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- The analysis provides very interesting results. It seems there are relatively few good locations. The team did not address whether those locations are available and what challenges would be in their development. (For example, Hydrogen Analysis [H2A] assumes a low cost for land, although perhaps this is not reasonable for these prized locations.) It would be helpful if the presentation could show how much each different credit is in the analysis. The presentation has one arrow showing final result. It would be great to see how much each different credit reduces cost (carbon capture and sequestration credit, production tax credits, etc.) since this assumes that cost and performance targets for electrolyzers are attained. A sensitivity analysis would seem prudent since the cost and performance targets for electrolyzers are very aggressive. The use of a proton exchange membrane (PEM) electrolyzer was assumed. For the ammonia and steel production, it is recommended that the project use a solid oxide electrolyzer that could utilize waste heat and achieve efficiencies in excess of 80%. Efficiencies as high as 85% have been reported for solid oxide electrolyzer cells (SOECs) with waste heat at 150°C or lower. The SOEC is a better technology for this application.
- Good progress has been made on exploring the levelized cost of hydrogen production in four land-based locations for ammonia and steel production. The accomplishments are consistent with the DOE H2@Scale initiative goals by enabling low-cost hydrogen produced from renewable power for various end-use applications. Comparing the cost of hydrogen, a total cost was presented comparing all cases. However, a breakdown of all costs (electrolyzer, renewable, and storage) would be meaningful to provide clarity on which component dominates in terms of cost and region. While the storage amount of hydrogen is certainly evaluated, the amount of storage required for the various locations were not discussed in the presentation.
- The project is well aligned with DOE goals. Progress with initial analysis results seems pretty good so far.
- Accomplishments present various scenarios for hydrogen use, depending on region and energy source. Credit- and non-credit-based scenarios are incorporated to show policy impacts.
- The project has spent $2.5 million since August 2022, but the produced data is limited. It would be great to know how funding was spent by category. In addition, the project needs to explain the data more clearly. It is not clear why NH_3 prices varied from state to state while steel prices are nearly constant across different states. It is not clear why Wyoming has the lowest green H_2 and NH_3 prices, and the presentation does not explain what negative H_2 and NH_3 prices mean. The project did not show the data sources and major components for the calculations/models.

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.

- Multiple laboratories are working on each task; the accomplishments indicate that there is good collaboration between the laboratories thus far. There is no collaboration from industry or academia yet, only from an industry think tank. It would be helpful to collaborate with industry so as to get more realistic input and enable a robust feedback loop.
- Collaborative aspects are limited but not unreasonable for an analysis project.
- Collaboration shows use of multiple national labs for output. Industry involvement or verification of cost inputs would provide more robustness.
- The project is the collaboration of multiple national laboratories. For this kind of project, industry engagement is very important. However, this project did not involve any industry partners.
- The project should have had some input from the steel and ammonia industries.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The output of this project is very highly relevant to H2@Scale; one of the greatest benefits of large-scale hydrogen storage is that it allows the economic production of renewable energy and then makes that energy available at a later time when required by the consumer. Therefore, this work is going to inform the economics of which applications make economic sense, as well as where and at what scale.

- This industrial sector is pretty important, so the work is highly relevant and has significant potential impact. The aspect related to continuous operation (steady-state) is very important for these types of industrial applications and so should be even further emphasized for potential industrial up-take.
- The impact of different scenarios is well described and will help to guide the most cost-effective configurations for installations. The project confirms that Inflation Reduction Act policy is of substantial help to accelerate deployment.
- If successful, the project can become very impactful, as it is one of a few projects that focus on renewable/hydrogen integration.
- Industrial decarbonization is a huge challenge. This is the type of analysis that needs to be done to understand whether this can be achieved. For it to be useful, the analysis must be conservative and not use aspirational assumptions. The current assumptions look overly optimistic. The team needs to validate them with an industrial (not academic) advisory board.

Question 5: Proposed future work

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

- Proposed future work aligns well to address challenges and barriers described. It looks to further explore system capabilities to optimize installations.
- Given the fairly recent initiation of the project, the future work presented in the main portion of the slides is within the scope of this project. The proposed details of this work are somewhat vague, but the work scope is important.
- The proposed future work is comprehensive and clear.
- Future steps seem appropriate, given the current status of the project.
- Other electrolyzer technologies must be included. The realistic reference design needs to include significant involvement from an industry player with experience designing and building real plants. At a minimum, an industrial advisory board should be included.

Project strengths:

- The project does a good job of integrating and building on other models that describe the "building blocks" of the overall ecosystem. The project also does a very good job of addressing a very important element of implementing H2@Scale and renewably producing hydrogen for fuel from intermittent renewable power.
- This is a strong team with well-rounded support from multiple national labs and an academic partner. There is a good selection of scenarios to compare and assess.
- The project addresses a very important area, is extremely well-funded, and includes a large team from the national laboratories.
- The project addresses an important and hard-to-decarbonize sector. The project has strong modeling capabilities and good overall assessment aspects.
- If successful, the project can become very impactful, as it is one of a few projects that focus on renewable/hydrogen integration.

Project weaknesses:

- No major weaknesses were identified, but the project could be strengthened with input from industry collaborators to validate that the methods and impacts being researched are the most important to the industry.
- The following are project weaknesses:
    - This project does not have a list of tasks and milestones, despite having such a large budget. It is hard to know what it aims to achieve quarterly and ultimately.
    - The project did not interpret many data calculations clearly.

  - The project is the collaboration of multiple national laboratories. For these types of projects, the engagement of industry partners is very important. However, this project did not involve any industry partners.
- The project is limited to looking at PEM electrolysis, which is currently relatively high-cost but was modeled with low-cost assumptions. It is unclear whether there will be review/validation by industry groups that actually do ammonia production to get their reactions/concerns.
- The project needs to have an industrial advisory board that can provide real-world feedback. The assumption that all of the electrolysis performance and cost targets will be achieved is aspirational. The team needs to do a sensitivity analysis.
- Industry verification would provide additional value.

Recommendations for additions/deletions to project scope:

- Perhaps it is not possible to include, but it would be interesting to look at other electrolysis technologies, including SOEC with potential waste heat recovery. A sensitivity analysis should be conducted around the optimistic PEM electrolyzer costs, as the project team currently seems to be painting too rosy a picture. A near-term case is suggested with higher (current) costs and the future costs with cost targets (as electrolyzer cost reductions have been pretty stubborn to reduce).
- The project needs (1) to have concrete tasks and quarterly milestones, (2) to explain how the large budget was spent for such a simulation/calculation project, and (3) to explain the calculated data more clearly.
- The project needs to have an industrial advisory board that can provide real-world feedback. The assumption that all of the electrolysis performance and cost targets will be achieved is aspirational. The team needs to do a sensitivity analysis. For this type of hydrogen generation, SOEC technology would be preferred to PEM or alkaline.

Project #SDI-002: Hydrogen Energy Storage System at Borrego Springs Toward a Hydrogen-Enabled 100% Renewable Microgrid

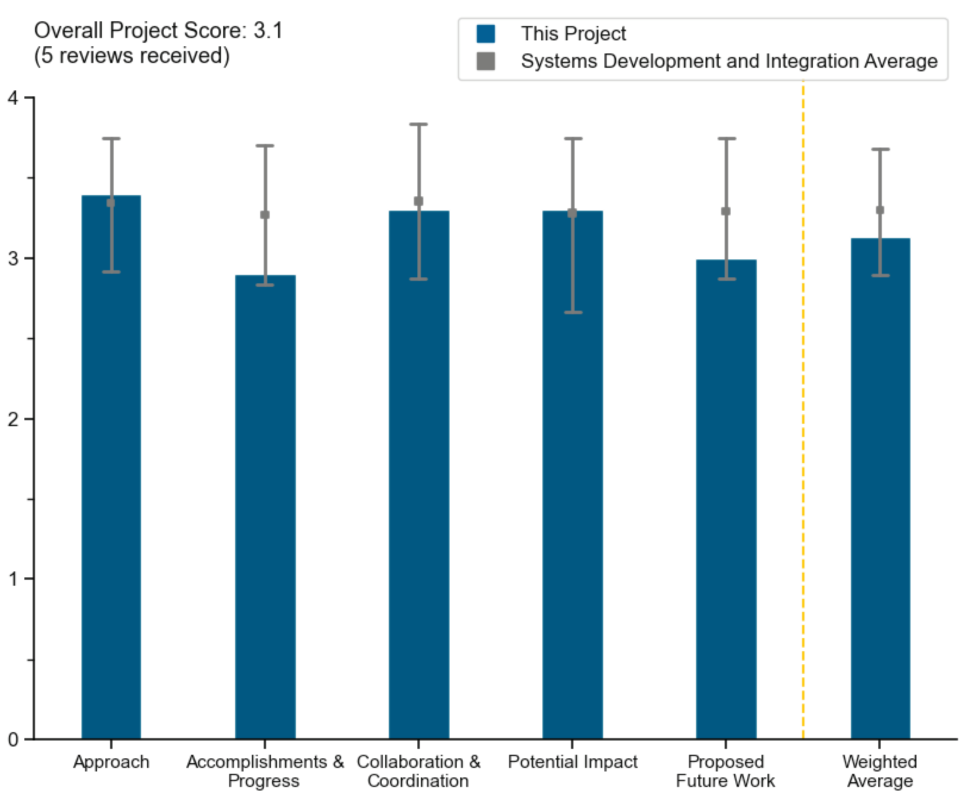
Kumaraguru Prabakar, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.22
Start and End Dates	9/1/2022–8/30/2024
Partners/Collaborators	San Diego Gas and Electric Company, PXiSE Energy Solutions
Barriers Addressed	• Field deployment of electrolyzer and grid-forming fuel cell inverter to support advanced microgrid operation • Disseminate field deployment results and characterize through data collected from the field and technical report • Document and disseminate safety requirements for substation collocated hydrogen assets (electrolyzer and fuel cell assets)

Project Goal and Brief Summary

The project is focused on implementing, characterizing, and analyzing advanced hydrogen distributed energy resources and controls with the goal of achieving a 100% renewable microgrid in Borrego Springs, California. The major goals include establishing intelligent control of hydrogen resources to stabilize the microgrid and reduce photovoltaic curtailment, developing hardware and conducting power hardware-in-the-loop (HIL) performance analysis, and evaluating the microgrid's operational characteristics and resilience improvements under different hydrogen configurations. The project aims to integrate hydrogen energy storage systems into energy system planning tools, quantify emission reductions and resilience benefits, and demonstrate the feasibility of a 100% renewable microgrid. The project will provide insights into the performance, resilience, cost benefits, and system requirements for large-scale deployment of hydrogen-enabled microgrids.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 is a very interesting project that includes hydrogen technologies in an existing remote microgrid. Several key aspects to this approach are innovative and well targeted, including integration of several microgrid technologies, benefits quantification of replacing diesel generators, and others. The project is ambitious but potentially impactful.
- The team has a well-laid-out plan for the two phases of research and deployment. Project planning, model development, and optimizations have started. A well-thought-out plan was presented in the presentation.
- Project objectives are clearly identified: implement, characterize, and analyze advanced hydrogen distributed energy resources and controls toward a 100% renewable Borrego Springs Microgrid.
- The approach of HIL analysis and Renewable Energy Integration and Optimization Platform (ReOPT) development to add missing modules is a great approach. However, it is not clear that the objectives of optimal sizing from ReOPT are reflected in the hardware selections.
- This project focuses on energy storage using hydrogen.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and DOE goals.

- The project is a new start, and the team has started the first phase. The team has made an appropriate level of progress and has a reasonable schedule to proceed.
- The project has good requirements toward stated objectives.
- Progress has been good so far but with some equipment and integration challenges.
- The project has spent ~ only $34,000 since its inception in September 2022 and has generated barely any data at this time. It seems that there has been a significant delay, but the cause was not provided. The project does not include clearly described tasks and subtasks, nor does it include clear and measurable milestones, considering the large budget.
- This is a new project. Only the progress made in the first quarter was mentioned. Not enough was presented to gauge the accomplishments and 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.

- The National Renewable Energy Laboratory (NREL) has partnered with San Diego Gas and Electric Company (SDG&E) and PXiSE Energy Solutions, the microgrid controller vender. The project will also require a fuel cell and electrolyzer vendor. This team seems to have the skills and capabilities to successfully complete the project.
- The project has one industrial partner, SDG&E, and a vendor, PXiSE Energy Solutions, a subcontractor to SDG&E. Electrolyzer and fuel cell vendors are not yet finalized.
- Collaboration and coordination seem fine. This is a strong project team with good collaboration/integration and a strong utility partner helping to deal with some cost overruns.
- Even in a relatively narrow project, the team has done a great job of collaborating across the value chain.
- SDG&E and PXiSE Energy Solutions are good collaborators. At this time, fuel cell and electrolyzer vendors have not been identified. It is not clear why these vendors were not determined during the proposal stage.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Remote microgrids anchored by hydrogen/fuel cells with other generation and storage technologies has been a major area of interest from DOE for many years. It is great to see projects finally working to validate these concepts in the real world. The project has high potential to develop important lessons learned for future projects.
- This project will showcase the resilience benefits of additional hydrogen assets to stabilize microgrids. The project will develop both models and hardware to meet the objectives. This project meets many of the DOE goals.
- This is a potentially impactful project. It is suggested that the project team consider multiple uses of hydrogen, which could be important in a resilience event. This could be not only fuel for resilient power generation but also transportation fuel.
- The output of this project is highly relevant to demonstrating the resilience benefits of hydrogen technologies to microgrids.

Question 5: Proposed future work

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

- The work plan and schedule plan are reasonable for meeting all the goals and overcoming the barriers in front of this project.
- The proposed future work of executing this project is great.
- Proposed future work is good. There are probably some significant project risks yet ahead, but the project plan seems sound.
- The proposed future work is perhaps a reiteration of the project's work scope.
- The project team is aware of important future work. The proposed future work is reasonable. However, the project does not specify how to execute this future work, given the slow progress of this project.

Project strengths:

- This is an ambitious project to demonstrate how hydrogen/fuel cells can be integrated into a pretty complex microgrid. Collaboration among the project partners is strong. There is potential for direct impacts to improve the electrical reliability of this real-world community.
- This is a well-thought-out project that incorporates both modeling and HIL. The project will be very beneficial in incorporating hydrogen assets into microgrids.
- NREL has abundant resources to perform this project. SDG&E and PXiSE Energy Solutions are good collaborators.
- Strengths include access to existing facilities at Borrego Springs and the principal investigator's expertise in power electronics and controllers.
- This project addresses a key challenge in the industry today.

Project weaknesses:

- As discussed during the presentation, decisions around equipment sizing have been somewhat arbitrary so far because of financial limitations rather than technical optimization-type analysis. If these are properly caveated for this project, this is a relatively minor but still important limitation. It is suggested for the future that the project allow for a larger system that is more optimized, which would be an important future extension, presumably based on successful completion of this phase.
- The project does not include clear and measurable milestones, despite having such a large budget ($4.67 million), nor does it provide clearly described tasks and subtasks. The project has a significant delay (the start date was September 1), but the cause of the delay is unknown. The project generated barely any data.

- The team lacks resident expertise in hydrogen assets that are planned for addition to the microgrid: hydrogen fuel cell, electrolyzer, and hydrogen storage.
- This project is limited in scope to “electricity” storage.

Recommendations for additions/deletions to project scope:

- It is recommended that the team go beyond California Independent System Operator (CAISO) pricing to look at the true electricity price in a resilience event. This true price may be infinite if no grid power is available. Understanding the actual pricing (based on supply and demand), in collaboration with SDG&E, may influence the techno-economic analysis and get more accurate results.
- The project needs to clearly provide its tasks and subtasks, which is required for DOE projects, as well as quarterly milestones and annual go/no-go milestones. The project needs to identify fuel cell and electrolyzer vendors as soon as possible. In addition, the project needs to accelerate the progress because of the delay in the first year.
- It would be great to learn more about how the microgrid (once completed) would function in a power outage situation, what loads would be picked up or shed, and the implications for the community.
- The project should add external national labs or industrial partners with expertise in fuel cells, electrolyzers, and bulk hydrogen storage.
- Dissemination and publication of the results of this project will be crucial in advancing hydrogen adoption.

Project #SDI-004: Hydrogen Coach Bus Fueling Demonstration

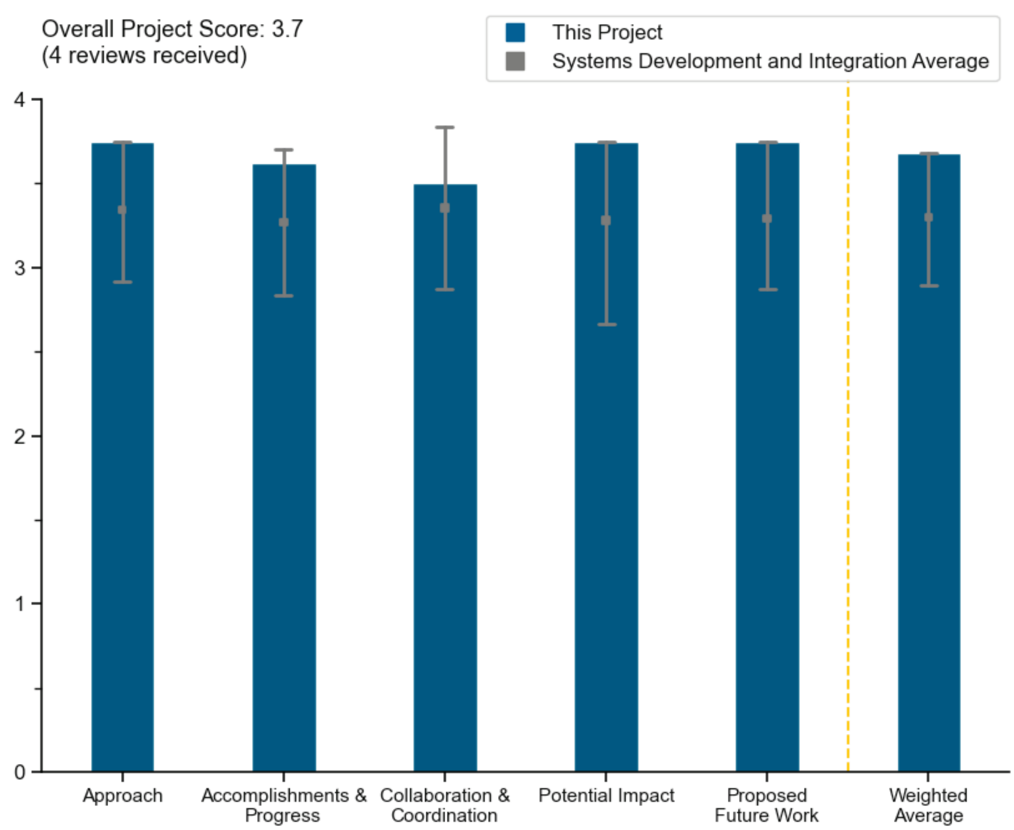
Richard Boardman, Idaho National Laboratory

DOE Contract #	WBS 7.2.9.19
Start and End Dates	10/1/2022–9/30/2024
Partners/Collaborators	FuelCell Energy, Stark Area Regional Transit Authority
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Controls and safety

Project Goal and Brief Summary

The goal of this project is to support the implementation of solid oxide fuel cell hydrogen production at a cost of \$1.00/kg at megawatt scale. The objectives include developing a safe and reliable design for post-processing gases from >100 kW solid oxide electrolyzer cell (SOEC) systems, installing a hydrogen refueling station, demonstrating the operation of heavy-duty fuel cell electric vehicles (FCEVs), and reducing carbon emissions in the Idaho National Laboratory (INL) bus fleet. The project involves various tasks such as system design, installation and commissioning, and detailed process modeling, as well as the integration of SOEC systems and the verification of FCEV suitability, paving the way for the conversion of the INL bus fleet to net-zero carbon options.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 five tasks are clear and are required to build out a successful demonstration. Conceptual process flow is needed for something as integrated as a high-temperature solid oxide electrolyzer to bus fueling. Commissioning will be key to learning to use these new technology components. Stark Area Regional Transit Authority (SARTA) is an excellent location to test with buses, considering SARTA's extensive experience. INL's focus is primarily on post-processing hydrogen from the SOEC, but the most exciting element will be the bus coach fleet demonstration. The listed tasks and approach to technology acceleration are all very logical.
- The project approach is very practical in terms of plan and execution for installing a major hydrogen facility, so it should be able to yield a template for design and engineering, procurement, and construction work for other similar facilities, which should, in turn, reduce cost and speed adoption of SOEC hydrogen production, post-processing, and use.
- Solid oxide electrolysis has the potential to be a cost-effective solution to meeting Hydrogen Earthshot goals. INL has unique capability and setup for a successful project. That being said, the main project goal of demonstrating scaled-up SOECs has the potential to become overshadowed by the coach demonstration. The project goals can be stated a bit more clearly, but otherwise, all goals are relevant.
- This project is well organized and should make significant progress on reducing multiple technology/ demonstration barriers.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- The concept will be able to work with dynamic operation and will be at a significant scale of 320 kg per day. The lessons for supporting the grid with very efficient electrolyzer will be key to meeting DOE goals. It was also interesting to see the detailed process model with detailed specifications, which can be put out to bid with high confidence in the economic projections. It would have been very helpful to share how conventional electrolyzers at ~\$500–\$1,000/kW compare to the current stack cost target and balance-of-plant estimated cost projections. The project also led with \$1/kg cost target at megawatt scale, but the number does not mean anything without including an input electricity assumption (e.g., 1 to 3 cents/kWh).
- Having the site construction largely complete and major components procured indicates significant progress less than one year into the project. However, with some design work still ongoing, care needs to be taken not to create situations in which, for example, safety reviews at the advanced design stages result in backtracking or physical rework.
- The project has a very good start. It is exciting to see the arrival and integration of hardware components.
- The project is quite new, so the researchers are still in the planning phase, but the project seems to have good momentum at this stage.

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.

- INL has showed outstanding coordination and collaboration with FuelCell Energy and SARTA and in working with various suppliers. The focus on hydrogen production and commonly used 350 bar fueling of a bus allows the project to focus on the SOEC, which is the highlight. It will be great to explore the comparisons between the hydrogen coach and the electric coach and even explore the range for an extended fuel cell electric bus.
- This project shows excellent coordination with partners on both ends (H_2 production and offtake) and offers opportunities for coordination with additional partners in parallel and the future.

- The presenter mentions that there are two project partners (FuelCell Energy and SARTA) but does not really discuss their roles or how they support the project other than providing pieces of equipment. More detail in this area would be helpful.
- Taking advantage of the SARTA Borrow-A-Bus program is a great idea. Further collaboration could be warranted in a few areas, specifically for data analysis.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- It is somewhat difficult to assess progress to goals without some financial projections around energy input costs needed to reach $1/kg (megawatt scale), or what cost portion the gas processing system will add to some conventional capital cost comparison to competing electrolyzer technologies. SOECs have been speculated on and proposed for years. It is great to finally see this being tested in the real world with buses. The phased approach with on-site testing, followed by integration with the actual bus fleet, will be incredibly relevant to DOE goals and have a very high impact, considering the high probability of success from the incremental testing and integration.
- Both the use of SOECs for hydrogen generation (because of their efficiency and compatibility with thermal sources such as nuclear) and the use of on-site hydrogen production for heavy vehicle fueling have great potential for lowering the cost of hydrogen production and expanding the use of hydrogen in transportation.
- The project seems to be tackling two different areas of demonstration: (1) SOEC hydrogen production and (2) fuel cell bus use in extreme conditions. Both areas will benefit from this project.
- Successful execution of this project would support multiple technology and implementation goals.

Question 5: Proposed future work

This project was rated **3.8** for effective and logical planning.

- The contracts for the hydrogen post-processing system are very important, as is working with vendors early on for fabrication. It is good to see SARTA and other fuel cell vendors being considered for 2023. For 2024, it will be great to see the SOEC gas conditioning system in operation. The key milestone will be to see the full system commissioned with storage, compression, and dispensing in place. It will be great to see end-to-end operation and compare SOEC station operation to efficiency or limits on the conventional bus stations under operation with SARTA or elsewhere. Especially interesting will be how the post-processing system affects efficiency or the overall system cost when projected at scale.
- The work ahead to install, commission, and operate the system is clear. It would be helpful to understand the metrics that will be used to evaluate the project's technical and operational success and to understand the plans and next steps after the demonstration concludes next year. Significant infrastructure installation is taking place. It is unclear what happens after 600 hours of running one coach.
- The timeline seems tight, but if the project can be completed in a reasonable time, this is a good set of tasks.
- The proposed work is very good.

Project strengths:

- This is a great Systems Development and Integration and technology acceleration project because it is creating a very real piece of infrastructure from commercial building blocks that can be shown and demonstrated. Prospective adopters of the technology can see and feel a real installation, which is very helpful. Also, it seems like the project plan and high-level designs can be used as templates for other SOEC hydrogen production/fueling installations.
- The flexibility of the project is a major strength. There are opportunities to test/demonstrate additional electrolyzers, to test additional vehicle types, and to gather data on FCEVs in challenging climate conditions on medium-distance routes.

- The partners from INL, FuelCell Energy, and SARTA are outstanding. Demonstrating SOECs at scale and focusing on just post-processing is an important strength of this project.
- The project tackles a couple areas of interest, and INL seems uniquely suited for this project.

Project weaknesses:

- There are no obvious weaknesses.
- It would be great to see more discussion of how the oxygen could be used in the future as byproduct revenue or incorporation for onsite use. It would also be nice to see some local university engagement as part of workforce development goals. It would also be good to see more techno-economic analysis to highlight where SOEC development is compared to conventional electrolysis, as well as how long it might take to reach commercial deployment as needed by the upcoming hydrogen hub proposals.
- The project presentation is light on details about the collaboration partners and their roles. It seems like this project will be of much value for them in showcasing what can be done. The project should take advantage of that. Part of its appropriate role should be greater experience and familiarity of a large circle of participants, which will help foster more future adoption.
- With a tight timeline, achieving tasks on time may be difficult, especially with a dispensing system installation included in the project.

Recommendations for additions/deletions to project scope:

- The project summary slide mentions an objective to “verify suitability of heavy-duty FCEV to provide backup power,” but this objective was not discussed, and it is unclear whether it is being pursued. Perhaps in a two-year project, this should be taken out of the scope, although it is definitely a useful project in the long run and maybe should be looked at as a follow-on project.
- The project should share integrated energy efficiency and bus use with energy used for compression storage and dispensing to compare to other bus station archetypes. Cost and technical comparisons to conventional electrolysis technologies could be added.
- Addition of data analysis by other relevant national laboratories would help increase the success of this project.

Project #TA-001: Membrane Electrode Assembly Manufacturing Research and Development

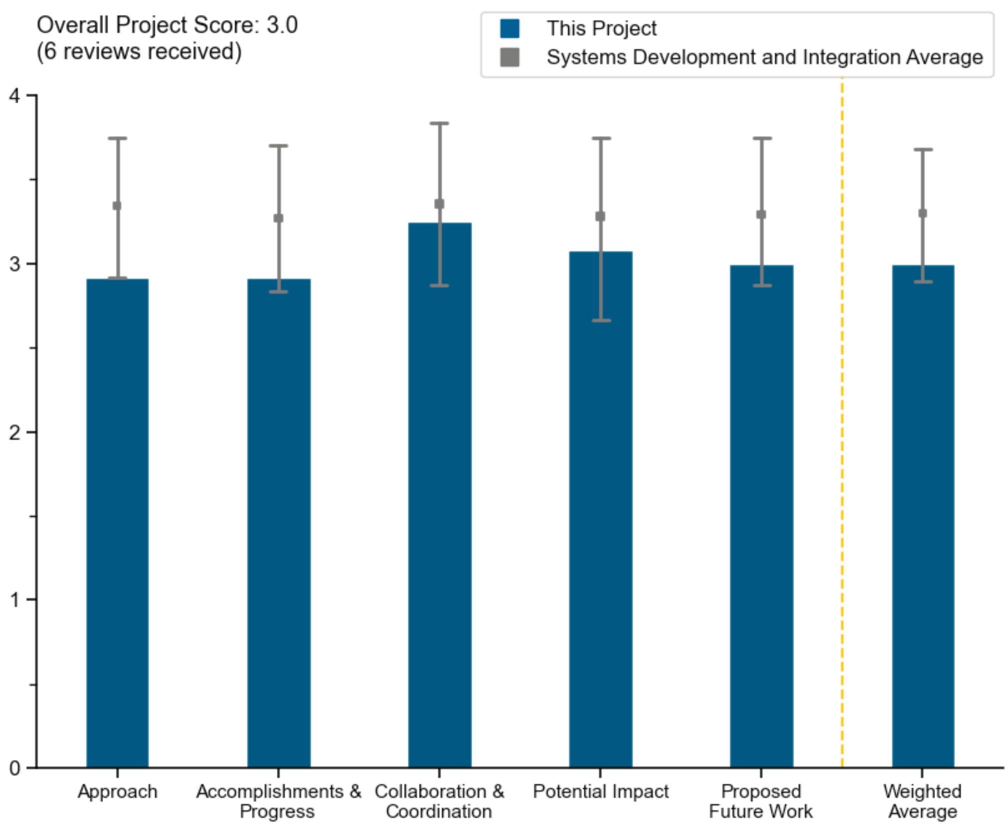
Peter Rupnowski, National Renewable Energy Laboratory

DOE Contract #	WBS 10.1.0.501
Start and End Dates	7/1/2007
Partners/Collaborators	Chemours, 3M, Nel Hydrogen, DeNora, Giner, Fortescue Future Industries, Advent Technologies, Lawrence Berkeley National Laboratory, National Research Council–Canada, Fraunhofer-ISE, University of California, Los Angeles, University of Massachusetts Amherst
Barriers Addressed	• Lack of improved methods of final inspection of membrane electrode assemblies

Project Goal and Brief Summary

The objectives of this project are (1) to understand quality control needs from industry partners and forums, (2) to develop diagnostics by using modeling to guide development and in situ testing to understand the effects of defects, with a focus on heavy-duty fuel cell and low-temperature electrolysis applications, (3) to validate diagnostics in-line, and (4) to transfer technology to industry partners.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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.

- The approach is well defined and leverages both industry and the international community to understand needs. Research is aligned with inputs received from these interactions. Other consortiums are engaged to support research and development (R&D) activities.
- The team presented optical approaches to qualifying defects in the high-speed manufacturing of membrane electrode assemblies (MEAs) for fuel cells and electrolyzers. The great challenge is the strong adsorption of light in the ultraviolet-visible (UV-VIS) range of the optical spectrum by the electrode and support materials. The combined theoretical and experimental studies on the effects of electrode layer variability seems to be thought through better.
- Strengths include the phased approach: understand industry input first, then develop methods. This project is linked to other funding opportunity announcement projects; it addresses major components. It would be good to connect the dots between the requirements from industry (speeds, types of measurements) to the techniques developed, for example, in a table or with green/yellow/red status like the imaging comparison across cameras/exposure times.
- At a high level, the approach involves interacting with industry to determine needs and challenges, but choices about what to work on seem to be at the discretion of the principal investigator, and some of the choices made are surprising. A formalized process to determine industry priorities, such as a request for information, should be considered. The UV-VIS-near-infrared (NIR) spectroscopy work would benefit from an improved approach. Comparing membranes with different thicknesses and different mechanical supports and additives confounds the analysis and prevents meaningful correlation of the results. A better way to do this experiment would be to use a membrane of constant thickness and add controlled amounts of cerium, or other radical scavengers, so that only one variable is being changed at a time.
- The principal quality inspection methods being developed at lab scale do provide relevant data, but they are not considering the speed, accuracy and consistency required for roll-to-roll (R2R) manufacturing.
- This is a project on the use of analytical techniques to measure fuel cell properties and assess fuel cell performance.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and DOE goals.

- The research team has performed the tasks as outlined. The camera system was built; the optical responses of the MEAs were characterized. The optical data, unfortunately, does not provide much information about quality or defect concentrations within the MEAs. The modeling and experimental characterization of layer thickness variability on fuel cell performance has made significantly more progress.
- Accomplishments are well described, and efforts appear to support project goals. Issues identified are either being worked on or fully resolved. The work supports the need for continuous-catalyst-coated membrane (CCM) inspection of R2R-produced parts.
- The project appears to be on track with meeting milestones and clearly presents which measurements were or were not successful.
- The work follows the statement of project objectives and is of high quality.
- Good progress is being made, but it is a little hard to tell how close this is getting to the requirements. The project shows a good mix of methods for point measurements on overall process vs. continuous measurements for defects. The project team should consider how good is good enough, whether the technology is 100x or 2x away from the needed speeds, and whether a solution can be engineered (e.g., perhaps moving the camera in line with the web line and returning to a start point) or if a new invention is needed.
- The accomplishments and progress show some mixed results. Overall, the project does not appear to have yielded many successes or valuable results. The work on chromatic confocal probes looks interesting, but there are no results yet. The optical transmission work shows some preliminary results, but the extremely

long integration times raise questions about the applicability of this approach to high-speed manufacturing. There are no results that can demonstrate or validate the value of this approach yet. The results of the UV-VIS-NIR spectroscopy study are not very meaningful since the test was not designed properly. It is not possible to determine from the results whether the differences in absorption were due to the Ce or due to differences in thickness and reinforcement. Indeed, the comparison with the x-ray fluorescence (XRF) results show that there is little correlation between XRF-measured Ce and UV-VIS-NIR measurements. The XRF measurements show a surprising amount of Ce in the nominally Ce-free NR212, calling into question multiple aspects of the accomplishments and progress in this area. The results of the Lawrence Berkeley National Laboratory (LBNL) modeling on membrane thickness variation match expectations, but these results do not seem to tell us anything new or provide much insight that can be used by industry.

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.

- Cooperative research and development agreements (CRADAs) were executed; this project is also tied into multiple projects. The team is working with multiple competitors in the space, showing the importance of the project to industry.
- The project collaborates with industry, U.S. national laboratories, foreign partner laboratories, and U.S. universities.
- The project showed great use of industry, national labs, and academics.
- The project makes good use of DOE facilities for state-of-the-art results. The model of the CCM is generic and assumes any thickness variation is uniform and consistent, while quality issues typically are defects in material/process quality. A welcome enhancement would be a trilaterally defined set of "acceptable" specifications coming from the performance model, the industrial partners, and the detection limits of the developed test methods that are enhanced with their development.
- The project involves coordination with industry to determine manufacturing R&D needs, but the process of determining prioritized manufacturing R&D areas does not seem to be well defined. Some interaction with LBNL on modeling is included, but the work does not seem particularly relevant to a manufacturing R&D project.

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The relevance to the Hydrogen Program is very significant. The ability to characterize MEA layer thickness variance is critical for fuel cell and electrolyzer MEA quality control. Developing a greater understanding on how the layer variability affects performance and durability is also of critical importance.
- Further planned development and work represented to date will provide significant value to CCM manufacturers where automated inspection is required to keep pace with production fabrication processes.
- Assuming the developed methods for quality control are implemented in a relevant manufacturing environment, this research can significantly speed up production and avoid rework of stacks.
- Some of the work may be valuable to industry manufacturing efforts, but the lack of a disciplined and documented approach to identifying industry needs makes it difficult to evaluate the relevance and impact. If this project is continued, the project team should rigorously document existing industry needs and then demonstrate that the project approach is actually making progress toward addressing those needs.
- Quality control is absolutely essential to scale-up, which is essential to reaching the cost targets. Inspection can become an enormous bottleneck unless measurement speed meets or exceeds manufacturing speed, and huge amounts of scrap are generated if a process deviation occurs and is not rapidly caught.
- After all this good work, there is not much innovation or prediction of what is needed for a better fuel cell power source.

Question 5: Proposed future work

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

- The current limitations are openly discussed, and the presenter verbally indicated "flash" methods would be developed to increase analysis speed. Planned involvement with industrial partners and suppliers is critical, as their openness on real production issues, compliance with quality standards from the International Organization for Standardization, and a list of "radical scavenger" ingredients to look out for in the membrane will really focus this development on the application at hand.
- Proposed work aims to refine techniques and make correlation between inspection, observation, and in-cell performance. The work will be of great value in understanding defect tolerance and scrap reduction.
- The reviewer did not have time to review future work in detail, but generally, the team has many ideas for moving forward and is continuing to collaborate with industry.
- The continued modeling and experimental studies on how defects affect MEA performance are worthwhile efforts. More focus on optical characterization methods as compared to x-ray and thermal imaging is probably not going to yield much benefit. The strong optical adsorption greatly limits the value of the UV-VIS methods.
- The focus on identifying industry needs is appropriate, but a clearer and more formalized plan is needed.
- The future work is to do more of the same.

Project strengths:

- The modeling and experimental effort that characterizes the effects of variance in the membrane thickness on fuel cell performance is quite valuable. The team recognizes that optical methods do not seem to show much promise as compared to x-ray methods. The membranes are too adsorbing in the optical spectral range. Lithium batteries are inspected using x-ray tomography. The team's future plans to pursue x-ray methods are highly recommended.
- Engagement with industry is a strength, as is the ability to look separately at catalyst layers, membranes, additives, etc. The project is making progress in distinguishing differences in components more accurately.
- The project has great collaboration with academics, labs, and industry. The research is well-planned. Issue identification and mitigation strategy are project strengths.
- The topic is absolutely relevant to scale production while improving quality.
- The team has extensive interactions with partners and collaborators.
- The team is highly skilled and set up to do the measurements.

Project weaknesses:

- The Coolsnap camera used for imaging may be obsolete. Modern complementary metal oxide semiconductor imagers have better spectral range, faster frame rates, and higher quantum efficiency. Advanced image processing techniques, such as Bayesian inference, may help improve MEA characterization when the signal-to-noise ratio is very low. The penetration depth of UV light may be too low to properly characterize the UV adsorption attributed to Ce. No physical model of the UV adsorption by Ce ions was presented. MEA Ce standards could be made via ion exchange to better calibrate the UV adsorption model.
- The project would benefit from a more focused and disciplined approach. Some of the project activities do not appear to fall within the reasonable scope of an MEA manufacturing R&D project. While the segmented cell and membrane modeling efforts are interesting, they seem surprising focus areas for a manufacturing R&D project. If this project is continued, the Hydrogen and Fuel Cell Technologies Office should provide close oversight of project activities to ensure that they are relevant and useful.
- Many techniques to evaluate the state of the art are reported, but there is no clear path or focus for predicting what changes to the state of the art are needed to improve fuel cell durability and performance.

- Results could be better tied back to where the technology needs to be; significance should be stated on a slide. A dashboard of methods and status could be created showing green/yellow/red or progress toward the goal.
- Single-point measurements may not paint a full picture of CCM quality and would be improved if the scan area could be increased.
- The development is positioned in a lab environment, lacking deep immersion into industrial production requirements.

Recommendations for additions/deletions to project scope:

- Benchmark data on commercially available equipment for quality control (S++, high-resolution bright field, dark field cameras) should be provided. Without disclosing proprietary intellectual property, relevant detectable quality issues should be demonstrated to indeed lead to preliminary failure (this could even be an artificial, self-inflicted defect).
- The efforts to further develop UV-VIS optical methods to quantify MEA defects and layer variability probably should be deleted from the project. The use of modern image-processing techniques applied to high-throughput x-ray characterization should be added to the scope.
- The team should assess results they have generated and give recommendations for improving the state of art to improve fuel cell durability, performance, and alternatives for lowering cost.
- The project should continue to engage with industry on tools of highest need and relevance of outcome and allow for flexibility in the project if a method is not yielding the desired quality/speed/resolution.
- The membrane thickness modeling should be deleted.

Project #TA-016: Fuel Cell Hybrid Electric Delivery Van

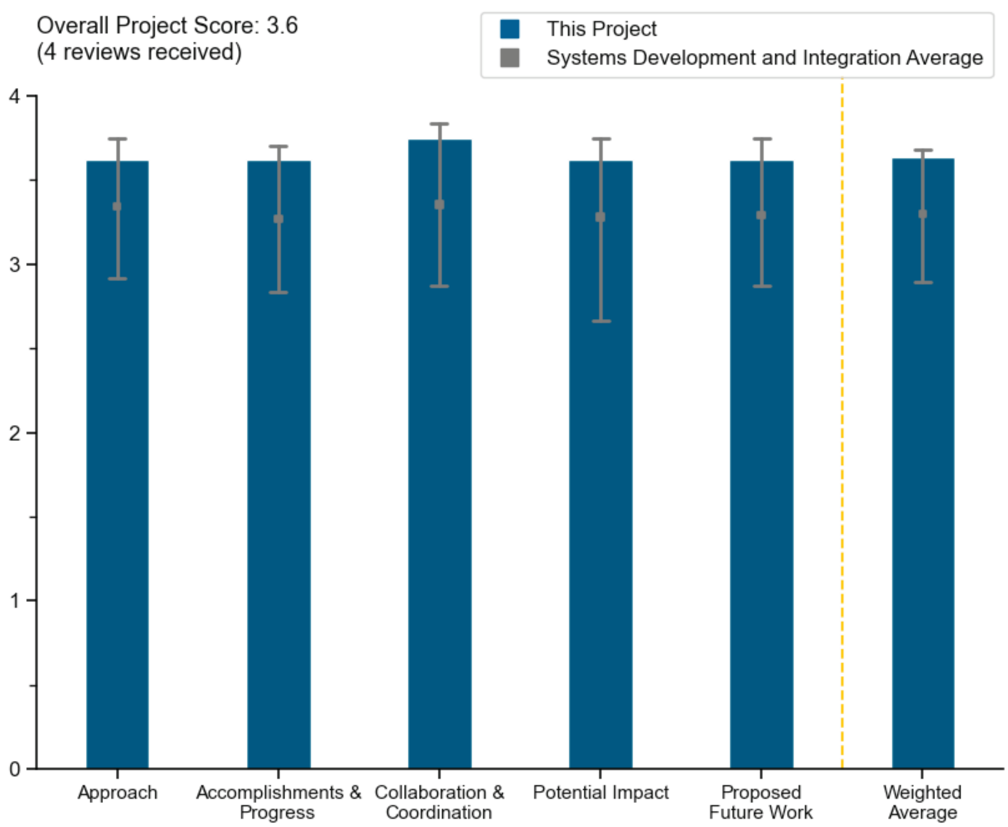
Jason Hanlin, Center for Transportation and the Environment

DOE Contract #	DE-EE0006523/0009
Start and End Dates	7/15/2014–2/28/2024
Partners/Collaborators	California Air Resources Board, South Coast Air Quality Management District, California Energy Commission, Southern California Gas Company, United Parcel Service, Cummins, Universal Engineering Services, University of Texas at Austin – Center for Electromechanics
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 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 medium-duty fuel cell hybrid electric trucks.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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.

- This project has identified (and overcome) challenges directly related not only to the fuel cell application but also to the general issues of repowering existing trucks and providing training/support to get them accepted into regular service. The Phase 1/Phase 2 structure of the project was also a very good approach and certainly helped improve the prospects of completing Phase 2 successfully.
- This project is needed to bring about confidence in hydrogen and fuel cells into this delivery market that needs to be shifted to renewable energy. The approach of the team will bring about this confidence.
- The approach is/was practical and achieved progress, as the number of hurdles that this project encountered is robust.
- The overall objective in the second slide talks about driving range, and in the results, driving range improvements are not seen, although fuel cell power improvements are seen. The Phase 2 vehicle test and evaluation are planned to be completed June 2024. Barriers A & F identified needs that should be addressed completely in Phase 2.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- Getting the vehicles built and delivered and everyone trained was a great accomplishment, given the soft-side challenges in the United Parcel Service (UPS) organization that were described, in addition to the technical challenges. The experience of the trucks in service will be exciting accomplishments for next year.
- While delays were encountered at the beginning of the project, the accomplishments in the last year were very good. Having the first package delivered shows this accomplishment.
- The project substantially increased driving range with a single fueling event.
- Good progress was made on fueling with the following accomplishments: (1) improved the communication protocol with the hydrogen fueling station and (2) created a fuel cell shutoff function as a method of risk mitigation during hydrogen fueling. For the added hydrogen door sensor, the project needs to indicate how data collection on this can improve the fueling scenarios. Clear cost metrics are missing, even though they are mentioned in the objectives. Indirect metrics were given on fuel economy, but the cost category is missing. The accelerated introduction of the technology adoption rate appears mostly due to the fleet partner's internal barriers and being uneducated instead of contractual.

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 partners are appropriate and bring a good deal of value. Many of the contributors will be able to use the project outcome going forward in their businesses. Having National Renewable Energy Laboratory (NREL) as the data analysis team is also a key to project success.
- It sounds like working with UPS has been quite challenging. In addition, the general effort to coordinate with nine project partners was certainly significant. However, the proof is in the results; the trucks are all built and ready to deploy.
- The project included a broad group of partners and peripheral support entities, and completing this project took a community of stakeholders.
- The project was a well-collaborated effort from all parties. The project's prioritization of safety and work is great.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- A major accomplishment here is getting the people who are going to drive and work on fuel cell electric vehicles in the commercial environment on board and comfortable using new technology.
- A successful project could open the door to this option of renewable energy to delivery trucks.
- Data collection can significantly improve the DOE research, development, and demonstration goals.
- Relevance/potential impact was somewhat diminished by UPS staff turnover and the project timeline. Other similar vehicles have been built in the interim outside this project and have been commissioned for operational use (by other entities not directly engaged).

Question 5: Proposed future work

This project was rated **3.6** for effective and logical planning.

- The reviewer wishes the project team the best of luck in getting the trucks deployed.
- The proposed future work is appropriate for the final project phases.
- More Phase 2 work is expected to be completed on vehicle testing and evaluation. Detail should be provided on what exactly the issue is in "Issue – Utilizing public hydrogen refueling infrastructure prevented a significant number of demonstration days."
- The recommendation is to report only on vehicle test and evaluation results and project management (Tasks 7 and 8) in 2024 and 2025 instead of rehashing all project details again after many years of presenting this project (make reference to previous Annual Merit Review presentations).

Project strengths:

- Commercial fleet operators will be notified to consider zero-emissions vehicle options other than battery-only. The project is targeting a vehicle class that falls outside of many "standard" vehicle classes (last-mile delivery van) and product offerings of large medium- and heavy-duty vehicle original equipment manufacturers. The project is developing a more robust direct current (DC)-to-DC convertor for medium-duty vehicles, a component which is in short supply in the market.
- Dividing the project into a two-phase approach could greatly help with knowing the development issues beforehand. The leadership turnover challenge was resolved well. Hydrogen fueling improvements are seen in the project: the communication protocol and hydrogen door sensor.
- The project is undertaking direct commercial deployment, with the opportunity to acclimate an existing industry to hydrogen/fuel cell technology.
- This project is very relevant to the industry and creates potential to bring about acceptance and adoption of the technology.

Project weaknesses:

- The presenter was pretty direct about the delta cost challenges in retrofitting a diesel delivery van to a fuel cell hybrid powertrain. This is not a weakness of the project per se, but it would be a good area to dig into in detail to see how this challenge could be addressed.
- More metrics should be added in results to quantify the results on the team's data analytics. Mileage improvements should be added. The end goal of Phase 2 data should be added, i.e., what the team is planning to do with this data and whether there is a plan to improve the data gathered.
- Delays to the timeline are the main weakness but are not necessarily unexpected.
- The contractual commitment and timeline have been repeatedly affected by the fleet operator partner's new findings and perspectives.

Recommendations for additions/deletions to project scope:

- It would be helpful to know how the powertrain and drivetrain developed through this project can be integrated into the University of Texas at Austin E-Bus (specifically), to provide (more generally) a second life to small transit buses at the ends of their economical lives, those in need of repowering, or vehicles for college transit operations.
- A total cost of ownership analysis could help the project get a handle on the issue of the cost of retrofitting delivery vans with fuel cell hybrid electric vehicle powertrains.
- This is not necessarily an addition, but the data evaluation at NREL needs to be a major outcome of the project to show feasibility.
- There are no recommendations for additions or deletions to project scope.

Project #TA-017: Innovative Advanced Hydrogen Mobile Fueler

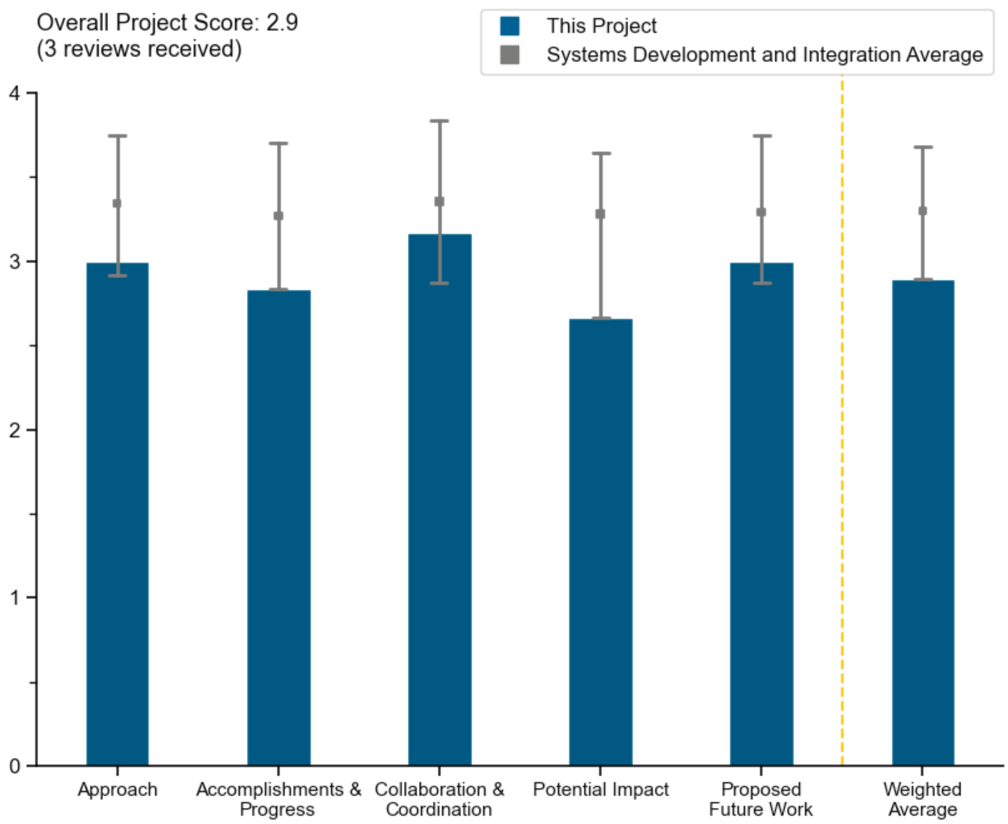
Sara Odom, Electricore Inc.

DOE Contract #	DE-EE0007275
Start and End Dates	7/1/2016–6/30/2023
Partners/Collaborators	Electricore Inc., Air Liquide, HTEC Group, QAI, 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 AHMF will be deployed to support hydrogen stations and vehicles; fueling data will be gathered for analysis by the National Renewable Energy Laboratory's Technology Validation Team. The project's economic findings and market opportunities will be published. To reduce risk, the AHMF 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 Systems Development and Integration 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.

- As this project nears completion, it is clear that the tasks identified by the project worked well to organize the project efforts and matched well with the overall objectives.
- Overall, the project has encountered many hurdles to this point and is finally filling 35 MPa buses. The capacity fueling from buses will be useful but does not offer the complexity of a 70 MPa fueling and somewhat undervalues the work with the high-pressure bank storage U.S. Department of Transportation (DOT) special permit. Lessons were learned on how a mobile refueler could be constructed to meet the heavy-duty truck refueling. Obviously, with the station's downtime learning for light-duty transition to heavy-duty, there is no doubt that mobile refuelers will be needed to support the refueling network expansion.
- Electricore Inc. (Electricore) had a good approach to the work, with some challenges highlighted: expiring permit to use the middle cylinder, consumables of liquid nitrogen (LN2) that may not have been fully tested, and the current use case of a cascade fill with orifice flow control to fill only buses for now. The project clearly has not met targets demonstrating fast fills for 70 MPa to 95% state of charge.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- COVID-19 greatly delayed the project demonstration start, and it is not clear when it will meet 70 MPa full fills at a faster rate. There were some good learnings about shore power and the ability to explore zero-emissions power generation for remote operation. The results of this trailer project showcase the need to have liquid hydrogen mobile fuelers at much higher dispensing capacity and to reduce the challenges of precooling balance-of-plant needs, including size, power, and consumables. The Type 4 high-pressure tank enabled use for 95 MPa on-road transport, which was a good accomplishment, even if it has not been used as much as expected.
- This project has demonstrated solid accomplishments. The three most important are completion/demonstration of the system itself, allowing for validation and data collection; the use of off-the-shelf technology to solve the hydrogen cooling problem in a limited footprint; and advancement of permitting for hydrogen storage and transportation.
- Given the complexity of the schedule delays and other pivots throughout the project, the project made good progress and collected information that will be useful.

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.

- This project engaged appropriate partners well—in particular, component suppliers for the design–build of the unit and permitting, national labs for data analysis and modeling, industry partners for technology and additional support, and government agencies for safety analysis and permitting.
- There was overall good coordination and collaboration across the project. It was good to be proactive with the mobile refueler requirements of the International Code Council (ICC) and National Fire Protection Association (NFPA).
- Electricore had several good collaborations listed. The approach of using existing Air Liquide equipment should have allowed for faster project development. The team was also able to get one of the cascade tanks more rapidly; unfortunately, owing to project delays, the use and life expired before the team was able to test the fueling.

Question 4: Potential impact

This project was rated **2.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The most impactful development following from this project will be the establishment of permitting guidelines for high-pressure mobile hydrogen storage and transport. This provides a path forward for any other entrants into the space.
- These small-capacity trailers may have been useful a few years ago. It is not clear how useful these trailers at 15 kg/day are now or will be in the next few years. Individual components may be of interest, such as low-cost orifice-based fueling (especially maximum flow rates) and in-parallel advanced storage technologies, which might use the LN2 system for early validation at small scale or in limited demonstrations.

Question 5: Proposed future work

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

- With only a month left, it is not clear whether the project will actually be able to reach 70 MPa dispensing at full capacity and reaching 95% state of charge, as stated in the project goals. Three challenges remain for Electricore: achieving faster fueling than orifice-based cascade fills, increasing supply hydrogen capacity, and conducting economic assessment for the total system cost (not dependent on used or donated components). DOE and the community will be excited to see how the mobile refueler can be used beyond 2023.
- This question is not as applicable, as the project is nearing completion, but the stated intent of Air Liquide to continue use/demonstration/data collection using the AHMF is good to see.
- Outside funding/support could be possible for refueling of several different vehicle classes.

Project strengths:

- Despite challenges in supply chains and schedule due to the global pandemic, the project was successfully carried through. Real-world data has been/is being collected in a practical application.
- The project has a strong, motivated team. It is addressing high-capacity fills and is working the difficult DOT Pipeline and Hazardous Material Safety Administration special permit process, as well as implementing codes and standards harmonization across ICC and NFPA requirements.
- The strength of the system was to showcase a standalone 70 MPa fueling system for remote low-capacity operation in a very short timeframe. It is not clear that the team will be able to demonstrate this before the end of the project.

Project weaknesses:

- This project’s weaknesses stem from delays in the project, procurement of parts, and full demonstration of the original project goals. It is not clear how feasible or realistic it is to use the LN2 supply for 70 MPa fueling. At only 20 kg of dispensing capacity, it is not clear that there is much use in allowing longer fueling and simply increasing onboard capacity.
- No 70 MPa fueling was accomplished, which was a main objective of the original project.

Recommendations for additions/deletions to project scope:

- As the project is at end of life, it is not clear that there are any opportunities for additions or deletions to the project scope. A clear summary of total usable capacity and limits of the LN2 system for back-to-back fills at 70 MPa and 35 MPa high-flow fueling would be valuable. The discussion of shore power vs. onboard generator would also be very helpful for planning higher-capacity systems for more clear use scenarios.

Project #TA-018: High-Temperature Electrolysis, Stack, and Systems Testing

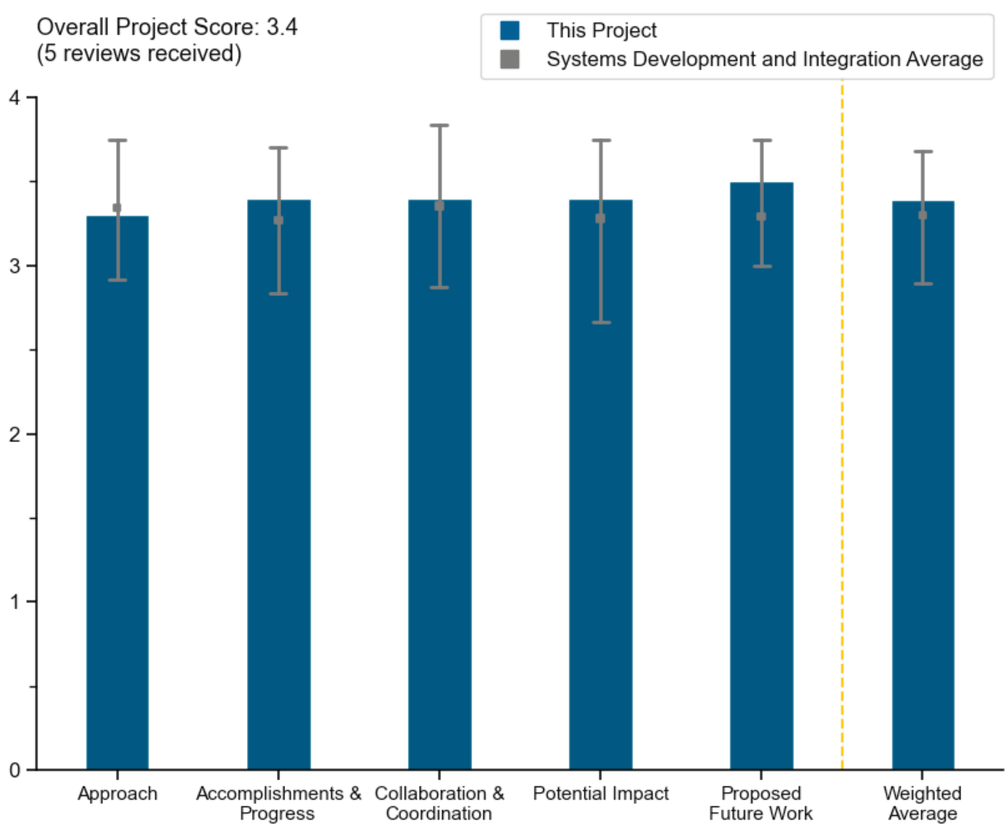
Micah Casteel, Idaho National Laboratory

DOE Contract #	WBS 7.2.9.1
Start and End Dates	9/30/2020
Partners/Collaborators	Strategic Analysis, Inc., Bloom Energy, FuelCell Energy, OxEon, Nexceris, Xcel Energy, Topsoe
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 material 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 to simulate real-world applications, including nuclear-to-hydrogen hybrid energy 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 Systems Development and Integration 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.

- Great progress has been made to provide access to a large stack and system (future) testing platform for third-party stack and system evaluation. Extended operation on 5 kW stacks and a 100 kW system is encouraging.
    - Perhaps it would be beneficial to revise hazard and operability (HAZOP) and plan systems with multiple redundancies (justifiably, as it will cost more) to ensure prolonged and uninterrupted operation (where needed). However, in some cases, interrupted operation might represent supply–demand variability in hydrogen production; thus, many lessons could be extracted from such events. The team has already indicated the need for boiler redundancy.
    - Perhaps it would be beneficial to consider incorporating accelerated tests on stacks/systems to enable predictive degradation analysis. Accelerated tests at stack/system level might look very different when compared to cells and thus might need to be developed separately. It would be very interesting to see plans for accelerated test approaches.
    - With test bends in place, many smaller and start-up companies would see significant benefits with access to Idaho National Laboratory's (INL's) testing capabilities. Perhaps it would be beneficial to understand how larger original equipment manufacturers (OEMs) would gain any technical/efficiency/cost benefits from the third-party validation tests at INL since these OEMs already have test data from internal research and development centers and customer sites.
- INL has established excellent HTE stack testing capabilities and is leveraging those capabilities on this project to support multiple HTE stack and system developers. As INL expands and scales its stack testing capabilities, the researchers are learning valuable lessons and sharing these lessons with the technical community. They are obtaining baseline stack performance and durability data and sharing this information (to the extent allowable) with the community. They are providing DOE with an assessment of where HTE stack technology stands with respect to performance and durability targets. One recommendation is to include a real-time means of assessing stack leakage (perhaps with a tracer gas). Since leaks often manifest as performance improvement or lack of degradation, the true stack degradation that may be happening can be hidden. INL observed this in one of the stack tests.
- The objective of this systems development and integration project is to support industry to enable economical hydrogen production (at $1 per kg H_2 at megawatt scale) using solid oxide electrolysis cell (SOEC) systems. The challenges, barriers, and goals are clearly identified. The proposed technical approaches are reasonable. The work plan is well thought out. It is likely that the team will be able to overcome the critical barriers and achieve project goals.
- The approach to performing the work is excellent. Different approaches may be used for testing stacks/systems from different vendors. However, there is a need to summarize lessons learned indicating what is common and what is different.
- There is a clear need to generate stack test results independently, although INL test stand stability, quality, and capability could skew results.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- Good key performance indicator numbers have been reported, for example, 14 tons of hydrogen being produced, stable operation to the point of being perceived as "boring," and test stand issues being resolved. The project displayed clear regard for safety and attention to detail with regard to the continuous HAZOP review.
- INL tested multiple third-party stacks in the past year and increased the size of stacks that were tested. The third-party testing provided to stack developers provides critical feedback and also provides DOE with an assessment of where industry is relative to the stack performance and durability targets.
- The reported performances of the FuelCell Energy stacks and the Bloom Energy stacks are very encouraging. It seems that the project objectives and critical barriers are being adequately addressed. In

addition to the stack voltage and current, it would be helpful to provide some additional information about individual cell performance, such as the current density in A/cm^2 of active electrodes and the cell voltage under various testing conditions.

- Progress has been made toward the project objective. Some metrics need to be developed to measure progress and accomplishments.

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 and coordination are absolute strengths of this project. INL has established excellent relationships with most (if not all) of the industrial members of the HTE community. Trust is one of the most important components of collaboration, and INL has certainly earned the trust of its partners, who have been willing to send them stacks (and systems) for testing.
- This project involves a large number of partners, including two other national labs, six industrial SOEC developers, and one industrial SOEC user. It seems that the team functions well in performing the planned tasks and achieving several project objectives.
- Although the number of tested partner stacks is limited to FuelCell Energy and Bloom Energy, this project is well connected to related projects and actively engaging third-party stack testing.
- The project has excellent collaboration and coordination with different stack/system developers.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- There is strong impact on advancing stack suppliers in development who need validation to proceed, but at higher technology readiness levels (e.g., Bloom Energy), there may no longer be a need for DOE to support.
- While good progress has been made in testing several commercial SOEC stacks from FuelCell Energy and Bloom Energy, it would be more impactful if an effective "accelerated" testing protocol/procedure could be developed so that SOEC systems can be reliably evaluated in a much shorter period.
- Demonstration of testing capabilities for different developers helps to advance progress of the technology toward DOE goals/objectives.
- This project is accelerating the development and acceptance of HTE as a highly efficient approach for hydrogen production.

Question 5: Proposed future work

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

- INL's plans to expand its stack and system testing capabilities in support of industry developers is exactly what industry needs to accelerate development efforts.
- Expanding test capacity, while pushing dynamic operation for high-temperature stacks (a typical weak point) is an extremely valuable way to demonstrate true performance capability.
- The proposed future work seems to be reasonable for addressing the remaining challenges and barriers. It would be more impactful if more efforts could be devoted to "accelerated" testing of commercial systems under a wider range of conditions.
- The proposed future work is effective for making progress toward the project objectives.

Project strengths:

- The project is (1) providing a stack testing service that accelerates industry's SOEC stack development progress and (2) keeping DOE updated on the technical progress toward meeting HTE stack performance and durability goals. Collaboration is also a project strength.

- INL showed strong expertise and a trusting relationship with partners, thus providing a solid foundation for expanding collaboration and knowledge transfer.
- Excellent progress has been made in testing commercial SOEC systems under typical conditions.
- The project has developed a unique testing capability for large stacks/systems from various developers.

Project weaknesses:

- As SOEC and solid oxide fuel cell (SOFC) product maturity increases over time, together with the level of secrecy in disclosing information, the added value of this testing validation service may become less relevant or just too small.
- Some more analytical analysis to gain more information about the performance of individual cells would be very helpful.
- Clear and well-defined objectives have been lacking in testing done to date.

Recommendations for additions/deletions to project scope:

- Recommendations include anticipating the growth of the SOEC/SOFC market demand and incremental implementation of such products; additional business cases need to be assessed for multiple applications, going beyond continuous operation. Of course, this discussion has to strongly engage all stakeholders.
- A cost study is also included (but subcontracted to an outside firm) in this project. It is unclear how the cost study contributes the stack/system testing effort.
- It would be very helpful to develop an “accelerated” testing procedure of commercial systems under a wider range of conditions.

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

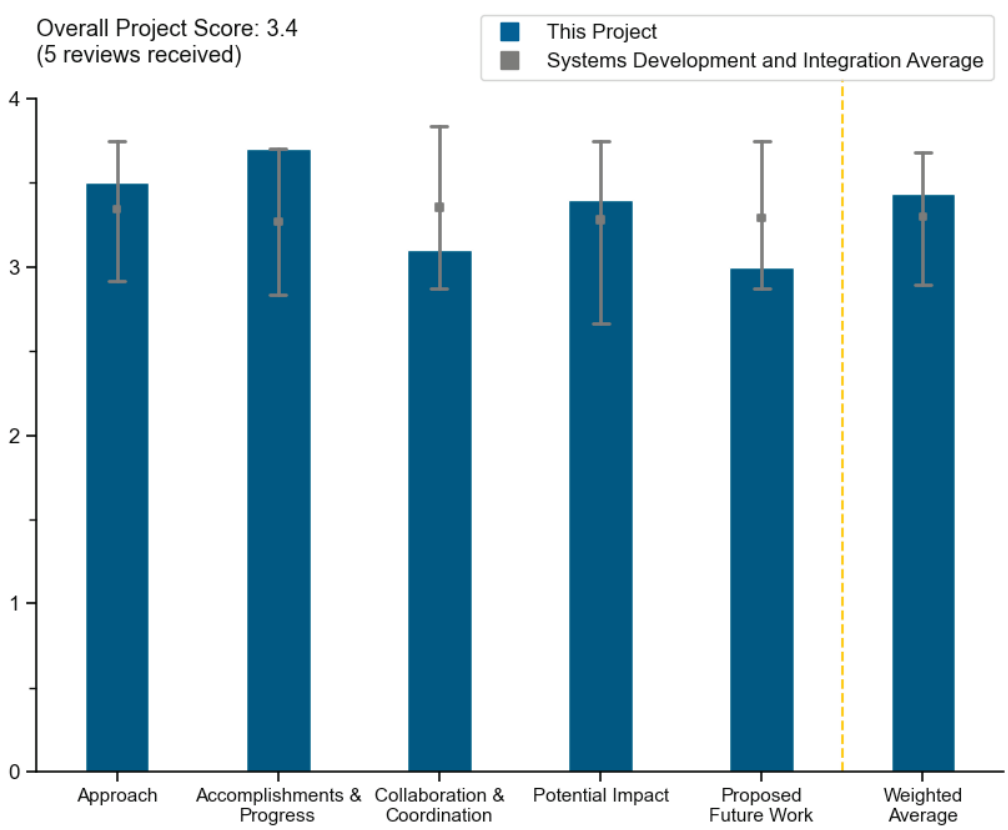
Uuganbayar Otgonbaatar, Exelon Corporation

DOE Contract #	DE-EE0008849
Start and End Dates	10/1/2019–10/1/2023
Partners/Collaborators	Exelon, Idaho National Laboratory, National Renewable Energy Laboratory, Argonne National Laboratory, Nel Hydrogen
Barriers Addressed	Site selection: the criteria for site selection Regulatory: the relevant regulations that affect nuclear hydrogen production Market-related: 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 a Constellation nuclear power plant. A 1 MW proton exchange membrane (PEM) electrolyzer and supporting infrastructure will be installed, providing an economic supply of in-house hydrogen consumption at the plant. Researchers will also simulate the scale-up operation of a larger 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 Systems Development and Integration 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 project has successfully achieved full operation, and it is expected that the final milestone (demonstration of dynamic operation at the site using the front-end controller developed by the National Renewable Energy Laboratory [NREL] and Idaho National Laboratory [INL]) will be achieved (allowing for considerations of cybersecurity, as mentioned during the presentation). The project approach was/is excellent.
- The approach is a combination of installation, demonstration, and analysis work that is critical for enabling nuclear-sourced hydrogen. The key components of the approach include demonstration of dynamic operation and economic hydrogen production. The project is effective in contributing to the demonstration of an economic supply of hydrogen to nuclear facilities for their own hydrogen consumption. The presentation did not provide enough information to determine whether the challenges on site selection and regulatory impacts, presented in the project overview, were answered. While Argonne National Laboratory (ANL) did an impressive market analysis, it misses the mark on capturing and communicating the considerations of a nuclear facility versus placement of electrolyzers at any other cost-competitive location.
- The approach is fine since it should achieve the major goals of this project, which is to demonstrate how a water electrolysis system can be used at a nuclear power plant. It could have been outstanding if more time were allocated to actually collecting data on the electrolyzer system. For example, to date, only steady-state operation has been demonstrated. It would be useful to demonstrate transient operation and determine the response time, and it is not clear if this will be done as part of this project. Since the project is scheduled to end on October 1, 2023, it is unlikely that any extended data on the system (e.g., reliability and decay rate) will be included in this project. This relatively short operational period is a common problem with DOE demonstration programs, which often end shortly after the demo system is commissioned. Extensive testing should be included in the project, and the operational results should be shared with the community.
- This is an excellent project that integrates nuclear power with an electrolyzer for an onsite demonstration. The project also includes some modeling work. The project does not specify how the waste heat would be utilized for the electrolyzer operation to enhance the overall system efficiency. The project does not include measurable milestones such as system efficiency, operating conditions, and duration (i.e., 5,000 hours).
- This is an excellent project that integrate nuclear power with an electrolyzer for an onsite demonstration. The project also includes some modeling work. The project does not specify how the waste heat would be utilized for the electrolyzer operation to enhance the overall system efficiency. The project does not include measurable milestones such as system efficiency, operating conditions, and duration (i.e., 5,000 hours).
- The overall approach here is great, but there is some concern that much of the scope is being executed by national labs, possibly in a very uncoordinated way.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- This project is near completion, and no significant challenges were identified. Some technical/equipment issues were reported and appropriately addressed by engineering design efforts. Collectively, the project achieves the DOE goals of research, development, and demonstration for the hydrogen technology; the project also advances the DOE efforts to sustain nuclear power as part of a secure and robust electric power grid.
- This is a meaningful project with many accomplishments. Most strikingly, the 1 MW PEM water electrolysis system has been installed in the nuclear plant for the purpose of integration. This is a first-of-its-kind integration. The project has included some simulation results that are also informative. Milestone 8.0 is for steady electrolyzer operation. It was labeled as “completed,” but there was no reported data as of the Annual Merit Review.
- The installation and demonstrations of the system, initially in steady state and now in dynamic operation, are great project progress. The scope of analysis that the ANL team conducted is truly impressive, although details of the analysis were not provided, making it difficult to assess the quality of results.

- The project is nearly complete, having successfully met most milestones and addressed significant questions.
- It is good that the electrolyzer started operating on March 7, 2023. However, it is disappointing that it took more than three years after the project started to achieve this milestone. It does not allow much time to demonstrate the operation of the electrolyzer under various modes and conditions, which is a major lost learning opportunity for the DOE Hydrogen Program.

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 seems to be coordinating well, and the presentation clearly communicated how the project will coordinate with Advanced Research on Integrated Energy Systems (ARIES) and other DOE-funded demonstration projects to address previous reviewer comments.
- The project has a strong team including the Constellation Energy Corporation, INL, NREL, ANL, and Nel Hydrogen. Each participant has unique expertise but is complementary to others.
- Based on the information provided, the collaborative relationship between Exelon/Constellation, Nel Hydrogen, and the DOE labs was good. Very little information was made publicly available during the project performance by any of the participants, making it difficult to conclude anything other than the stated grade.
- Nel Hydrogen's contribution is obvious, and its collaboration with the prime appears to be good. ANL's contributions on hydrogen markets and emissions savings are good, but it is not clear why the Nine Mile Point Generating Station is not included in this analysis. It is surprising that NREL and INL, and not Constellation, were used to develop controllers for this system. In any case, it is not clear if these controllers are good, since no transient testing of the electrolyzer has been done to date.
- It would be preferred to see formal collaboration with the Electric Power Research Institute, Nuclear Energy Institute, etc., or other utilities.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Demonstrating the dynamic operation of electrolyzers and performance over time provides critical data that is lacking in the field. Understanding the needs of nuclear facilities and the intersection of hydrogen and nuclear energy is a critical opportunity for low-carbon hydrogen production, and the lessons learned from the project will build confidence.
- This project is highly impactful, as it will set a great example of how to utilize nuclear power to generate green hydrogen. The project execution and results are very encouraging to the hydrogen community.
- This project aligns with Hydrogen and Fuel Cell Technologies Office and H2@Scale goals of demonstrating multiple end uses of hydrogen and the usefulness of the electrolyzer in grid services.
- The project was very successful in producing an integrated demonstration-scale system at a nuclear power plant. Several design and licensing hurdles were overcome to facilitate the installation, which has significantly advanced the potential for future deployment at larger scale. The choice of technology, however, may limit the economic value of any large-scale project as compared to high-temperature solid oxide electrolysis. The efficiency of the high-temperature systems with the availability of thermal energy from a nuclear power plant (with relatively low impact on net generation) will be required to achieve hydrogen production at a competitive cost long-term. This is likely to be the case, considering some forecasts for long-term power demand growth with increasing power prices.
- Demonstrating that a water electrolyzer can enable a nuclear power plant to maintain steady-state operation while delivering varying power output is certainly well aligned with DOE's H2@Scale Program. However, this project has not yet demonstrated that the electrolyzer can do this, since transient operation has not been demonstrated, nor has the project demonstrated electrolyzer operations optimized to maximize the value of electricity and hydrogen production.

Question 5: Proposed future work

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

- This project is nearing completion and has achieved its objectives. The score provided is based on the reported future applications of the hydrogen system, which is outside of the DOE scope. The project team has done an excellent job of providing future advancement of the demonstration system to maximize the long-term economic value of the integrated process.
- Future work beyond operating the electrolyzer is not clear. However, if the Midwest Alliance for Clean Hydrogen (MACH2) Hydrogen Hub is funded by DOE, this should bring many opportunities. This project has also identified and started work with national labs in several areas that could, in themselves, be useful future scopes.
- Constellation has committed to investing $900 million through 2025 for commercial clean hydrogen production using nuclear energy. This includes participation in MACH2. The project needs to produce more electrolyzer operating data in the rest of the project time.
- It is commendable that the project included lessons learned in the future work. The completion of installation and dynamic operation is key for the team to meet project targets. It is not clear whether there are any plans to make the ANL work public, or how that work is being evaluated and compared with other research funded by DOE.
- The proposed future work (on slide 16) is limited to three bullets that all state that additional work may be done, if additional external funding is secured. It is not clear what else, if anything, will be completed during the last few months of this DOE project.

Project strengths:

- This is an excellent project that integrates nuclear power with an electrolyzer for an onsite demonstration. The 1 MW PEM water electrolysis system has been installed in the nuclear plant for the purpose of integration. This is a first-of-its-kind integration project. The project has a strong team. Each participant has unique expertise but is complementary to others. The project execution and results are very encouraging to the hydrogen community. Constellation has committed to invest $900 million through 2025 for commercial clean hydrogen production using nuclear energy.
- This project is very well developed and is focused on the integration of energy processes that have the potential to support and sustain nuclear power while realizing measurable decarbonization of the electric grid. The progression of this overall effort to advance to commercial scale and the application of the produced hydrogen are excellent.
- The project has gained much positive attention from media, funding agencies, and collaborators, which is a great mark of success. The project looks on track to complete all milestones and has done a commendable job responding to past reviewer comments and suggestions.
- It appears that the financial contribution from DOE was <50% ($5.8 million, with a total project budget of >$14 million). This is good for a demonstration project. This project has the potential to successfully demonstrate a useful application of electrolyzers, if transient operations for extended periods are included.
- This project asks questions and starts research in several impactful ways, plus it will have a payback just from the cost of onsite hydrogen.

Project weaknesses:

- This project provided valuable information at a demonstration scale for the installation of a hydrogen production process at a nuclear power plant. However, the low-temperature electrolysis technology has already been tested and validated, and the effort does not advance the PEM process. There was nothing reported on monitoring the dynamic behavior or the long-term reliability of the electrolyzer. The project incurred the cost of integrating the low-temperature system behind the meter. The project would be as successful with the PEM system powered from an onsite grid supply with a meter. It is assumed that the installation behind the meter was done to qualify for the proposed production tax credit. However, the industry should have argued, and still should argue, that clean (nuclear) generation that would otherwise be curtailed and instead is used to produce hydrogen should qualify.

- It was hard to evaluate the analysis value in regard to vetting the feasibility of hydrogen development at nuclear facilities (aside from general end-use evaluation). For example, it is not clear how key decision points are being made, such as using the hydrogen at the plant versus selling it or building storage versus a pipeline. There are gaps on how the project is addressing key research challenges/questions on regulations and generalizability to other nuclear facilities (beyond simply hydrogen price and Hydrogen Delivery Scenario Analysis Model [HDSAM] delivery), which were also highlighted by past reviewers.
- A project budget of >$14 million for just a 1 MW electrolyzer demonstration and some analysis is much more than one would expect. The cost of the 1 MW electrolyzer should be <$3 million. Clarification is needed as to whether the cost of non-reoccurring engineering (i.e., product development work) at Nel Hydrogen is also included here.
- There is nothing really innovative about this demonstration project. It can demonstrate that this obvious use case for an electrolyzer can be realized, if the team does successfully complete some transient operations with the electrolyzer. It would be even better if the project included some extended operational period to demonstrate durability and reliability. If Constellation wants to demonstrate something innovative, then the utility should consider demonstrating that turbine cooling can be done with a hydrogen stream that is recycled using an electrochemical hydrogen pump to purify and compress the hydrogen. This would mitigate hydrogen consumption and emissions.
- The project does not specify how the waste heat would be utilized for the electrolyzer operation to enhance the overall system efficiency. The project does not include measurable milestones such as system efficiency, operating conditions, and duration (i.e., 5,000 hours).
- The weakness is that this project does not really solve any of these scopes that are managed by the national labs; it only opens them up to future work.

Recommendations for additions/deletions to project scope:

- In the long term, it would be desirable to see Constellation include clean hydrogen production with carbon capture for the subsequent production of carbon-neutral, non-electric energy products (syngas, methanol, Fischer–Tropsch fuels, etc.) to assist in decarbonization of other sectors.
- DOE should ask Constellation if the utility is willing to do a no-cost extension of the schedule to include the collection and dissemination of electrolyzer operational results. More extended-operational data of electrolyzers in real-world applications is needed.
- It is recommended that the project revisit the simulation based on the performance observed in the installed dynamic operations. This is (understandably) not included in the scope but should be considered by DOE as a follow-on project.
- The project needs to produce more electrolyzer operating data in the rest of the project time period. The project should specify how waste heat would be utilized for the electrolyzer operation to enhance the overall system efficiency.
- There are no recommendations for changes to project scope.

Project #TA-035: Power Electronics for Electrolyzer Applications to Enable Grid Services

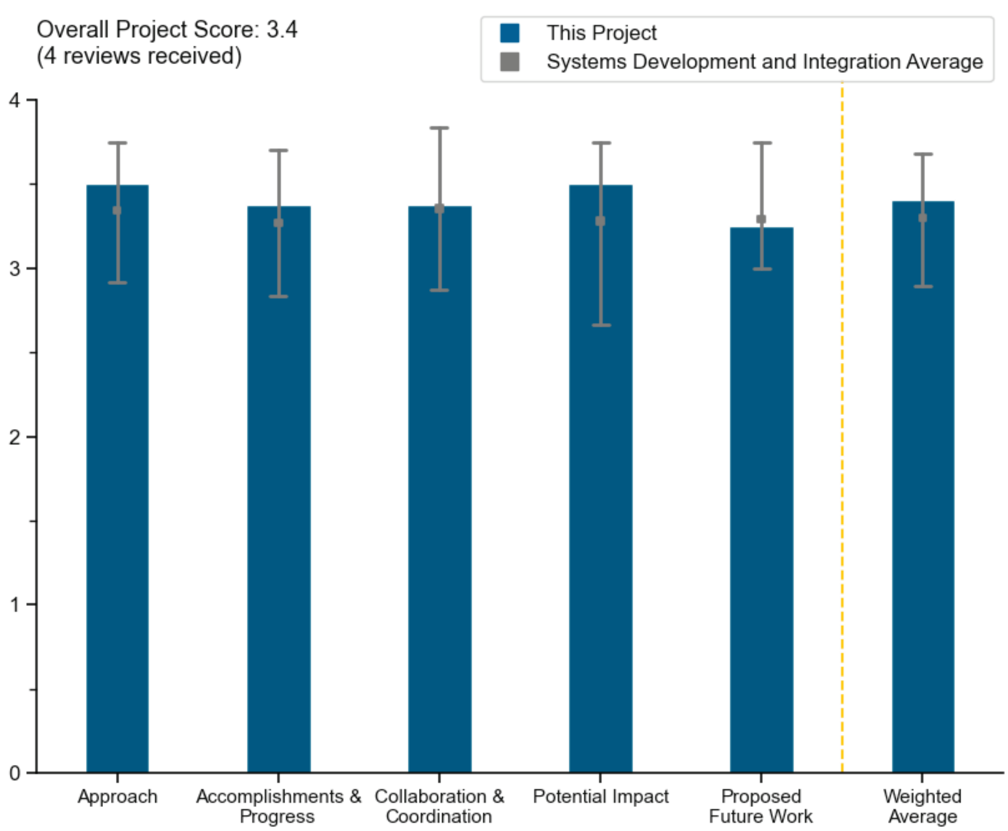
Robert Hovsapian, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.5
Start and End Dates	3/1/2020
Partners/Collaborators	EPC Power Corporation, Nel Hydrogen, Typhoon HIL, General Electric, SunSpec Alliance
Barriers Addressed	• Lack of standardized controls interface for electrolyzer applications in real-world operation as per grid codes and interconnection, interoperability standards, and scalability analysis • Coordinated control of multiple electrolyzers, including interaction with other power electronically interfaced distributed energy resource technologies in hybrid energy systems • 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 Systems Development and Integration 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.

- Great modeling work is proposed to integrate control architecture to maximize electrolyzer integration with renewables.
- Identifying a standardized approach for integrating electrolyzers into the grid is valuable, particularly for communicating grid-relevant signals. To date, most of the project's targeted operations are in response to existing grid conditions, rather than receiving direct signals from the grid. It would be good to include utilities as part of this effort to help guide grid-relevant signals.
- This project will continue in Fiscal Year (FY) 2023 and FY 2024. The team has added additional power converter companies to the project. The team has a well-laid-out plan to continue the research in FY 2023 and FY 2024.
- There is a clear need for this protocol standardization and a demonstration of its functionality.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- A framework for testing electrolyzer response in a simulated environment has been created, and results are promising. The slide with data from the 1 MW electrolyzer and 1 MW fuel cell is interesting, but it would be nice to see the demand/output from the electrolyzer/fuel cell in separate plots. There are likely low-load/-output values that need to be maintained for both units, and it would be valuable to understand those interactions—for example, whether the electrolyzer can be turned off completely or whether there is a low-load limit that must be maintained to achieve the expected response times. The same goes for the fuel cell.
- There has been great progress toward project goals. There is a good blend of modeling and verification through real installation of electrolyzer equipment, controls, and storage, which will help to optimize integration of these systems and support broader deployment of technologies.
- Clear results have been achieved in a relevant hardware-in-the-loop (HIL) environment.
- The team has made significant progress on the tasks laid out in the project plan.

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 great collaboration with industry and the lab. Leaders of respective technologies are pulled in to support and develop both modeling and installed systems to verify the approach.
- NREL has partnered with EPC Power Corporation, Nel Hydrogen, Typhoon HIL, General Electric, and SunSpec Alliance and is in discussions with Semikron Danfoss and Hitachi Energy.
- The partners are actively contributing to create a working system, and more industrial parties are brought into the conversation.
- It is suggested that the project include some utilities in this conversation to gain a better understanding of what control points would be of interest. There are also monitoring data streams that utilities would likely be interested in tracking but not controlling. These could be valuable for consideration as the standard is being developed.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project contributes directly to the Hydrogen and Fuel Cell Technologies Office's "Hydrogen Shot," which seeks to reduce the cost of clean hydrogen to $1 per 1 kilogram in 1 decade ("1 1 1").
- Current electrolyzers have few options for external controls. This is a valuable project in that it provides a framework for future development around the integration of electrolyzers with the grid.

- The impact of this work will further support electrolysis and integration with renewables to optimize installations and create greater value and cost reduction of hydrogen.
- The true value of this project will become apparent once Institute of Electrical and Electronics Engineers (IEEE) standardization has been achieved.

Question 5: Proposed future work

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

- The team has laid out a plan for FY 2023 that is reasonable for the tasks and goals for this project: (1) identify three power conversion and control vendors for different capacities of electrolyzer systems; (2) establish a high-level test plan for integrated testing of electrolyzer and power conversion and control and develop SunSpec Alliance validation and automated testing for identified vendors; and (3) conduct experimental validation using controller HIL.
- Proposed future work will continue the verification of modeling with actual testing of installed equipment. Demonstration work planned with additional direct current (DC) power sources is being considered. The intent is to engage with additional suppliers to get a better survey of stakeholders.
- It is encouraging to see more validation of scalability and modularity of hybrid systems.
- It could be valuable to consider different electrolyzer technologies in the context of response rates, start-up times, minimum loads, etc. Proton exchange membrane (PEM) electrolyzers have different response characteristics and operating envelopes from solid oxide fuel cells or molten salt electrolyzers. If it is not already being considered, a brief comparison might be made between the different electrolyzer technologies and the different integration/control paradigms they might require.

Project strengths:

- This project is valuable in that it provides a potential framework for future electrolyzer integration with the grid in a standardized manner. Following the SunSpec Alliance model is a reasonable starting point.
- The team and collaboration are strong. The project looks to develop predictive models confirmed with testing at scale.
- This project is taking the initiative to solve a pressing issue that can find direct application. There is a clear demand.
- Power electronics are a weak point in integrating hydrogen and fuel cells. This research is necessary for the advancement of the technology.

Project weaknesses:

- Utility perspective is lacking in this project. If these devices are expected to provide grid services, it would be useful to get input from utility operators to provide guidance on what those signals may look like. Evaluating different electrolyzer technologies is also of interest.
- It may be difficult to unite enough stakeholders to gain critical mass for standardization, if matters like reliability, security, and bidirectional communication are not sufficiently addressed.

Recommendations for additions/deletions to project scope:

- It is critical to achieve a stable, decentralized energy network whilst integrating a great variety of sources and sinks. This protocol could play a decisive role by making a very compelling case for its implementation, for example, by also addressing additionality requirements and “certificates of origin” compatibility.
- The project should compare electrolyzer technologies and include utility perspectives on using electrolyzers for grid services.

Project #TA-037: Demonstration and Framework for H2@Scale in Texas and Beyond

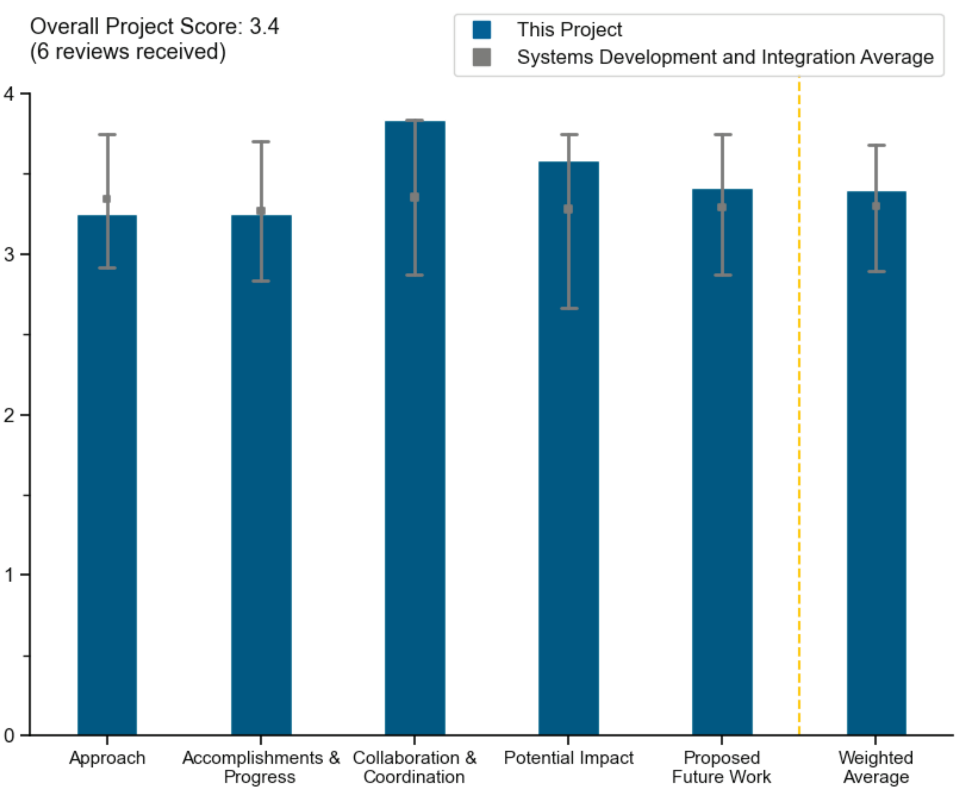
Rich Myhre, Frontier Energy, Inc.

DOE Contract #	DE-EE0008850
Start and End Dates	10/01/2019–7/31/2024
Partners/Collaborators	Air Liquide, CenterPoint Energy, Chart Industries, Chevron, ConocoPhillips, Frontier Energy, GTI Energy, Low-Carbon Resources Initiative, McDermott, Mitsubishi Heavy Industries America, OneH2, ONE Gas, ONEOK, Shell, Southern California Gas Company, Texas Commission on Environmental Quality, Toyota, University of Texas at Austin, Waste Management
Barriers Addressed	• Need to demonstrate hydrogen and fuel cell technologies in complete, integrated systems operating under real-world conditions • High investment risk for developing H_2 delivery infrastructure, given the current absence of demand for H_2 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. 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/Gulf Coast region that leverages existing hydrogen generation, distribution, and infrastructure assets to enable deployment of stationary fuel cell power and hydrogen-fueled vehicles. The plan will summarize opportunities, challenges, and key partners, as well as identify the economic and environmental benefits of at-scale hydrogen deployment for the region.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 constructing a demonstration of mixed-source hydrogen to mixed onsite demand for very relevant hydrogen production and use technologies. A safety analysis is a key component of the project. The project includes an assessment of the hydrogen supply chain in Texas, providing context on variables that drive cost and influence technology deployment. This type of project is highly relevant to DOE H2@Scale. The project is well poised to take a critical look at key barriers to scaling up the use of hydrogen in the Texas region, including validation of hydrogen use for drones and the mixed-source onsite production of hydrogen from natural gas, biogas, and renewable-powered electrolyzers.
- This is a very interesting project that combines multiple resources and technologies with a goal of reducing dispensed costs of low-carbon hydrogen. Overall, the approach seems sound, with a strong project team and a good focus. It would be helpful to see a clearer definition of "least cost" in terms of how capital costs are being treated from an overall cost perspective, and how the underlying solar and wind systems to produce electricity are being included from a cost perspective. It would have been good to hear a little more about how the "hybrid" approach of using solar photovoltaics and simulating wind will be carried out, as well as limitations relative to physically combining these technologies.
- As a sort of predecessor to the upcoming DOE Regional Clean Hydrogen Hubs (H2Hubs), this project will demonstrate several types of production, a fuel cell for stationary power, and fueling for several vehicles, and calculations will be used to look at a larger hydrogen ecosystem. The project will also, to at least an extent, demonstrate the integration of all these production/delivery/use cases to make a functional system that serves all.
- The well-thought-out approach covers most aspects. There needs to be community engagement and outreach. This is an excellent opportunity to gain community buy-in on hydrogen, both locally and nationally. The approach of multiple ways to generate hydrogen, storage, and different types of end users is very good.
- The project has multiple facets, with interesting comparisons between electrolyzer- and SMR-based hydrogen and multiple energy sources. The demonstration should provide data on several use cases of value.
- This project is addressing critical questions but has some gaps. Most notably, the physical demonstration is not clearly linked to the framework/roadmap. The technology selection is not clearly aligned with the framework scope, and there is no apparent connection to scale (i.e., the data center will require vast amounts of hydrogen, and possibly hydrogen storage, not utilizing the SMR). The scope should be reconsidered away from physical deployment toward analysis of well-known technology and reconsidered with the requirement that any physical scope should have a defined purpose and explicit hypothesis that supports the framework.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The project has done a good job adjusting the approach to changes. For example, the team re-negotiated some contracts to get lower prices. The Hydrogen Optimization with Deployment of Infrastructure (HOwDI) model was very useful in developing the plan. The low projected dispensed cost of \$3.79/kg H_2 with tax incentives is encouraging. It should be remembered that these are tax credits, so they work only when a taxable profit is made. The site-level and equipment-level hazard analysis looked very complete. It was good to hear that the principal investigator is responding to the hydrogen safety panel recommendations. The cost analysis for pipeline hydrogen delivery is good.
- Significant hardware procurement has been completed; hazard and operability (HAZOP) studies are ongoing. There has been an impressive amount of safety analysis through process hazard analysis and functional hazard assessment with third-party engagement, which changed the layout onsite. Construction has started for pads and interconnects.

- The project has made marked progress toward the installation and operation of the demonstration site, including procurements, safety and hazard analysis, engineering design, and skid analysis. The project also has made substantial progress on the hydrogen region framework and economic model, including near-completion of a five-year report plant.
- All major equipment is ready; much is in place, and the rest is coming. HAZOP studies are complete, based on this replanned layout for greater safety. Site construction and preparation are under way. The project is being used to educate the next set of engineers in the energy area.
- The project is somewhat behind schedule, but recent progress has been good. The project is well targeted toward key DOE goals of validating and proving out low-carbon and renewable hydrogen systems.
- Given the scope as it exists, the milestones and delays this project has accomplished have been reasonable.
- The cost analysis would benefit from doing the analysis for onsite production of hydrogen from water electrolysis.

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 highlighted ongoing work related to H2@Scale in Texas and demonstrates successful communication among an impressive number of companies and institutions. There was not enough information to evaluate the data portal proposed for the 13th quarter, but it could go a long way to further enabling collaboration and dissemination of key results and data.
- The project is sort of inherently high-collaboration. About 20 partners mostly support and consult, with all providing at least perspective and advice and some giving physical goods (e.g., Toyota is providing fuel cell vehicles). Many are poised to implement codes and regulations, build production, use units, etc., so they can make this happen if the economic case emerges.
- This is a large team that seems to have roles well defined. It is missing a community outreach and engagement program, which the university could lead. The partners increasing their cash-in when the firm bids came in high shows that they are committed to this project's success.
- Collaboration is excellent. The only suggestion is to consider adding a hydrogen pipeline operator, such as Air Products, to the project.
- The project has a good team of collaborators, including the University of Texas (UT) partner, who can provide independent analysis and evaluation.
- There is a large number of relevant partners. There is tangible hardware with fuel cell vehicles to make the project accessible to the public. Several partners are listed as "support" with no real details.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project is highly relevant to the H2@Scale objective and addresses the critical gap in demonstrating hydrogen production and delivery and use at scales of ~100 kg/day. The demonstration will provide real-world information on the use of hydrogen in drones, a new application. Finally, the project will support improved estimates of construction, contingency, and finance considerations, despite its being a first-of-a-kind integrated system. These non-technical components of hydrogen projects are poorly understood, and additional information on permitting and risk mitigation will benefit other projects.
- The impact depends on whether an H2Hub is chosen in the Gulf area. If so, then the impact will be largely to advise that hub, as the hub will be a massively larger effort in the same space. Of course, this is in no way the project's fault. However, if by some chance there is no Houston area H2Hub, then this will serve as a rather reduced version of a hub and will show what a hub there might do. The amount of data the project will gather in the time remaining may limit impact. The researchers think they might get good data in the time allowed, but delays in commissioning and integration could easily prevent that. Even with a no-cost extension, the team might not have much replication of data and, thus, no real handle on uncertainty in the values.

- Demonstrations of this type and scale are necessary to gain regional acceptance and show how different use cases work together.
- This is very relevant to the Hydrogen Program for both the Hydrogen and Fuel Cell Technologies Office and the Fossil Energy and Carbon Management Office. The only gap would be a community outreach effort.
- This is a highly relevant project with potential for significant impact.
- The framework is highly impactful. It is less clear that physical deployment is impactful.

Question 5: Proposed future work

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

- The proposed future work to complete the demonstration project and finalize the economic analysis report will bring substantial value to the project and toward overcoming the key barriers listed. It would have been helpful to hear more information on the data portal and the type of information being provided there (and to whom). The end goal is ambitious, and the project does not have that much time remaining; the team will have to focus to stay on task once the demonstration is operational.
- The planned future work is excellent. The cost analysis should include onsite hydrogen generation with no pipeline. It is recommended that the project add a community outreach effort, which could be led by the university partner.
- Future work seems well chosen, based on status and end goal. There is a nice level of detail, so one can be confident the team is doing the right work.
- The plan in the next budget period is to actually operate equipment together. The timeframe for operation may be shorter than planned (12 months originally). The equipment will not be ready until a few months before the end of the project.
- Future work should emphasize the framework and lead to an understanding of how any physical deployments will contribute data to the analysis.
- The remaining project timeline may not be sufficient, given project delays, which is somewhat concerning. It is unclear how much time will be available for data collection, realistically. If more time is needed, it is not clear whether the project team is in a position to continue under a no-cost extension to reach the desired outcomes.

Project strengths:

- The project did a commendable job with a value engineering assessment to lower bids for Phase II and III by 12%. The project shows a clear progression toward (1) being operational, (2) meeting milestones for skid and controls verification, (3) safety and hazard assessment and response, and (4) procurement. The project seems to have an effective method for engaging with multiple team members from industry and academia to inform decision-making.
- This is well-funded by both DOE and industry. The project is making a demonstration facility that demonstrates a variety of different hydrogen generation methods (reforming and electrolysis) with other unit operations. There is strong industry support, with 19 partners. The project is located at a university, which makes it a learning laboratory.
- The project may serve to enhance H2Hubs projects if the learnings are in an easily actionable form by the end of 2023. This is a first attempt at a small-scale ecosystem for hydrogen. The team is willing to adapt when needed (e.g., replanning the UT site based on HAZOP studies and fire review).
- The project is ambitious, combining multiple feedstock/sources and technologies. The project team is strong.
- The project has great collaboration and an impactful framework scope.
- The project addresses multiple elements and includes a strong safety analysis.

Project weaknesses:

- It was unclear from the presentation and submitted information how the demonstration, which uses SMR without carbon capture and sequestration and electrolyzers powered on solar and wind, aligns with and is informed by the scenarios in the Monte Carlo analysis using HOwDI. It is unclear why the demonstration would not be better represented in the economic modeling, or how the variable correlations inform the demonstration. The demonstration is built, and it will have a certain hydrogen production price based on the capital and feedstocks and markup; none of this is properly linked to the information coming from HOwDI. To be clear, the modeling capability of HOwDI is impressive and important as a standalone assessment tool for Texas. Engagement with community members on the framework report was difficult to evaluate.
- Wind energy sources are only being simulated, so this is a good stepping stone but not an actual physical integration. Biogas is being directed rather than physically reformed, so project lessons learned will be somewhat limited as a result, vis-à-vis applications in which biogas would be used directly.
- The project needs to increase the community outreach plans. The educational plans should expand beyond just college-/university-level teaching. The project can make results available for technical schools and unions for hands-on training modules. The project represents a large investment for what could be a very short demonstration unless the project is extended.
- The usefulness of the physical deployments is unclear.
- The project is behind on time and over budget.

Recommendations for additions/deletions to project scope:

- The key data being collected from the demonstration in the subsequent period is not clear. Success is based on driving a hydrogen vehicle around, but more information is needed to evaluate the approach for measuring and monitoring performance (e.g., hydrogen leakage, energy efficiency, cost, feedstock consumption, and community feedback). It is suggested that the project include a summary of findings to support how teams model the scale-up and deployment of similar hydrogen networks.
- The project needs to increase the community outreach plans. The educational plans should expand beyond just college-/university-level teaching. The project can make results available for technical schools and unions for hands-on training modules. The project would benefit from a pipeline.
- If project needs to be extended to demonstrate critical equipment demonstration, incremental funding should be added to accommodate.
- There should be a high point at which the five-year plan for the Port of Houston/Gulf Coast region is ready (December 31, 2023) and can be shared with any Texas-based H2Hub and perhaps with other hydrogen hubs.
- The scope should focus on the framework, not the physical deployments.
- There are no recommendations. Project results are happily anticipated.

Project #TA-039: Solid Oxide Electrolysis System Demonstration

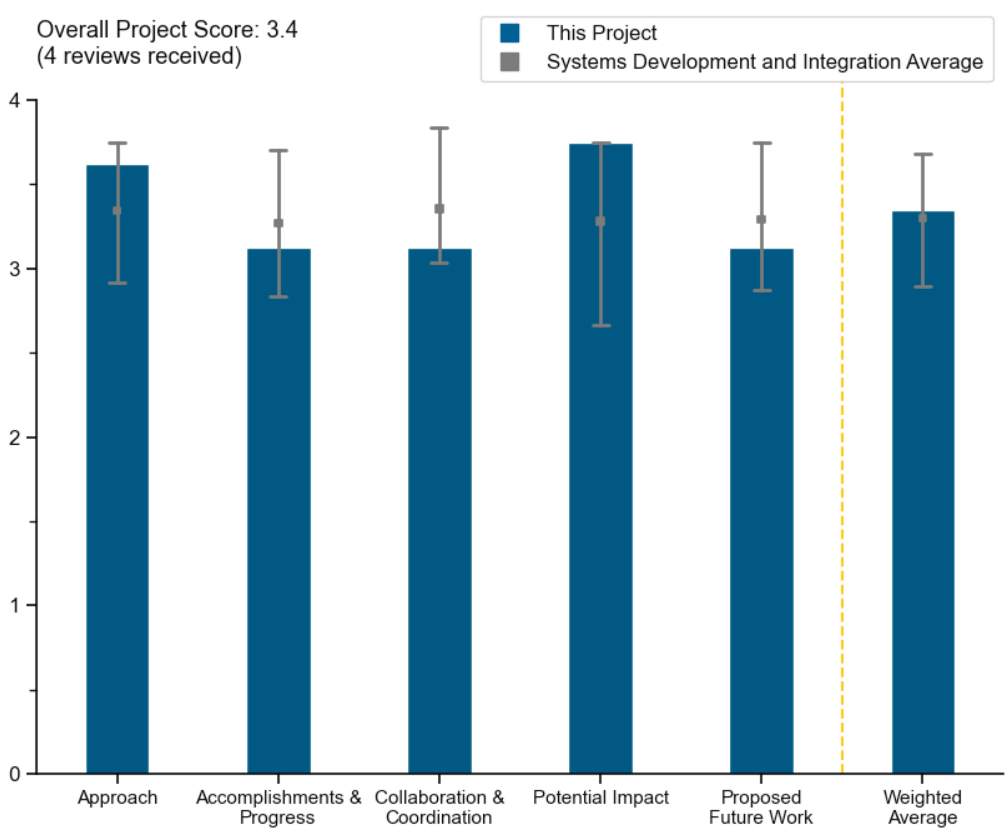
Hossein Ghezel-Ayagh, FuelCell Energy, Inc.

DOE Contract #	DE-EE009290
Start and End Dates	10/1/2020–5/31/2024
Partners/Collaborators	Versa Power Systems, Idaho National Laboratory
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Electricity generation integration

Project Goal and Brief Summary

The project will complete design, engineering, procurement, assembly, integration, and demonstration of a solid oxide steam electrolysis hydrogen generation system. The project will validate the technology's potential as a high-efficiency, low-cost alternative for hydrogen production at nuclear plants. Researchers will design, build, and test a 250 kW (input) steam electrolysis system using hardware-in-the-loop simulation of light water reactor operation. Objectives include validating solid oxide electrolyzer cell (SOEC) technology performance and reliability for steam electrolysis and hydrogen production in a packaged system; developing system operational and control strategies specific to the nuclear industry; demonstrating key features of SOEC electrolysis systems, including high electric efficiency and waste heat utilization, in a 250 kW class unit prototypical of larger-scale systems suitable for integration with nuclear plants; and acquiring the data necessary to valorize the integration of SOEC systems in light water reactor facilities for increasing their operational flexibility and profitability by switching between electricity production and hydrogen generation.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 to demonstrating the operational performance of a prototype integrated high-temperature solid oxide electrolysis system with nuclear power is effective and well developed and contributes to overcoming most technological barriers. Accomplishing the demonstration objectives is considered highly feasible. The size of the demonstration is appropriate for the purposes of demonstrating the SOEC technology performance and is accommodated by the Idaho National Laboratory (INL) Energy Systems Laboratory (ESL) facility design. However, the use of the INL ESL facility and the controller hardware at the proposed demonstration scale may not address large-scale plant integration constraints as they relate to electrical loading and variable steam demand from the plant. These physical system limitations may result in a different operational space for the SOEC system when integrated. Regardless, the performance of the SOEC system (e.g., stack efficiency and response characteristics) will be well demonstrated during this project. No detailed information was presented on the large-scale techno-economic assessment (TEA) to follow the demonstration project. Based on similar efforts already completed for an integrated generic high-temperature SOEC system, the TEA results will be weighted based on the application of the high-temperature steam electrolysis (HTSE) system (e.g., dynamic load following vs. baseload operation) and the specific electric grid and market conditions. Analysis of a range of large-scale operating conditions would be advisable. As it relates to the future TEA, the researchers are advised that the reference to nuclear plant "waste heat" is misleading. A nuclear plant considers waste heat to be the heat that must be rejected from the condenser (i.e., Rankine Cycle), which is insufficient to satisfy the requirements of promoting the HTSE process water to steam. Typical condenser discharge is about 125°F at atmospheric pressure. The thermal energy from the nuclear plant needed to produce steam for the HTSE (to achieve maximum overall HTSE efficiency) would be taken from the turbine inlet (high-pressure or low-pressure, depending on design). This will have a corresponding reduction in steam flow to the turbine and a reduction in electrical output. This needs to be factored into the TEA.
- The approach that FuelCell Energy set out to execute in this project is solid, exactly what is required to design and demonstrate a high-temperature electrolysis system that is targeted for use with a nuclear power plant.
- The project objectives were clearly outlined, and the work plan was well thought out for design, fabrication, and testing of a 250 kW SOEC system. It is likely that the project will be able to overcome several critical barriers and achieve project objectives.
- The approach to performing the work is effective, with the focus on designing, building, and evaluating the stack and balance of plant (BOP) before system integration.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- Progress on the project is proceeding in accordance with an adjusted schedule, given the noted issues with supply chain and stack production. The FuelCell Energy representative stated that company resources are presently dedicated to increasing stack manufacturing capacity. The added capacity should now facilitate the stack manufacturing with minimal delay. It appears that the manufacturing schedule aligns with the efforts at the INL ESL. The conditions that resulted in the delay were reasonably beyond project control.
- To date, significant progress has been made, and excellent system performances have been demonstrated. For example, the project has successfully demonstrated a 250 kW SOEC, with anticipated performance and reliability for hydrogen production from steam electrolysis in a packaged system. It seems that the project is on track to achieve its goals toward commercialization of the SOEC technology.
- Fabrication of BOP components is complete. The progress of stack fabrication is not clear without detailed information.
- It is a bit disconcerting that all DOE funds have been spent and the stacks for the demonstration system have not been built. The BOP for the system is nearly completed, but one has to wonder if this project will be completed without additional DOE investment.

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 coordination between FuelCell Energy and INL is excellent. The visitation at the INL facilities confirmed the collaborative efforts to support the FuelCell Energy SOEC demonstration by both participants. This collaboration is fully expected to achieve the end goal of verifying the SOEC stack performance and durability under (simulated) dynamic operation.
- The collaboration and coordination among partners seem to be effective, including testing of an SOEC system at INL.
- FuelCell Energy has an excellent partner in INL for hosting the high-temperature electrolysis system demonstration. FuelCell Energy might have included a nuclear power plant operator as a project partner (or at least collaborated informally) to make sure that the project's demonstration system design had all the appropriate functionality to facilitate future integration with a nuclear power plant. It is questionable to consider Versa Power as a collaborator, given that Versa is 100% owned by FuelCell Energy.
- No information is given regarding collaboration and coordination with vendors/suppliers of key BOP components.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This high-temperature SOEC demonstration project advances technology that is critical to the Hydrogen Program and has the potential to significantly advance progress toward DOE research, development, and demonstration (RD&D) goals and objectives. The economic viability of clean hydrogen production via nuclear power is directly dependent upon improvements in the electrolysis stack efficiency and resulting system total efficiency. This project advances progress toward SOEC technology development and supports the DOE Office of Nuclear Energy objectives to maintain domestic nuclear power as part of a resilient and secure grid. Improvements in stack efficiency will be required to achieve DOE cost goals and to incentivize industry (current fleet) to integrate hydrogen production and will inform advanced reactor development. This project provides verification of the electrolysis technology's performance and eliminates a significant risk for first-time, at-scale plant demonstrations.
- This project, if completed as originally proposed, has significant potential impact. Integration of high-temperature electrolyzers with nuclear power plants is an extremely promising approach for achieving DOE's hydrogen cost targets.
- This development and demonstration 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.
- Testing and demonstration of a 250 kW solid oxide electrolyzer has the potential to advance the technology and demonstrate progress toward DOE goals and objectives.

Question 5: Proposed future work

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

- The proposed future work is consistent with the described project plan and progresses in a logical manner.
- The proposed future work seems reasonable for addressing the remaining challenges and barriers and for achieving the project objectives.
- FuelCell Energy's proposed future work is fine and includes all that is needed for completing the project as originally planned. The question is whether FuelCell Energy will complete the project without additional financial support from DOE.
- Proposed future work lacks details, especially on timeframes and end dates.

Project strengths:

- The project provides in situ performance demonstration of the SOEC technology, and the results of the dynamic performance testing are directly applicable to larger commercial-scale applications. The performance demonstration de-risks the installation of this technology in nuclear facilities and provides a tested/verified input for the economic analyses of these integrated systems. The project provides an actual demonstration of an integrated system that will assist in the design of interfacing systems for larger-scale applications at nuclear power plants. This again provides an element of risk reduction for the utility. The performance data likewise provides input for the design of integrated energy systems for advanced reactors. The HTSE/SOEC TEA will provide supporting economic bases for integration at existing domestic plants and for advanced reactors. The integrated technology provides options for nuclear plant economic viability that will be required to achieve electric grid (and other sector) decarbonization goals. The collaborative arrangement between FuelCell Energy and INL appears to be excellent and will ensure successful project completion.
- FuelCell Energy has a solid oxide cell and stack technology upon which the prototype electrolysis system is based. FuelCell Energy has a solid system design, and the hardware is ready for stack installation and system testing.
- Demonstration of the SOEC technology at the system level is important to its commercialization.
- The main project strength is the design, fabrication, installation, and operation of a 250 kW electrolyzer.

Project weaknesses:

- It may be useful to evaluate SOEC performance in a wider range of operating conditions to better characterize the behavior of the SOEC system for various applications.
- The project's main weakness is the lack of detailed schedules on various activities in the critical path of the project.
- A project weakness is the budget challenges.
- No weaknesses were identified with respect to the stated project goals.

Recommendations for additions/deletions to project scope:

- The demonstration (analysis) should consider the energy input associated with the steam inlet (INL steam to FuelCell Energy—simulation of nuclear thermal energy) and the associated degradation in electrical output. This should be factored into the overall efficiency. Stack testing, to the extent possible, should account for typical nuclear plant system response in electrical loading, steam supply, temperature variations/transients, and those associated with other interfacing systems. It is suggested that the project include additional scope to assess system response to black-out power conditions, which could be of value for nuclear plants performing failure mode and effects analyses for integrated systems design.
- There are no recommendations for additions/deletions to the current project scope.

Project #TA-042: Next-Generation Hydrogen Station Analysis

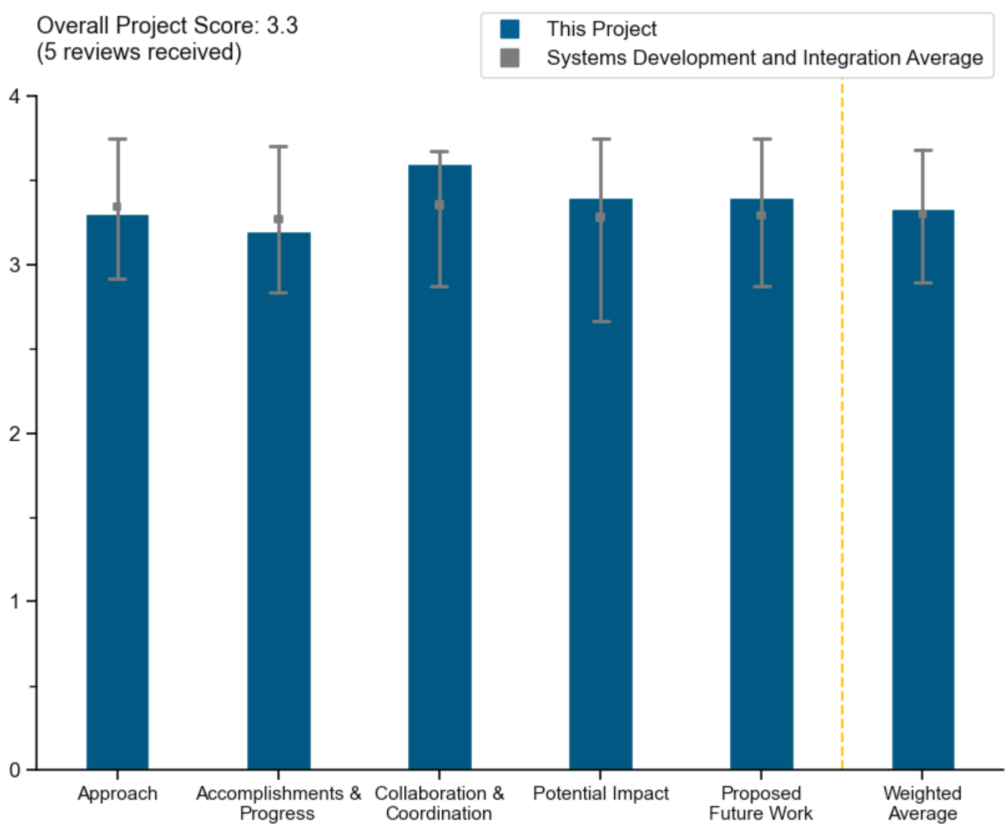
Genevieve Saur, National Renewable Energy Laboratory

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, International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and Association of Hydrogen Supply and Utilization Technology (HySUT), Gas Technology Institute, California Department of Food and Agriculture – Division of Measurement Standards, University of Maryland Center for Risk and Reliability, Air Liquide, Air Products, California State University, Los Angeles, Equilon Enterprises LLC, First Element Fuel, H2 Frontier, ITM Power, Iwatani Corporation, Linde plc, Messer, Proton OnSite/Nel ASA, Shell, Stratos Fuel
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 for status, benchmarking, technology readiness, value proposition, and research needs. 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 reliability, fuel economy, range, and driver behavior.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 National Renewable Energy Laboratory's (NREL's) approach to evaluating work is outstanding. The team is objective, thorough, and comprehensive in collecting data from new refueling stations. This is critical to meeting DOE targets for infrastructure cost and ultimately the cost of hydrogen to customers even beyond light-duty fueling stations. The objectives are directly aligned with DOE needs and include the critical feedback from end users and stakeholders.
- Overall, the project has a great approach to capturing data and presents it with no direct correlation to a data provider. Since the project will be developing composite data products (CDPs) for heavy-duty refueling stations, now is the time for involved stakeholders to possibly fix some of the issues on the reporting requirements, especially as pertains to maintenance and safety events. Reliability data will be critical with the data. The project should also evaluate needs now to be ready for station evolution—for example, if bi-directional communication gets implemented.
- The project has an established, optimized, and proven data collection and management process (>12 years). It is unclear how, outside of government entities and academia, the vast and growing number of data parameters collected continues to provide value toward overcoming barriers for industry (per impact stated on slide 2).
- The detailed data product/CDP process has been developed into an effective tool for aggregating and sharing data. It does still have the downside risk that the private companies that provide the data will not necessarily provide all the data that might be needed to get a complete picture of station operation.
- The project's overall approach looks fine. Quality of the analysis will always depend on quality of the supplied data, which will be variable across station providers.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The project is doing an excellent review of the total number of vehicles on the road and highlighting the increased throughput from liquid hydrogen stations. This is critical data to be shared with DOE and stakeholders in parallel programs and efforts where high-throughput hydrogen will require liquid storage and eventually dispensing. NREL is also making this data available to the public through the CDPs. All these items contribute to DOE goals to reduce the cost of deployment. Costs are increasing, but that should not reflect on NREL's project efforts. The utilization is increasing, and the capacity at stations is increasing. DOE needs this data to plan for the next steps in hydrogen for transportation. The stations can double their average throughput with increased demand. The data on impurities by production type is also important for sharing with stakeholders and to improve quality assurance across the industry.
- Many of the accomplishments discussed (more stations, more fuel dispensed, lower cost) are noteworthy but not necessarily results of this project, per se. The accomplishments of daily station profiles, hydrogen quality reporting, and component reliability (assuming good data on this can be had from the station operators) are accomplishments of this project and very valuable to the industry.
- The project has good analysis and distribution of the aggregated analysis products.
- The project has good accomplishments highlighting the increasing utilization of the stations in California.
- It is unclear whether hydrogen fuel demand increase is an accomplishment for this specific project. The project does not indicate a root cause follow-up on why the data shows the reported accomplishments (for example, the data does not give insight into why fueling times are shorter and why there is an increase of demand at certain stations).

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.

- Having all the station operators participate is a major accomplishment (admittedly driven by requirements of the California Energy Commission funding). It would be helpful to understand that the project is getting uniform/consistent data from each operator. One notable bit of information that would be very helpful for codes and standards development (and increased customer satisfaction) would be data on what the ending state of charge (SOC) of all fills is, as there are reports of problems with stations stopping fills prematurely because of how SAE J2601 defines the required pressure ramp rate, but it is difficult as an industry to quantify that problem at this point.
- There is excellent collaboration with station owners, funders, and providers. This can be seen in the level of detail about the stations and various challenges from impurities to throughput. NREL is also open to working with heavy-duty station operators, which will be key for DOE, as the Hydrogen Program has shifted to fuel cell targets for larger fuel cells in transportation than those used in cars, as seen over the last decade.
- Collaboration is appropriately broad and coordinated.
- Collaboration is a strength for this project.
- Many, if not all, parties operating hydrogen fueling stations report data to NREL because of contractual obligations.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This trailing data is important for DOE to alter research, development, and demonstration (RD&D) and to focus on next steps for the Hydrogen Program, especially for the shift from gaseous-based stations to liquid-based stations. This may eventually lead to liquid dispensing and is a key aspect of DOE's RD&D roadmap.
- There is no substitute for having good data. The data products have been developed and matured. Hopefully, as the number of stations continues to expand, the project can add some additional targeted data (such as end-of-fill SOC).
- Current analysis and reporting provide a useful set of outputs for those working in the space. The development of data around reliability should have a similar impact.
- Station data collection that can help identify trends and RD&D needs will have a high impact.
- The project provides fueling station data to DOE. However, it is unclear how this translates directly to setting and achieving DOE RD&D objectives, particularly translation of light-duty retail station data to future new medium- and heavy-duty fueling stations. It is not clear how the data collected provides insight, other than to station operators, for improvement of station components and/or development efforts for next-generation station technology.

Question 5: Proposed future work

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

- The proposal to expand data collection and analysis to maintenance/reliability sounds good. It does seem that this type of information would be helpful in planning station uptime, and possibly in station design (selection of components), in the future.
- Transition to heavy-duty trucks is an obvious future direction. Keeping the light-duty station data is also important to capture data related to larger-capacity liquid hydrogen stations. The project needs to look outside of California to capture data as much as possible, although this is more difficult to implement.
- The future work proposals, as outlined, all appear valuable and aligned with the reviewer questions and comments. It would be good to understand the planned/expected funding picture a bit better. This project has been going on for 12 years. It is not clear whether the project is open-ended or whether the team has to

reapply at some point (and if the latter, whether the team would ask for something different). One slide says that the DOE contribution for 2022 was $200. Perhaps that is a typo.

- The online maintenance tool will be important to keeping costs down and highlighting problematic suppliers. The community is looking forward to more data on medium- and heavy-duty station reporting, especially as the cost of hydrogen is expected to come down, thanks to higher throughput. There may be challenges with higher flow rates and larger-capacity cooling systems.
- The project could consider reducing the number of data parameters collected. The project could consider the conventional fuel industry key performance indicators (KPIs) for fueling stations.

Project strengths:

- The project has had a strong track record over many years of creating the go-to source of summary data about the performance of overall U.S. hydrogen station system performance. The project should continue making sure that the industry knows where to look for all the published data.
- NREL's strength is the open nature of CDPs and operators' willingness to share the data because it is anonymized. This is a unique capability in the world. Most critical data shared also includes impurities, and measurement technologies are used for quality assurance at the fueling stations. The project has a large number of data providers, and long-term data collection allows for observation of trends.
- The project delivers analysis in both public and private forms, serving both the data suppliers (and so incentivizing them to collaborate, hopefully) and the public consumers of the information.
- The project has a large number of data providers. Long-term data collection allows for observation of trends.

Project weaknesses:

- The project has limited weaknesses. Most issues are outside of NREL's control, such as sharing actionable data and good-quality data sets. Sometimes data is missing or partners are not able to comply with obligations or requests.
- The project has a large number of parameters for which data is collected. It is unclear how data is used for station component development and improvement that (eventually) increases station availability. This is a rapidly developing technology area, with shifts that are difficult to capture in data collection and that create difficulty for observing actual trends for hardware/software components.
- The major weakness, as acknowledged by the project, is that access to data is not guaranteed, and a (possibly) increasing fraction of operating stations may opt out/age out of reporting.
- The project is only going to be as strong as the data that comes from the station operators. It is unclear if the project is actively updating the data requirements associated with new funding.

Recommendations for additions/deletions to project scope:

- The project could reduce the number of parameters after assessing what the conventional fuel industry collects data for (i.e., KPIs). The project could include root cause follow-up for data patterns recorded by, for example, looking at time-stamped data and comparing this to fueling station availability and issues reported on fuel cell electric vehicle driver social media groups. When reporting on data from stations, the project could distinguish between stations with different numbers of fueling positions (of particular interest for medium-/heavy-duty hydrogen stations).
- If the project is connected to H2-041, perhaps that project's work could inform and support what data could be requested in the future and what analysis would be helpful.
- Additional funding or scope should be included for heavy-duty and medium-duty stations where equipment may not be ready for metering at the much faster flow rates.

Project #TA-043: Solid Oxide Electrolysis Cell Stack Development and Manufacturing

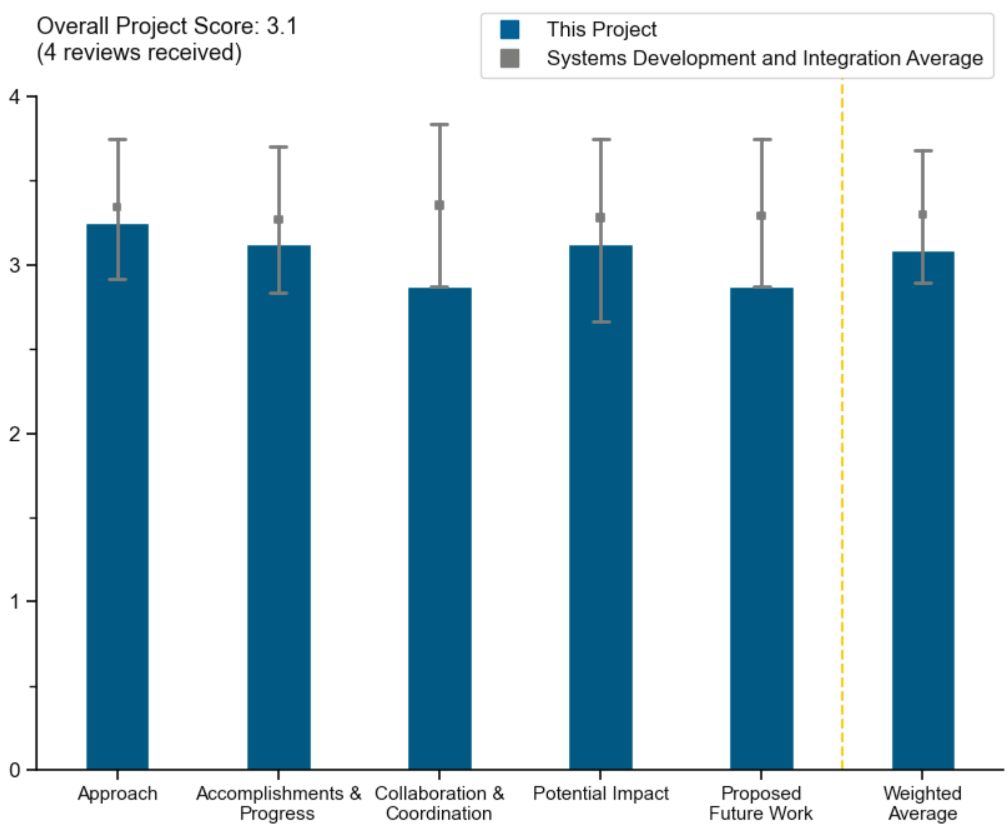
Olga Marina, Pacific Northwest National Laboratory

DOE Contract #	WBS 7.2.9.2
Start and End Dates	10/1/2019
Partners/Collaborators	Idaho National Laboratory
Barriers Addressed	• Hydrogen cost • System efficiency • Manufacturing • Renewable electricity generation integration

Project Goal and Brief Summary

Pacific Northwest National Laboratory (PNNL) and Idaho National Laboratory (INL) are collaborating to perform research and development to reduce the cost of high-temperature electrolyzer operation and improve stack durability and efficiency, thus reducing hydrogen cost and increasing hydrogen production. The project team will also initiate stack and related component degradation studies using a baseline stack, develop in operando health monitoring equipment for stacks, develop a predictive stack digital twin, and perform post-stack-test characterization analysis for solid oxide electrolysis cell (SOEC) original equipment manufacturers.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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.

- This presentation shows excellent progress toward reproducibility in cell manufacturing and testing via developed fabrication and testing procedures. The team has put major effort into eliminating any cell non-flatness challenges and successfully measured short stacks (1.3 kW, 4,300 cm^2 cells) with promising current density, and the team is on track testing the larger stack (5 kW) and achieving the set goals. Successful thermal cycles were also demonstrated. Electrochemical impedance spectroscopy (EIS)/ distribution of relaxation times (DRT) analysis incorporation is extremely encouraging to separate ohmic and polarization losses in stacks. The following comments are suggestions to further improve on the scale-up and validation processes:
    - Since all stacks will be tested at INL, considering how stack fabrication reproducibility will be ensured would be valuable. Identifying gaps in reproducibility is rather challenging unless the stacks are tested in-house. The approach to ensure reproducibility of cells involves measuring multiple ~1 kW stacks, but scaling up to 4x5 more cell layers in a single stack may introduce more variation, making it challenging to ensure reproducible cell fabrication, stacking, sealing, and conditioning. INL can follow the same testing procedures for each stack, but clarification is needed as to how this information will identify the root cause between performance variation of different stacks. Drafting a clear plan to address such scaling/manufacturing challenges would be valuable.
    - Working with larger industrial partners on quality assurance (QA)/quality control (QC) cell and stack fabrication or consultants coming from the large fuel cell/electrolyzer industry is worth considering. While major original equipment manufacturers will not share proprietary information, the major lessons they have learned could benefit PNNL in allowing smaller startups to follow their examples in fabricating and testing cells and stacks. For instance, Cummins Inc. is funded by DOE to assemble an automated manufacturing line with many stages of QA and QC. This could potentially serve as a good example to tighten cell and stack specifications.
    - Investigating accelerated stack tests (beyond single-cell tests) in order to effectively simulate long-term operation would be valuable. Further expanding on the matrix structure, including more on/off cycles, would be valuable.
- The main objectives of this project are to improve SOEC stack durability and efficiency, increase hydrogen production rate, and reduce hydrogen production cost. The challenges and barriers are clearly identified. Proper technical approaches for achieving the objectives are outlined, and the work plan is well organized. Overcoming the critical barriers and achieving project goals is likely.
- The approaches being pursued are all important to the development and manufacturing of high-temperature electrolysis stacks. The value provided by stand-alone development of new cell and stack designs is not clear without an industry partner to take the technology further.
- The project shows a proactive approach to improving material and interface issues, as well as solving practical problems to secure good test data for deep analysis. The queries and issues coming from the industrial stakeholders, however, have not been elucidated clearly.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- Operating a short stack for hundreds of hours generated significant data for building and validating models, as well as validation of practical improvements to the system. The project goals are very ambitious, and the achieved results provide a firm basis upon which to expand. The goal of the project is to help industry recognize issues quickly, fix them accordingly, and bring their improved stack products to market quicker, providing a toolbox rather than constructing its own PNNL stack prototype.
- PNNL's work on post-mortem characterization of tested stacks provided by industry is extremely valuable, as PNNL possesses characterization and analysis capabilities to which most industrial stack developers and manufacturers do not have access. PNNL's development of techniques for measuring impedance in stacks under load could be valuable in developing a real-time understanding of stack degradation. Predictive

models established for glass sealing, temperature distributions, and thermo-mechanical stress–strain relationships can also provide value to stack developers. While operating a stack at target density of 1 A/cm^2 was successful, the stack degraded rapidly (to ~0.7 A/cm^2) under that condition.

- Several areas have shown excellent progress, including fabrication of single cells, cell stacks, multi-physical modeling, and electrochemical testing of cells and stacks.

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.

- As indicated by the presenter, larger players in this high-temperature field should be more involved in defining issues to be solved and identifying the scope of the potential solution. The test station with a large-active-area short-stack test enables statistical analysis of cell-to-cell behavior and distinguishes material degradation, which could be transferable to commercial platforms.
- The principal investigator was able to collaborate with INL and industrial partners in identifying issues critical to manufacturing, understanding the mechanism of degradation, optimizing operating conditions, and developing micro-/nano-structure to enhance performance and durability.
- PNNL's support of stack developers by providing post-test characterization of stacks is exemplary.

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Solving durability issues with material solutions and understanding practical problems are key to delivering long-lifetime operation. The health monitoring, in combination with digital twin modeling, can guide the operational strategy, provided it can be connected to single cells in a commercial stack.
- The project will provide excellent support to the DOE Hydrogen Program to achieve the Hydrogen Earthshot's $1/kg H_2 target.
- The stack characterization support provided and stack development tools established on this project are all important to the solid oxide community, but they seemed to be only a small fraction of the work performed.
- However, without a development/commercialization partner, much of PNNL's work performed to develop large-area-electrode-supported stacks may have limited impact.

Question 5: Proposed future work

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

- Problem-solving is necessary to secure stable stack operation, but introducing stamped metal components into a prototype stack design may create more issues, without contributing to a more attractive cell design that will interest industry. Key is that potential issues (such as shorting) are characterized and recognized early, so mitigation in the stack assembly process or in operation can be implemented in industry on proprietary stacks.
- The remaining challenges and technical barriers are clearly identified, and a suitable future work plan is outlined.
- PNNL is planning to continue the stack development work and build a 5 kW stack for demonstration testing at INL. Focusing on the core stack technology (sealing, current collection, shorting, etc.) that is making it difficult to build taller stacks might be better. Fixing these issues likely will improve performance and reduce degradation that is being observed in the stacks. Once these issues are resolved, building and demonstrating taller stacks might be warranted.

Project strengths:

- The wide scope of this project covers material, design, process, and modeling topics to resolve issues, with attention to details and input of data.

- The project centers around some important development at the single-cell and cell-stack level to support university researchers and industrial SOEC developers.
- A project strength is providing stack characterization support to industry and establishing stack development tools.

Project weaknesses:

- Developing an advanced prototype design seems to become the goal in itself, while this endeavor should carry commercial product development in its wake.
- The project is developing stack technology without a commercial partner to take it forward.

Recommendations for additions/deletions to project scope:

- The project should deliver workable solutions to problems known in industry, as well as methods to recognize these, as a key performance indicator to monitor project progress. Proposed advanced component developments may over-complicate any proprietary stack design that already has established production processes, causing more issues.
- The project should focus on improving performance and reducing degradation by addressing core stack technology issues (sealing, current collection, shorting, etc.) that have been encountered. The team might consider a smaller stack demonstration at INL so that more project resources can be devoted to the above.

Project #TA-044: System Demonstration for Supplying Clean, Reliable, and Affordable Electric Power to Data Centers Using Hydrogen Fuel

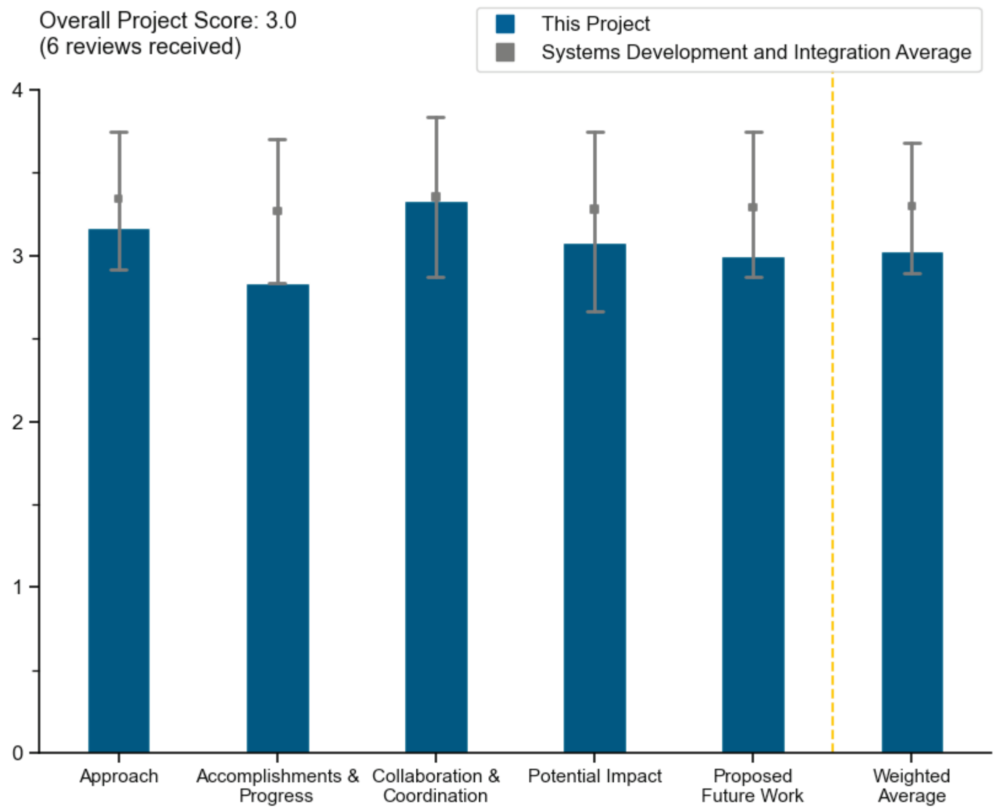
Paul Wang, Caterpillar Inc.

DOE Contract #	DE-EE0009252
Start and End Dates	10/1/2020–3/31/2024
Partners/Collaborators	National Renewable Energy Laboratory, Microsoft Corporation, McKinstry, Ballard Power, Linde plc
Barriers Addressed	• Scaling of proton exchange membrane fuel cells (multi-megawatt-scale) for data centers • Hydrogen sourcing, logistics, and environmental impacts • Performance and control for fast response and grid support • Liability coverage for large-scale hydrogen projects

Project Goal and Brief Summary

This project aims to conduct a first-of-its-kind demonstration of hydrogen-fueled backup power for a data center. The project team will scale a proton exchange membrane fuel cell (PEMFC) to megawatt scale. Performance targets include a full load rating of 1.5 MW and 48 hours of liquid hydrogen storage. All aspects of the complete power delivery system will be addressed, including (but not limited to) hydrogen production and delivery, site layout design, safety planning, component sizing, controls development, and permitting. The equipment will be installed, tested, and debugged, and data will be collected. Project completion will entail system decommissioning. This project supports the DOE goal of reducing greenhouse gas (GHG) emissions by heightening the viability and expanding the capabilities of a green fuel source, namely hydrogen.

Project Scoring



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 addressing what appears to be a viable near-term market for hydrogen energy storage. Critical control systems and power electronics are being addressed, as are hazards and siting requirements. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model provides conservative estimates of GHG savings, and savings are likely to be higher. The GREET model uses averages of published data for the grid that is already a few years old. The majority of new power added to the grid is renewable, and old fossil plants are being decommissioned. Likewise, GREET uses data for truck delivery, using data from current fleets (diesel), while future delivery fleets for hydrogen trucks are likely to be hydrogen-fueled. By the time fuel cell backup power generators are deployed, the grid and truck fleets will be greener than the GREET dataset indicates, and GHG savings will be greater than indicated. It is not clear how the project will determine system reliability, which is key for the backup power application.
- Installation and commissioning are planned for Fiscal Year (FY) 2023. Testing and debugging will also be performed. FY 2024 will be for data analysis and report writing. The plan is reasonable and can be accomplished.
- This is a straightforward project for demonstrating a stationary fuel cell for data center backup. The project seems to be doing well in overcoming some challenges, including identifying a new demonstration site. There is concern about the project timeline and how little time (one month) has been set aside for data collection and report writing at the end of the project. Ideally, there would be a somewhat longer period for data collection and analysis, and ideally testing during warmer/colder months, but it seems this is not possible with the project scope and budget.

- The approach involves making controllers and a system integration of fuel cell and battery components supplied by others. This is the first PEMFC development for a data center to date.
- The scope is clear: to implement PEMFC backup power, including batteries, at scale significant enough to be viable and transferable.
- Unfortunately, this project will not accomplish much as it is currently designed. The principal investigator states that the 1.5 MW PEMFC will not actually be connected to the data center. Instead, the electrical power will be sent to an onsite load bank. Additionally, the fuel cell will operate for only two months (slide 18). One can demonstrate that the PEMFC works at the factory, which one assumes has already been done for more than two months of operation. One can do a paper study and simulations to determine the appropriate size of the fuel cell system and hydrogen storage for this application. If the PEMFC system has never been operated with liquid hydrogen, then this will actually be a first-of-a-kind demonstration. It may also help Caterpillar get familiar with fuel cells. It is unclear what Microsoft really gains from this at all. Ideally, the PEMFC should be wired in parallel with the current power backup system (i.e., diesel gensets), which enables the PEMFC system to respond first, and if it does not (or it stops running), then the gensets activate.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- This project is well targeted toward DOE goals of validating fuel cell systems for various applications; data center backup is an interesting one. This project seems to be focused entirely on technical aspects, without much, if any, economic analysis, so there is a bit of a weakness in terms of addressing a larger suite of objectives and goals for DOE. However, the project appears to be on track, given a few challenges, including the demonstration site.
- The planning phase has been concluded successfully, awaiting successful factory acceptance testing of the fuel cell stacks. Their integration in the system will a be critical step to surmount, particularly when now operating at altitude.
- Validation testing on the fuel cell inverter has been accomplished. The team has laid out the plan building toward the demonstration. Site preparation has begun.
- There has been good progress, though with some delays due to supply chain issues. Fuel cell systems are in factory testing and expected to be shipped in July.
- There is a good deal of hardware in place, but the fuel cell from Ballard Power (Ballard) is late, so there has been no test of the system.
- It is unfortunate that it takes almost three years to install a fuel cell and battery energy storage system (BESS) in a behind-the-meter application. Since both the fuel cell and the batteries are containerized systems, one would expect the site design and prep work to be relatively straightforward. There is very little time allotted for the actual demonstration of the PEMFC system (two months), which is a major lost learning opportunity for the DOE Hydrogen Program. A major goal of doing a demonstration project should be to obtain real-world data.

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.

- This is a good project team that brings the technology provider/integrator with a major fuel cell manufacturer and the site host. Perhaps the project could be strengthened some with more of a third-party project evaluator, but this would appear to be challenging given the scope and timing, as the data collection and report writing phase is very compressed.
- The project team has industry leaders as partners in the project (e.g., Caterpillar, Ballard, National Renewable Energy Laboratory [NREL], McKinstry, and Linde).
- The project has managed to deal with changes in the backup power location, thanks to the competence of partners and frequent mutual interaction.

- The team is skilled and in good contact. The team is capitalizing on DOE inputs and resources.
- There is good collaboration amongst partners to date.
- It is not clear why NREL is the partner, rather than Argonne National Laboratory (ANL), since NREL's key contribution is using ANL's GREET model to assess GHG impact. Linde's and Ballard's contributions here are obvious and are good choices. It is not clear why a "supply of deionized water for fuel cell" is needed. The presenter was asked and did not know. Perhaps Ballard's PEMFC is not capable of operating in water balance.

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This is an important demonstration of hydrogen fuel cells and hydrogen storage operating as long-term energy storage/backup power. The project addresses an application in which reliability is essential and any outage is extremely expensive.
- This project can demonstrate the potential advantage of a PEMFC system as power backup, enabling fast start-up and dynamic operation, and generate data that allows further optimization between battery pack size and PEMFC power delivery capacity.
- Demonstration of showcasing the 1.5 backup genset will help push fuel cell adoption across the country.
- Success will provide practical knowledge of fuel cell technology. The short data collection period is a bit of a concern. Hopefully, it will be sufficient to generate key project findings and outcomes. As the project team has gone to all the trouble to install the system, it would be ideal to be able to test it over a wider time period, especially given the new project site, which has very disparate climate conditions throughout the year.
- The project, as it is currently designed, will have minimal impact. Additionally, it is not clear why a PEMFC and BESS system was selected for this data center application. Something like a redox flow battery (RFB) could be used as a long-duration energy storage solution. An RFB and BESS could enable black-start capability and could be used to reduce the data center's electricity costs as well—by cycling every day (i.e., to charge the RFB when electricity prices are low and discharge when they are high)—or to enable increased usage of onsite renewable power. The system that is (sort of) being demonstrated here is capable of doing nothing more than replacing diesel gensets.

Question 5: Proposed future work

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

- The project is entering its last year, and the remaining workplan seems reasonable.
- Demonstration of the unit is planned for this year.
- The fuel cell is being installed in the summer of 2023. The system should be testable, so next year should be boom or bust.
- Building and Testing will be the most critical phase of the project—but potentially the most time-consuming if risk mitigation is not considered sufficiently.
- Tests will be done with simulated power demands. It would be a better demonstration if the fuel cell test period was extended for longer time and actually powered the data center through outages or simulated outages.
- What is proposed is essentially just a two-month demonstration of the system, which will not even be connected to the data center. It is unclear what will be learned, other than that the PEMFC can operate on liquid hydrogen for this period. This project could potentially be far more valuable if the demonstration period is extended and the system is actually connected to the data center.

Project strengths:

- This is an interesting application for a fuel cell backup system. It is relatively novel compared to other systems such as a solid oxide fuel cell that typically operates continuously on natural gas. The partnership between the technology integrator and a major site host company is a strength, suggesting possible future commercial adoption.

- The project partners combine strong expertise in coherent fields. Upon successful delivery, multiple systems of similar configuration could be implemented elsewhere, making this a transferable blueprint.
- The project has a strong team with good engineering skills, and it uses well-established technology.
- A highly experienced provider of assured power systems (i.e., Caterpillar) is getting some experience with PEMFC systems.
- This project demonstration could help advance the commercialization of fuel cells.
- This is a good team of partners.

Project weaknesses:

- The very short data collection period is a bit concerning, but given the backup nature of the project use case, it may generate an appropriate amount of data. Some consideration of economics would be helpful. It is not clear whether any of that will be included. Clearly, a diesel generator backup would be less expensive (and in some jurisdictions will probably not be allowed in the future), but in a state like Wyoming (without strong air quality policies), it is unclear why a company would choose a much more expensive proton-exchange-membrane-based solution. Some consideration of this would be beneficial. Clarification is needed on what exactly the value proposition is for different parts of the country.
- This is not a very good application for a PEMFC and BESS system since it is simply a diesel genset replacement. A project budget of $12.5 million is much more than one would expect for just a 1 MW fuel cell demonstration and some analysis. The cost of a hydrogen-fueled 1 MW PEMFC system should be <$2 million. It is unclear if the cost of non-recurring engineering (i.e., product development work) at Ballard was also included here.
- The go/no-go decision follows the factory acceptance test of the stacks, and while the team is likely to pass, there is still a large risk of significant delay occurring with the actual system installation and commissioning on site.
- The scheduled test period in which the fuel cell will be running is quite short (~ one month).
- Component selection could have been better.

Recommendations for additions/deletions to project scope:

- To validate this application more fully, it is suggested that the project include a possible no-cost extension with data collection during both warmer and (especially) very cold periods to make sure the system can start up properly.
- The project team should consider extending the demonstration period and connecting the system to the data center. In any case, the team is asked to ensure that the PEMFC system is used by another DOE project after the decommissioning (e.g., at NREL’s Flat Iron site or some other site).
- The detailed hazard and operability study and risk analysis, including the operational strategy, could be reviewed more thoroughly in advance of the system sight acceptance test.
- The project needs to assess cost to justify replacing internal combustion engine generators.
- The time period for the demonstration should be extended.

Project #TA-045: Waterfront Maritime Hydrogen Demonstration Project

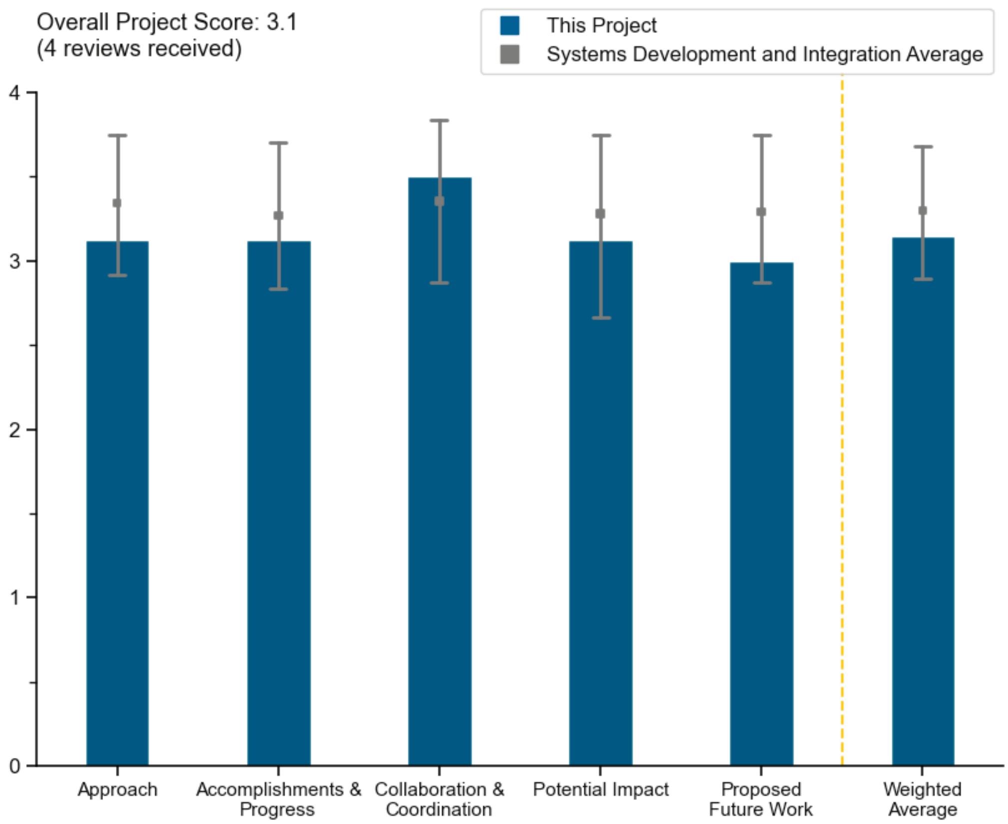
Narendra Pal, Hornblower Group

DOE Contract #	DE-EE0009251
Start and End Dates	10/1/2021–6/30/2025
Partners/Collaborators	Sandia National Laboratories, Port of San Francisco, Air Liquide, Bayotech, Inc., Nel Hydrogen US, Glosten, Moffett Nichol
Barriers Addressed	• Renewable hydrogen refueling infrastructure • Safety, codes and standards • Refueling protocol for vessel to vessel, vessel to land, and land to vessel • Techno-economic analysis data

Project Goal and Brief Summary

This project will establish a hydrogen production and distribution facility onboard a barge at the San Francisco Waterfront. The facility will be used to refuel hydrogen vessels with renewable hydrogen and recharge the batteries of diesel–electric hybrid vessels. This renewable hydrogen infrastructure will also support a land-based hydrogen network, creating an ecosystem of zero-emission mobility and resilience. This project will establish robust science-based protocols, procedures, operating parameters, and attendant training materials for the safe and routine generation and storage of electrolyzed hydrogen, creating a blueprint for optimally designing such a hydrogen barge and showcasing how the infrastructure can be replicated at other ports and similar locations across the United States. In addition, the demonstration will stimulate increased demand for hydrogen; advance the development of safety, codes, and standards for barge-based hydrogen technology; and promote the development of a hydrogen customer base along the San Francisco Waterfront, in the city of San Francisco, and in the greater Bay Area.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 overall plan looks good. The project is engaging partners in technology and permitting/codes in a novel application.
- The principal investigator (PI) and team have been working to develop pier-side infrastructure and develop fueling procedures at these locations. The team developed a piping and instrumentation diagram and drawings of the needed infrastructure and used simulations to understand refueling. The team has also assembled a test platform to test the refueling approach. The researchers worked with an existing code (National Fire Protection Association [NFPA] 2) and the U.S. Coast Guard to consider safety. The team did not perform a system hazards analysis and does not appear to have a plan to provide their insight/experience to others (e.g., whether the steps they took are sufficient to prevent accidents and ensure safety in the marine environment for others generally). System interfaces can be challenging to safety, and a strong safety culture is essential.
- The H_2 storage on the barge and current barge design seem to limit the system to fueling vessels with ~250 bar H_2 storage. A design that would enable filling both 350 bar and 700 bar H_2 storage would provide flexibility for future designs and vessels for which more H_2 storage is needed and would provide some insurance against becoming obsolete if high-pressure systems become the norm. Many trucks are now being designed with 700 bar tanks.
- The first two technical goals seem to be the main focus and are well thought out. The last three goals seem to be expected outcomes from a successful project rather than goals.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- The PI and team list four barriers: (1) developing a refueling infrastructure, (2) safety, codes, and standards, (3) refueling protocols, and (4) techno-economic analysis data. It appears that the project will have contributed meaningfully to demonstrating a refueling infrastructure and provide refueling protocols. The PI and team used an existing safety code and worked with the U.S. Coast Guard to address the state barrier, but it is unclear whether the effort is in this regard is really overcoming a barrier or sidestepping it (perhaps safety should not really ever be thought of, or described as, a barrier). It would be really helpful if the team could provide insight to others on what should be done to institute safety by design (some of this may be in a future milestone for the equipment, but the system as a whole should be analyzed). The work on the refueling protocols and refueling infrastructure appears to be innovative, if the team can secure an electrolyzer.
- There is good progress on process simulation for developing a refueling protocol.
- The planning and technical aspects of the project look to be on track to meet the timeline.
- Implementation of the fuel cell sub-system should be re-evaluated, given possible problems with the expected unit coming out of extended downtime.

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.

- Multiple collaborations are evident (e.g., with the U.S. Coast Guard, American Bureau of Shipping, Air Liquide, etc. on the refueling protocol). Collaboration will be key to the success of this project.
- Extensive collaboration and coordination were designed into the effort. The PI showed an organization chart and arranged the work with team leads from multiple institutions.
- Many different parties/stakeholders have been engaged, each with clear responsibilities and/or contributions.
- The project team has a good set of collaborators with the experience needed to meet the technical project goals.

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Creating/updating codes and protocols for H_2 fueling and infrastructure for portside operations/bunkering may be one of the most significant impacts, as it would extend beyond this specific project, easing the way for any future projects (DOE-sponsored or other). Data collection during operations will likely also be very useful.
- This project will serve as an introduction to having hydrogen fueling available for marine applications at a port and can pave the way for easier adoption.
- The PI indicates that the team created a blueprint for designing an H_2 production barge and worked through local regulatory approval. The researchers are trying to generate procedures for transfer, but that step remains incomplete. They indicate that another impact was to promote the development of a hydrogen ecosystem in the Bay Area. They did attend some conferences, but one would imagine that more would be needed to really develop an ecosystem. Attending conferences or meetings alone does not develop an ecosystem, leaving this aspect of impact indeterminate.
- The project would have higher impact if the barge could fill 350 and 700 bar storage tanks.

Question 5: Proposed future work

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

- The proposed upcoming work looks good.

- It appears that there is significant risk that the future work will not be accomplished because of inflationary pressures and because the electrolyzer is not in place. There is still regulatory risk, given that the U.S. Coast Guard has not approved the design basis. These risks are concerning.
- The schedule for future work seems appropriate. It appears the increased costs and lead times were identified as issues, but a path forward to address these issues was not identified.
- With the delay, using the fuel cell for providing electrical power as initially planned appears risky.

Project strengths:

- This project breaks new ground in extending H_2 production and delivery to a port/maritime environment and building up a basis in code/compliance. It appears the technical risks are well managed, as the system will integrate existing technologies for production and storage.
- The overall project strengths include the strength of the collaborators, the intent to work with the U.S. Coast Guard, and the modular refueling station. The initial drawings are compelling. The location of the barge site appears to be a plus.
- The technical aspects of this project are very good, and it appears that the team is knowledgeable in the needed areas to make it come together. Bringing a technology that is not commonly used to a well-established industry is not a small feat.
- The barge refueling concept has the advantages of a mobile refueler.

Project weaknesses:

- The justification for the fuel cell module should be expanded/clarified. From the materials, it was not clear what the benefits of including this would be, especially if a new unit is required (at ~$3 million additional cost, per the presentation). Clarification is needed on whether green power charging via shore connection satisfies the desired battery electric vehicle charging. It is not clear whether the fuel cell is needed to increase the peak power available for charging.
- The project does not appear to be developing safety, codes, and standards for refueling maritime hydrogen vessels, despite its being a stated project goal. There does not appear to be a plan to make that happen within the time remaining. It also appears that the team may not be able to complete the work within the agreed-upon budget, which is concerning. The plans for advancing an ecosystem appear to be limited to only meetings without other intentional contributions.
- Weaknesses include limitations with H_2 storage pressure and lack of ability to fill 700 bar storage tanks.
- Some of the non-technical goals identified either need to have planned tasks to show a path for achievement or should be changed to be potential outcomes instead.

Recommendations for additions/deletions to project scope:

- It was suggested that this technology would help to improve air quality in the port area, but it is not clear what the primary drivers of emissions are in a typical port or what it would take to make a real impact. It was suggested that a unit such as this could be moved from one port to another for "emergency support." The unit seems to require significant shore power connections. It is unclear in what scenarios that would be available and whether the H_2 barge would be needed.
- Some project scope may need to be deleted, perhaps along with some funds, because it is not clear that the team has the ability to develop a safety code or standard (much less codes and standards) within the schedule.
- Storage pressure should be increased, and/or the capability to fill 700 bar tanks should be added.
- Additional funding was identified as a need and should be addressed.

Project #TA-048: Advanced Research on Integrated Energy Systems (ARIES)/Flatirons Facility – Hydrogen System Capability Buildout

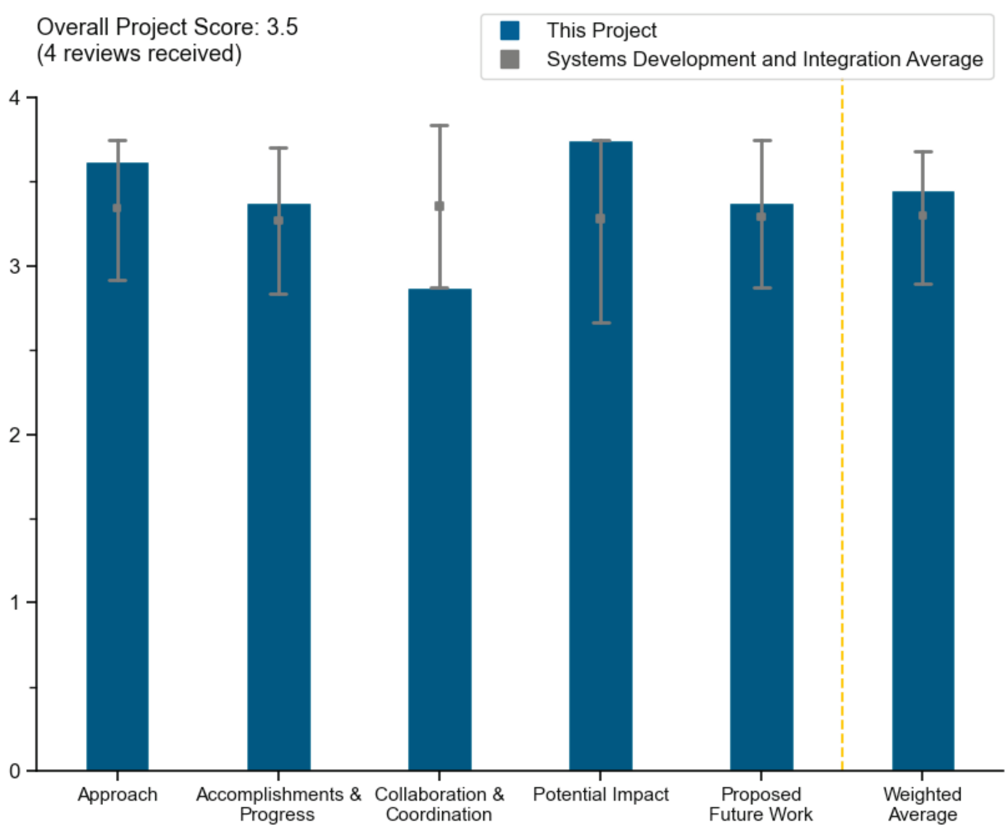
Daniel Leighton, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.9
Start and End Dates	5/6/2020–9/30/2022
Partners/Collaborators	Nel Hydrogen, Toyota North America
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 provide a testbed 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 Systems Development and Integration 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.

- Highly relevant to DOE H2@Scale, the project is well poised to take a critical look at key barriers to scaling up the use of hydrogen through demonstration and analysis of integrated production, connectivity, and use of technologies at megawatt hydrogen production scales. The project takes an exciting approach by developing a "core" technology demonstration, supportive infrastructure, and space for testbeds for emerging technologies that require demonstration at the megawatt scale, which may otherwise be challenging because of the high costs of approximate technologies (hydrogen production, water delivery, power delivery, etc.). Redundancy in the system is not clear, which may be a source of risk for companies and project teams considering the campus.
- It seems that industry could do these demonstrations. In some conversations that this reviewer has had, industry seemed interested in doing this type of demonstration and making their facilities available to others (including competitors) to try their technologies in the industry setup. The goals of demonstrating the power to hydrogen to storage and back seem similar, maybe even duplicative of other work, such as the Constellation (NE-002), Energy Harbor (NE-001), and Frontier Energy Inc. (TA-037) demonstrations. It seems that these projects could be made to be flexible, similar to what is being done at ARIES. The approach seems to be good for the stated targets. The project reported only the Hydrogen and Fuel Cell Technologies Office funds. ARIES is being supported by many DOE offices. The presentation really should have listed all of the DOE funds that have been and are being used to develop this portion of the ARIES facility. This is especially relevant since the presenters said that the electrolysis portion is being connected to other areas (wind, solar, and grid—and claiming to leverage those investments). The project is limited to one type of hydrogen generation: low-temperature electrolysis. The project lists no partners, which was surprising, given the industry interest in this area. The project would have benefited from an industrial advisory board.
- The project allows testing and integration of megawatt-scale renewable energy with a megawatt-scale electrolyzer, 20 MWh of hydrogen energy storage, and a megawatt-scale fuel cell at one site. Flexibility and ability to reconfigure to test different assets are important.
- This project represents an "execution" project that represents critical infrastructure for the national hydrogen roadmap.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- The project is currently building out the demonstration system. The integration of renewables, microgrid, compression, storage, and power generation appears to be well done. The research being done is not clear. It seems that the project involves building and operating systems. It is not clear whether loads will be simulated and whether validating some of the models for using hydrogen for long-duration energy storage will work with grid modernization. The lack of potable water is a concern but can be remedied. It would be beneficial for the team to reclaim the water generated from the project fuel cell for use in the electrolyzer, but this could result in concerns over the warrantees and/or agreements the project has in place with the electrolyzer original equipment manufacturers (OEMs).
- The scope of work is unclear, including equipment delivery, site build, and safety evaluations—aligning with the $0 DOE funding for Fiscal Year 2023. The project seems on track to be ready for operation and for accepting projects from other institutes, suggesting excellent progress.
- The infrastructure has been built and commissioned, equipment delivered, and sub-systems integrated.
- Safety evaluations have been completed.
- This project is almost complete and has met its goals of getting installed and commissioned. The project has successfully determined the next steps and will have a long line of users.

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.

- There are collaborations with Toyota, Nel Hydrogen, General Electric, and the Electric Power Research Institute (EPRI). Now that the system infrastructure is in place, collaborations will increase as the facility is used to test equipment from commercial entities.
- There seems to be industry interest. A major value would be collaboration with other DOE offices, such as the Wind Energy Technologies Office, Solar Energy Technologies Office, and Office of Electricity (for grid modernization). This was not addressed, other than the presenter saying the team is talking with those offices, and seems to be a gap. It is not clear whether the project is collaborating with any other national laboratory, which would be beneficial. Industry support seems to be in leasing equipment, but an industry advisory board was not mentioned.
- As noted in response to reviewers from the 2021 Annual Merit Review, the project is an installation project and does not include research. However, the presentation provided little to no information on how funded projects will be managed, particularly how data and privacy issues will be handled, and how multiple projects reliant on the same infrastructure will be coordinated to ensure adequate provision of utilities essential to the success of funded projects.
- Collaboration with OEMs is critical to getting the systems installed. However, future engagement should focus on and prioritize utility collaborations in the future.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The potential impact of the project is outstanding, as made evident by the number of cooperative research and development agreements (CRADAs) seeking use of the new campus for demonstrations. The 1 MW >50 kg scale is important, as it is large but not too large for prototyping emerging projects, such as novel uses of hydrogen or novel hydrogen storage.
- The project is developing a facility for industry to come and try out technology, with the future being dependent on industry paying to use it. With the hydrogen hubs and other demonstration projects, it seems that industry has the opportunity to do this themselves.
- The facility will allow for testing at commercial scales. The facility is important for conducting third-party validation of commercial products, testing integration of systems, and validating efficiency and performance.
- This is highly impactful infrastructure. There is extremely high interest in utilizing this facility, and it is suggested that DOE replicate it in every region.

Question 5: Proposed future work

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

- The proposed future work will fulfill the ultimate purpose of the installation project, introducing a critical new campus capability for DOE to test and demonstrate hydrogen production, storage, and fuel cell performance.
- This project is coming to a close, but the team has identified users and initial projects.
- Future work involves multiple CRADAs with industry.
- The project did not have a plan for how to work with other DOE offices, which seems to be a gap. More details on future funding to continue the development and the use of the site would be useful.

Project strengths:

- The project creates a capability that will support research and demonstrations critical to the lift-off of hydrogen through the inclusion of water, power, storage, production, and end use of hydrogen. The hybrid controller will provide not only a means of data collection but a means of monitoring.

- The project is well funded and has a good deal of stakeholder interest. The site has plenty of space to grow and has the potential for integration with other assets such as wind and solar.
- Strengths include flexibility and availability of all the components to demonstrate renewable energy production, energy conversion to chemical energy, long-term energy storage, and conversion from chemical to electrical energy.
- The work is very important, and the project has a good design for integration and future flexibility.

Project weaknesses:

- The project did not provide details on the approach used to handle wastewater from the deionized system. The project did not provide a baseline for projected costs, land use, energy, and utility needs or compare it with the ultimate cost and lessons learned during the course of the installation project. No details were provided on the power electronics and the potential need for refurbishment of purchased equipment necessary to stay "up to date" with developments in the hydrogen sector. For example, there was no explanation of how the coupling of the electrolyzers with wind and solar was determined.
- The lack of potable water is a concern. The continued support of the site was not well defined. This could be because those potential projects are considered business-sensitive and NREL could not release the information.
- It is hard to envision or build to every conceivable scenario. However, one weakness is that this facility does not include integration with a water/pipeline network to get a fuller picture of energy–water infrastructure.

Recommendations for additions/deletions to project scope:

- The team should discuss how they will work with other offices and how they can make the site available to other stakeholders, including other national laboratories, for use. The capability seems to be stovepiped, and while the presenter said the technology can be integrated with other assets at ARIES, it is not clear that such integration is being done. Further clarification is needed on asset integration and whether the assets will be tied into other grid modernization work. The team should consider a stakeholder advisory board.
- The team should work with EPRI to get expansions and replications funded under the Low-Carbon Resources Initiative.
- A hydrogen liquefaction capability and liquid hydrogen storage are recommended.
- A summary report of construction and installation cost and lessons learned would be valuable.

Project #TA-052: Solid Oxide Electrolysis Cells Integrated with Direct Reduced Iron Plants for Producing Green Steel

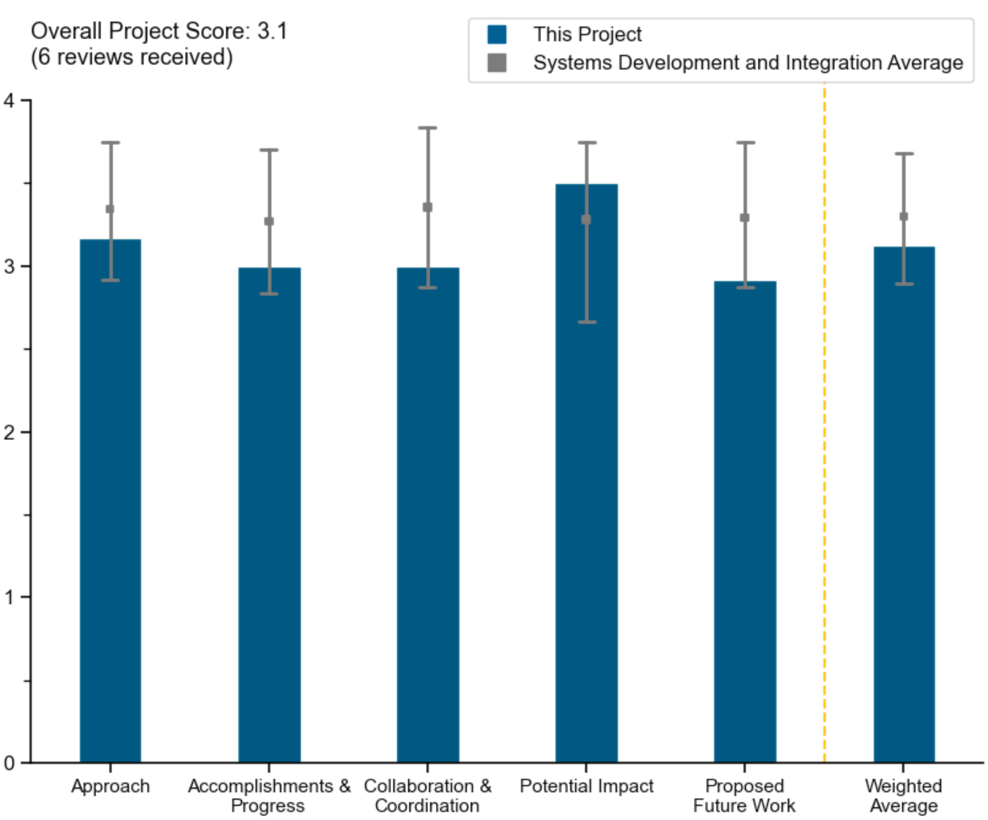
Jack Brouwer, University of California, Irvine

DOE Contract #	DE-EE0009249
Start and End Dates	3/10/2021–9/10/2024
Partners/Collaborators	FuelCell Energy, Versa Power Systems, Hatch Associates Consultants, Inc., Politecnico di Milano, Laboratorio Energia Ambiente Placenza, Southern California Gas Company
Barriers Addressed	• Capital costs • System efficiency and electricity cost • Renewable electricity generation integration

Project Goal and Brief Summary

The main goal of the project is to show the technical and—at scale—the economic feasibility of the thermal and process integration between a solid oxide electrolysis cell (SOEC) module and a direct reduced iron (DRI) furnace, paving the way for production of green steel. The SOEC system will be designed to produce enough hydrogen (>10 kg/day H_2) to supply a shaft furnace of an equivalent size of one ton per week of DRI product. The best-performing configuration will be scaled up via a feasibility design at a production capacity of 2 Mton/year of DRI. The project comprises the following phases: plant conceptualization and thermodynamic analysis, SOEC module sizing and nominal load design, testing in relevant conditions for DRI operation, design and commissioning of a DRI simulator, and techno-economic assessment of a full-scale system. The proposed hydrogen direct reduction system has the potential to reduce specific energy consumption up to 35% compared to conventional DRI and ensure the product specifications of a conventional DRI plant (metallization 96%).

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 objective of this system development and integration project is to validate the feasibility of integrating an SOEC system with a DRI plant for producing green steel. The challenges and barriers are clearly identified. The theoretical analyses and the proposed technical approaches are scientifically sound and convincing. The work plan is well-thought-out. It is likely that the team will be able to overcome the critical barriers and achieve project goals.
- The approach of this project involves several work packages on concept design, analysis, modeling, and experimental work. The approach is very effective for addressing the project objectives.
- The approach to the work is outstanding. The work packages made sense individually and as a whole.
- SOEC integration with a heat and steam source is very attractive because of the high efficiency. It is great to see some efforts on this front through both modeling and potential real prototype system deployment. Perhaps the team would consider the following comments/suggestions as ways to further strengthen modeling and experimental approaches:
    - The iron and steel market is large, but clear distinction should be made between virgin/recycled steel and respective market sizes since recycled steel does not require DRI.
    - Stack efficiency is attractive, but the stack efficiency will be dependent on actual system operating parameters, which can only be determined through a detailed system design. It would be beneficial to incorporate system efficiency beyond the SOEC stack and include the entire balance of system/ balance of plant needed to run the plant.
    - For additional funding, the team should be seeking industrial advisors to further strengthen the case and demonstrate early adoption of SOEC in the steel production market.
    - The team should create a clear plan for sulfur removal prior to steam injection into the stack.
    - There was a statement during the presentation that "electricity costs will be lowered," but the utilities and independent power producers are the ones controlling the costs. Deploying more renewables does not correlate to direct lower costs of electricity. The team should consider variable electricity costs depending on location and use ranges to conduct sensitivity analysis.
    - It would be beneficial to explain the electricity costs assumed for system modeling and the impact on the system efficiency if the DRI operation is variable such that the system cannot operate at target conditions. Detailed sensitivity analysis should be performed to truly understand optimal operating conditions and barriers.
    - It would be beneficial to provide a detailed sensitivity analysis for stack current density. The proposed stacks are running at moderately low current density of 0.5 A/cm^2, but FuelCell Energy stacks are capable of much more, according to recent presentations. It would be beneficial to demonstrate change in current density with increase in pressure when compared to atmospheric conditions to better understand efficiency improvements. Incorporating such sensitivity analysis into detailed plant design would be beneficial.
- The operation of the SOEC is certainly a critical item, but the project, as defined, has a much bigger scope. Other critical components that need attention include:
    - Evaluating a DRI shaft furnace using 100% hydrogen. It will behave much differently from an H_2/CO reduction gas. More effort needs to be spent on understanding the difference. This difference can greatly change the entire operating system.
    - Recovering heat and cleaning the exhaust gas for use. Much of the waste heat in steel mills is not recovered because it is extremely dirty. Future effort to find a filter is planned, but it will not be a small undertaking.
    - Investigating the longevity (i.e., mean time between failures) of the SOEC, material breakdown, and corrosion of extended high-temperature operation. If the SOEC is not a high-reliability item, it should be designed with many modules that are individually easily replaceable while the plant stays on line. Alternatively, a buffer needs to be built into the system that would allow the SOEC to be down for maintenance without taking down the remainder of the plant.

    - Designing or explaining the system for heating the reducing gas while simultaneously removing CO_2, O_2, etc. It is not a simple system, and the process heater used at the Nucor DRI plant in Los Angeles has had many failures that have taken the plant down many times.
    - Removing impurities, especially H_2S, in the tail gas. There needs to be a system for removing those impurities while still recovering the waste heat.
- The presentation lists capital costs, system efficiency, electricity costs, and integration with renewables as barriers. The principal investigator's (PI's) work contributes significantly to the first two of these. The arguments that somehow electricity costs will come down with additional renewables is uncertain. Once these electrical sources are priced onto the grid, they are sold at what the market will sustain (the gap is the profit margin or funding for the utility operator). The fact that the actual power output from renewable sources is substantially less than nameplate also leads to some questions regarding the long-term cost of renewables when incentives are retired. The project's integration with renewables thus far does not appear to be developed, other than indicating that this is a source of electricity. The assumption appears to be that the renewables provide steady electricity, which may not correspond to reality (a fine assumption if purchasing electricity solely off the grid, but then the first-pass benefit of renewable cost reductions vanishes).
    - Impurities were raised during the question portion of the review; this is a key question because the difference between first-pass design and final industrial design is often driven by the impurities and understanding where they go in the process. The PI and team would do well to focus more on the impurities in their process design to prevent costly redesign efforts upon implementation. The predictions of meeting cost or energy per mass may depend strongly on how impurities are handled.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- The team has indicated progress against two of the barriers. The strongest progress is the finding of 8.07 GJ/ton, which almost (but not quite) meets the 8 GJ/ton objective (there are still questions about impurities and water handling that may yet be influential). Additional progress is anticipated in future budget years. The PI and team are to be complimented for incorporating safety early in the design process by including a hazard and operability study.
- According to the technical accomplishments presented in the meeting, the team has demonstrated excellent progress toward the project objectives through measurable performance indicators. It seems that the project is on track to achieve its goals.
- Good progress has been made on the work overall, especially on the simulation side. The project had some initial delays and is behind schedule. The reviewer is confident that the work can be done within the extension granted.
- Excellent progress has been made in the design and analysis areas. Progress in solid oxide fuel cell testing is somewhat limited.
- The project goals could have been presented more clearly to assess progress.

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 PI has arranged to work with a number of partners or collaborators who serve in project-specific roles or as advisors. Some of these collaborators are prepared to move this project to the next stage. The specific inclusion of industrial partners is compelling.
- There are seven partners involved in this project. The role of each partner was not clearly presented, but it seems that the team functions well in performing various tasks and achieving some of the project objectives.
- Collaboration and coordination with other institutions/organizations is excellent.

- The work presented does show that the PI has established collaboration with most or all partners. Most likely owing to the limited time of the presentation, it was not very clear how engaged the partners really are. For example, slide 6 shows a desired DRI carbon between 0.3% and 0.8%; most of the industrial partners would recognize that the desired value is higher. Also, some of the gas compositions used for inlet of simulations seem a little off.
- It is not clear from the presentation that there is collaboration, other than having a large number of advisors on the board. The project seems to have concentrated on the SOEC, which is a major component of the system, but nobody has looked closely at other components of the system. The advisors have a good deal of experience in these areas, and this presentation does not demonstrate the advisors have been involved. In addition, there are no operational DRI shaft furnaces that use 100% hydrogen. They would operate differently from the standard shaft furnace. The modeled shaft furnace with CO and H_2 is set up to produce typical top gas, but it does not appear as though the DRI furnace modeling using 100% was reviewed by advisor partners.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project describes very well the market and potential of this integration between SOEC and direct reduction. If feasible, combining the two technologies will have a tremendous impact on the energy requirements to make steel by avoiding quenching–reheating cycles currently used with all technologies. This will be a game changer in energy demand—and thus in CO_2 and other emissions.
- Integrating an SOEC using waste heat to create hydrogen and targeting the iron reduction process are hitting a major target for reducing CO_2 emissions.
- The PI and team indicate that reducing CO_2 usage in the production of iron and steel is important to administration goals of reducing CO_2 generally. It is good that the project team recognizes that some carbon is essential to the production of steel, such that all carbon cannot be removed from these processes. Identifying pathways to reduce the cost to or below 8 GJ/ton bodes well for significant potential impact, recognizing that additional refinements may be needed, given that water treatment was not considered.
- This demonstration of an SOEC integrated with a DRI plant represents an interesting and important application of SOEC technology. This is well aligned with the Hydrogen Program and DOE research, development, and demonstration (RD&D) objectives. Thus, the success of this demonstration project has the potential to advance progress toward DOE RD&D goals and objectives.
- This project will contribute to the assessment and possible demonstration of the use of solid oxide electrolyzers integrated with DRI plants for clean steel production.

Question 5: Proposed future work

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

- The PI and team have a clear list of steps they will take to complete design and thermal integration. These steps build on the work completed through the current budget period. These future steps will contribute toward two of the barriers indicated. The PI and team do not appear to have a plan to integrate renewables other than from a grid source. This may be advantageous because the folks operating the grid then have to address problems with intermittency, but it does leave the PI without a compelling argument for decreasing cost due to the integration of renewables. It is unclear that integration with renewables should mean simply plugging into the grid and then operating at steady state.
- The proposed work as described is adequate, considering this is only the first review. There is much to be done on the stack side. The modeling of the DRI reactor could be improved, but overall, the accuracy of the model is not critical to the success of this project. Addressing potential issues such as contamination (e.g., particulates or chemical, like sulfur) is a much higher priority.
- The proposed future work is logical and reasonable for addressing the remaining challenges and barriers. However, it seems that many difficult tasks to achieve the project goals are still ahead.
- Perhaps there is a more detailed plan, beyond what was presented. A DRI pilot plant is a huge undertaking, and planning is not apparent in this presentation. There are many components that need to be designed/

detailed. This presentation does not list all the major sections, let alone how it plans to design or procure them. From this presentation, the project seems to lack detailed planning.

- Proposed future work lacks detailed schedules, especially completion dates.

Project strengths:

- First and foremost, this project is attempting to advance the understanding of integrating two technologies to improve the efficiency of ironmaking. If successful, this will be a game changer. The approach chosen is very sound. The PI's approach of simulating the direct reduction furnace, rather than attempting to make DRI, is commended. This is a much better approach and will avoid the many distractions of operating a small DRI pilot plant.
- A project strength is the thermal integration and the use of SOEC hydrogen direct reduction. The range of collaborators, from academic to industrial partners, is also a strength. The consideration of safety in the design phases is also a strength.
- The use of SOEC using clean waste heat is a good way to create hydrogen. The use of hydrogen to reduce iron ore will make the biggest impact in reducing CO_2 emissions in the steelmaking process.
- This demonstration project represents a unique opportunity for SOEC technology.
- The project's main strength is the design, analysis, and modeling of systems that integrate solid oxide electrolyzers with DRI plants.

Project weaknesses:

- The reviewer is not certain that a DRI shaft furnace reactor has been operationally demonstrated with 100% hydrogen reducing gas anywhere in the world. Without CO, the system will be fully endothermic. It will also have a H_2O/H_2 equilibrium reaction line that decreases as the operating temperature drops, which will slow or stop the reaction. The modeling of the shaft furnace is very complicated and will likely not operate the same way as the standard CO/H_2 furnaces. The presentation makes it appear that the shaft furnace has been modeled as a simplified block; in reality, the whole system is very complicated and completely different. In addition, the pellets contain sulfide impurities FeS and SO_2. The hydrogen picks up a percentage of the sulfide in the form of H_2S. When the tail gas from the shaft furnace is reused, these sulfides will need to be removed to prevent damaging the SOEC, or the SOEC will need to be hardened against sulfide corrosion. Other impurities such as phosphides and chlorides exist in the DRI, and trace amounts may come out in the top gas.
- The project weaknesses include the limited integration of renewables and the assumption that somehow electricity prices from renewables will go down when the system is connected to the grid.
- While some interesting progress has been made, it seems that many difficult tasks are yet to be performed.
- The main weakness of the project is an unbalanced focus on experimental work (stack testing and operation under relevant conditions).

Recommendations for additions/deletions to project scope:

- The following bullets discuss recommendations:
    - High-temperature fuel cells are generally known to have longevity issues, material failures, and corrosion due to the high temperatures. It may be useful to put effort toward determining life of the fuel cells (including long-term testing) or defining acceptable mean time between failures, as well as showing data or testing to show the fuel cells will meet life expectancy.
    - The team should consult with Midrex and/or Tenova on modeling the shaft furnace using 100% hydrogen.
    - Co-electrolysis should be used to reduce CO_2 to CO. The CO can be used in the DRI furnace to mimic existing technology. The new technology to demonstrate is the SOEC making hydrogen using waste heat from the DRI furnace. The suggestion is to keep it simple to provide a higher probability of success for the project.

  - The Nucor DRI plant in Los Angeles has been plagued by breakdown issues. A “lessons learned” is available and should be reviewed. It is believed that 90% of the failures occurred in material-handling equipment and the process gas heater. The material-handling equipment failures are likely scale-up issues, but the reducing gas heating system is something that should be looked at closely during the next stage.
  - It is recognized the recirculation gas needs to be cleaned, but no method of cleaning was suggested. Dirty gas is what prevents the steel industry from using waste heat in general.
  - The project should look into the impacts of carrying impurities such as sulfides, chlorides, and phosphides from the DRI back to the SOEC, with sulfides in the form of H_2S as a very high probability, as well as trace amounts of the other two impurities. The team should look into removing these impurities at high temperature or finding some way to recover and reuse the waste heat and clean the gas at low temperature.
- Since the PI and team have limited consideration of renewables directly, perhaps it would be better to delete this aspect from the scope so that the team can continue to focus on aspects of the work where they really excel. The PI and team are also encouraged to take additional steps to incorporate safety by design in their approaches to both steady operations and start-up.
- The project should proceed with the work as described; no changes are needed.

Project #TA-053: Grid-Interactive Steelmaking with Hydrogen (GISH)

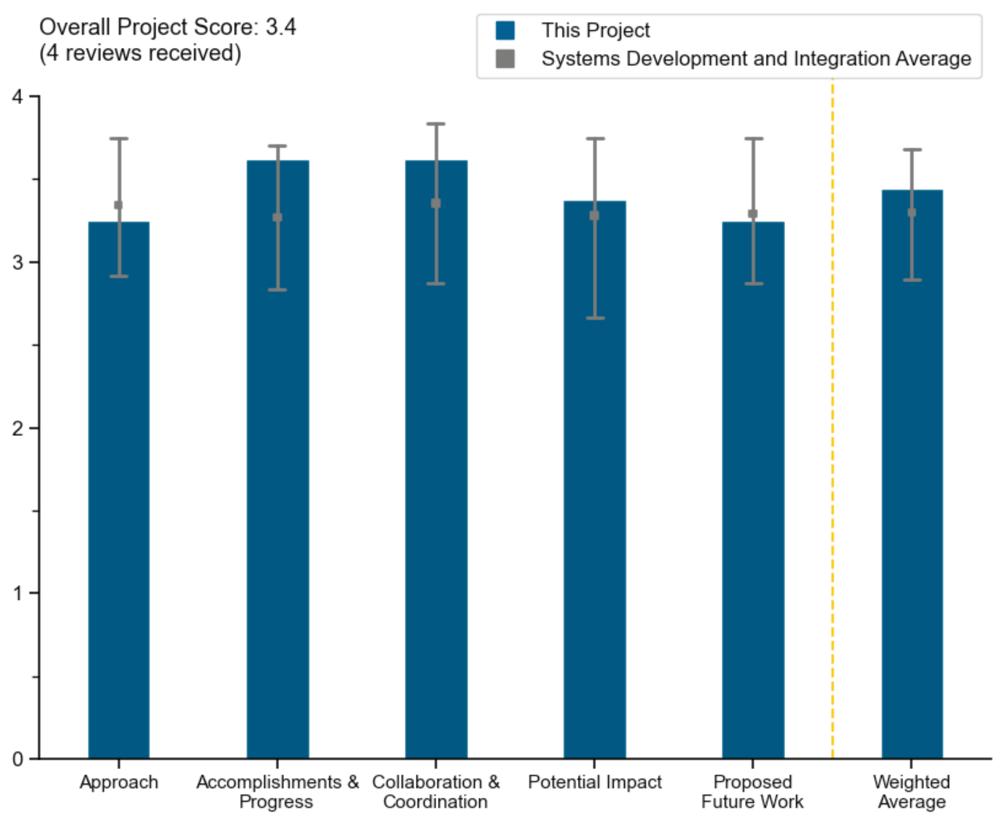
Ronald O'Malley, Missouri University of Science and Technology

DOE Contract #	DE-EE0009250
Start and End Dates	10/1/2020–4/30/2024
Partners/Collaborators	Arizona State University, National Renewable Energy Laboratory, Danieli USA, Cleveland Cliffs, Nucor, Steel Dynamics, Gerdau, Linde plc, Air Liquide
Barriers Addressed	• Rising materials and manpower costs • Materials and construction delays • Gas preheater design start-up issues • Hydrogen safety approvals

Project Goal and Brief Summary

This project aims to de-risk industrial investment in infrastructure for hydrogen-based direct reduction of iron and steelmaking in an electric arc furnace (EAF) by closing critical knowledge gaps in the current research, development, and deployment landscape. The project includes four main activities: (1) documenting the effects of mixed hydrogen and natural gas reduction kinetics for iron oxide and use of plasma to enhance reduction rates; (2) modeling scale-up of an innovative direct reduction pilot reactor to production scale, capturing the characteristics of the materials flow and the thermal profile; (3) developing models for EAF operation with variable carbon-based and carbon-free feedstocks; and (4) conducting a techno-economic assessment (TEA) to quantify the economic opportunity of the project steelmaking process. These efforts have the potential to incentivize the use of clean hydrogen in one of the nation's most CO_2-emissions-intensive industries, expanding hydrogen demand and thereby decreasing costs.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 principal investigator (PI) and team are pursuing two key objectives: (1) to develop a scalable model for mixed hydrogen/natural gas reduction and (2) to demonstrate feasibility of carbon-free direct reduced iron (DRI) processability in the EAF. The scalable model includes both mathematical modeling and physical experiments at pilot scale. These pilot-scale experiments are important because they advance the field with actual data and test assumptions. Two campaigns were completed, and the preheater was re-positioned as a result.
    - The barriers that the team addressed appear to be project barriers instead of barriers to the field. Safety should not be seen as a barrier. The PI and team are to be complimented for engaging the hydrogen safety panel early and on continued engagement.
- This is a good approach to a wide, complex problem. The project attempts to address many of the aspects related to ironmaking with hydrogen, including reduction and melting. This is a big task. The work has been broken down into reasonable work packages performed by different entities.
- This type of project is highly relevant to DOE H2@Scale. The project is well poised to take a critical look at key barriers to scaling up the use of hydrogen in steel, including validation of steel product quality, design and optimization of DRI and EAF based on hydrogen and natural gas feedstock provision, and correlation to pellet characteristics. The project takes an excellent approach that combines process modeling, kinetic modeling, lab-scale and pilot-scale experiments and product characterization, and industrial feedback. However, there was no coordination with other relevant efforts funded by DOE.
- The project has been designed in step-wise fashion, from analytical modeling to laboratory bench test, to pilot plant and comparing data, and then to field trials. There are many variables on a full EAF, and it is difficult to interpret the field trial data to determine success. The bench test reactors will be able to control the variables to better compare and confirm analytical models. All of this is good. The projects do not address the largest barrier to high hydrogen DRI adoption, which is the high cost of using DRI due to more slag, higher yield loss, extra heating, etc., whether it is hydrogen-reduced or not.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- The team has made outstanding progress on several challenging key milestones, including safety and go/no-go targets, despite material cost and delivery delay barriers. Key accomplishments include pilot reactor continuous operation, improved performance of H_2 preheating, 5% agreement of the reactor model and the pilot, initial results of a combined TEA and life cycle assessment (LCA), and new insights on energy consumption and safety.
- The PI and team have a solid plan that lays out specific accomplishments. The pilot-scale work is impressive and an important step in advancing from model to production. The combination of pilot-scale experiments and modeling is compelling. The approach allows for a more sophisticated advance toward scale-up by using process modeling rather than simple correlations that often use diameter as the primary basis.
- Multiple milestones have been set up to show progress. There seems to be excellent project management of these milestones. The past few years have been plagued with delivery issues, and the teams appear to be reacting to them as best as can be expected.
- Accomplishments to date have been very good, considering the global situation and the amount of work to be done. For example, getting the hydrogen safety review done and signed off is very commendable, as this is not a minor task. Having been able to perform two test campaigns in this timeframe is also noted.

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 work presented clearly demonstrates good collaboration and synchronization between some of the engaged parties. Slide 17 delineated the roles of the various entities, which was appreciated. There are many parties involved in this project (including competitors), and getting them to collaborate on this project is remarkable.
- The PI and team have a well-structured collaboration, with each team member sustaining particular responsibilities. The team includes industrial partners, including steel producers and gas suppliers, from each of the major aspects of the project.
- The collaboration between partners is clear cut and readily apparent. Multiple partners have been assigned portions of the project and are making progress on their specified goals.
- It is not clear how the partners collaborate with each other, but it does seem that there is adequate data-sharing and communication, at least on the melting experiments and kinetic modeling tasks. Clarification is needed on how the National Renewable Energy Laboratory (NREL) TEA/LCA modeling team is coordinating with the experimentalists to update and validate system-level process design and simulations. It is unclear who developed the reactor model and COMSOL models and how they are being integrated into facility-scale process designs and models for the TEA. Involvement of students, particularly underrepresented students, was not clearly described, making it hard to evaluate the diversity, equity, and inclusion aspects of the project. The approach for data exchange and coordination between team members was not clearly described.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The impact of hydrogen in ironmaking is immense—this is potentially the first new way to make steel since the iron age began. The project was rated in the context of other existing work on hydrogen reduction and melting. There are other institutions, especially in Europe, working on similar topics. The impact of each individual project will be somewhat difficult to evaluate, but all are very valuable, both on their own and in collaboration with one another. This is a big task.
- The project is relevant to DOE goals for deep decarbonization. The pilot-scale work adds significant impact.
- The approach and progress made are outstanding and directly address the barriers noted in the project overview.
- The largest amount of CO_2 produced in the steelmaking process is reducing iron ore to iron. Using hydrogen to reduce the iron ore can significantly reduce the CO_2 emissions in the steelmaking process. This project targets DRI pellet reduction of iron ore and is therefore well aligned with the DOE targets. The goals involve attempting to establish the usefulness of the carbon content in the pellets. The project is establishing the melting point of the pellets versus carbon content. There are other considerations to establish an optimum amount of carbon in the pellets for the overall benefit of the full load. This presentation has created a predictive model for melting point versus carbon but does not appear to address carbon optimization. The target metallization that plasma can be expected to produce is >89%, yet the industry consistently produces DRI at 92% to 96% metallization. This would appear to be a negative toward the plasma reduction. Some of the main barriers for steel mills using large percentages of DRI are cost related to gangue and yield loss to the slag when using DRI, and this presentation does not appear to address those barriers.

Question 5: Proposed future work

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

- The PI indicates four barriers: (1) rising costs, (2) construction delays, (3) gas preheater designs, and (4) hydrogen safety approvals. These barriers are project-specific and not necessarily the more global barriers. More globally, the PI and team appear to be tackling barriers to hydrogen/natural gas reduction and a carbon-free DRI process. In both senses, the future work outlined is appropriate and relevant.

- The proposed future work is aligned with the goals as defined. The plant trials are useful but will require a large number of heats to see a trend in data to determine success.
- The presenter notes the budget and timeline have been reworked. Clarification is needed as to whether April 30, 2024, is the new or old end date. If it is the new deadline, that is less than a year to complete a very large set of remaining tasks. The team will need to be very focused and coordinated to complete the scope of work.

Project strengths:

- This project targets the use of hydrogen in reducing iron ore. This is the highest CO_2 generation portion of the steelmaking process and can have a large impact on CO_2 generation in the steelmaking process. The project seems to be well organized in what it is going to do; project management is readily apparent. The project appears to be shared between partners, and roles are well defined. A number of the project objectives are of great interest to the industry.
- A wealth of experimental data is being generated, as well as knowledge gained from feedback from industry partners. Having data on the kinetics of reduction would go a long way toward addressing key process modeling and simulation uncertainties for the DRI. Similarly, linking DRI and EAF operation to feedstock, byproduct, and product properties is critical data to validate process models ultimately used to predict necessary hydrogen prices for industry lift-off.
- Strengths include the topic of ironmaking with hydrogen, the approach chosen by the project leads, and the different work packages that lead to building and (safely) operating a hydrogen furnace.
- The strengths of the project are the pilot-scale work that couples with modeling, the strong project team, the steady leadership of the PI, and the early engagement of safety expertise.

Project weaknesses:

- The various objectives do not appear to be tied together well. One objective is to model hydrogen/natural gas kinetics for reducing iron, with emphasis on high hydrogen. Another objective appears to try to overcome the weakness of carbonless reduction by modeling carbon content of DRI versus melting temperatures. Another objective uses plasma to reduce DRI. A fourth objective uses a TEA, but it is not clear which of the objectives will be used—whether all at one shot or each objective with an individual TEA. Any one of the projects could stand on its own, but as a group, they are hard to tie together. In addition, the major cost of using DRI is the additional cost related to the gangue. More slag is required to balance out the gangue, more heat is required to heat the additional slag, and yield loss occurs due to greater FeO lost to the additional slag. These listed cost issues are not part of this project, and as such, the TEA of using DRI is not truly complete.
- It is difficult to evaluate how industry partners are engaged and their level of participation. The presentation did not discuss translation of industry knowledge and experimental data to bound parameters used in mathematical modeling and process modeling software (such as ASPEN). Clarification is needed as to whether NREL developed its own DRI and EAF models for the TEA or is leveraging models developed in other funded projects. Integration of the hydrogen delivery system to the DRI and steel facility was not described, making it difficult to know whether the project will provide insights for hydrogen production delivery and storage. Overall, the presentation did not include enough background information or context for preliminary results to be translated into guidance for future research and development, particularly on the key sensitivities affecting decision-making.
- The overall project weakness is that the barriers to the field that this project overcomes were not clearly articulated. Perhaps it is the inclusion of plasma that makes the project truly unique, as others have been working on DRI-based plant design. However, the advancement to pilot scale is compelling.

Recommendations for additions/deletions to project scope:

- The TEA predicts a steel product cost of $583/t levelized cost of steel for 30% H_2 usage, while the Lawrence Berkeley National Laboratory team presented $584/t for 100% H_2 usage from the lab call project on hydrogen storage for steel facilities. Adding a cross-project comparison to ensure updated system-level design assumptions across DOE-funded projects would be an impactful way to guide LCA and TEA in this sector. Additional work to summarize key findings into guidance on pilot- and facility-scale design and CO/H_2 ratios would be beneficial. Much of the cost is due to feedstock. Perhaps there are opportunities to lower this cost—or perhaps it would be helpful to know how pretreatment of pellets affects DRI and EAF design considerations and performance.
- There are multiple cost barriers to using DRI in an EAF. Some consideration/acknowledgement should be given to what those other costs are and how hydrogen reduction may affect those other costs.

Project #TA-056: Ultra-Efficient Long-Haul Hydrogen Fuel Cell Tractor

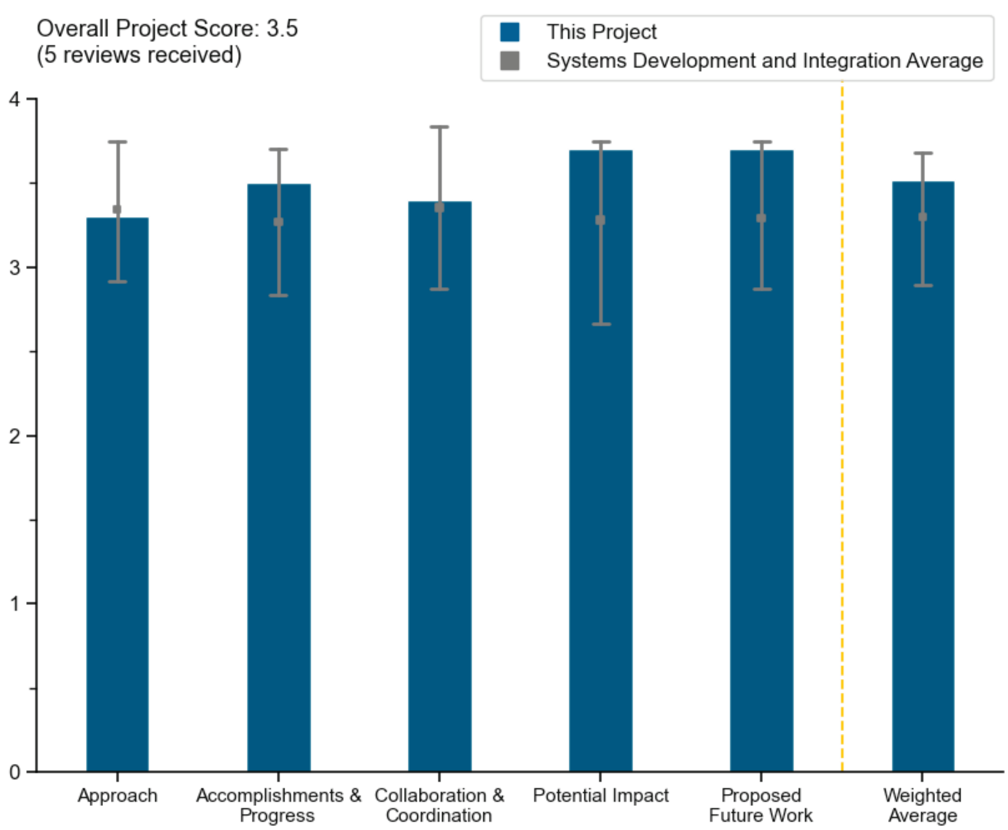
Darek Villeneuve, Daimler Trucks North America

DOE Contract #	DE-EE0009860
Start and End Dates	5/1/2022–4/30/2027
Partners/Collaborators	Linde plc, Michelin, MAHLE Behr, MAHLE Filter Systems, Auburn University, Oregon State University, Oak Ridge National Laboratory, National Renewable Energy Laboratory, Argonne National Laboratory, Schneider National, Walmart
Barriers Addressed	• Vehicle performance • Reduced carbon intensity of fuels • Maximized freight system performance

Project Goal and Brief Summary

Daimler Truck aims to demonstrate a substantial reduction (75% or greater) in greenhouse gas emissions and local pollutants from truck transportation while remaining economically viable and scalable. The project involves developing, building, and testing a Class 8 hydrogen fuel cell truck with specific targets for vehicle performance (6.0 miles/kg hydrogen over long-haul drive cycles, 600-mile range, equivalent payload to baseline diesel tractor–trailer, and analytical pathways to a 25,000-hour lifetime), carbon intensity reduction in fuel production, and maximized freight system efficiency. The project will address the challenge of decarbonizing heavy-duty transport and enabling hydrogen applications at scale. Accomplishments include defining the main design path, developing powertrain concepts, improving tire performance, and establishing a hydrogen supply plan, with future work focused on optimization, validation, and demonstration.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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.

- Daimler Truck has a clear approach to the work. The project's simulation of the fuel cell electric vehicle powertrain prior to build, including the safety plan, is quite difficult. The go/no-go decision is logical. The 700 bar tanks will de-risk the first demonstration and validate the simulations. The power battery also makes sense, but more details would be helpful. The potential to test liquid hydrogen (LH2) tanks is very exciting.
- The project is broken into budget periods with clear deliverables for each one and a go/no-go assessment at the end of each period. The B-sample initial vehicle build supports this very well by getting initial data/ results into the project at an earlier stage than would be possible with a single vehicle design.
- Barriers such as packaging, powertrain configuration, and market acceptance are well identified and addressed, but cooling and durability barriers are identified but not completely addressed. The assumption is that the project plans to address the barriers in coming years. The project should provide more details on cooling optimization. For example, the presenter mentioned that the minimum area of cooling system was to be determined. High-level details on the thermal circuit are needed.
- The approach involves building a beta truck and analyzing it and testing it, then designing the final truck and building it and validating it. The targets are best-in-class total cost of ownership (TCO), Baker-grade climb, and 11-hour run time at 65+ mph. However, the project does not provide a great deal of detail on how the approach will be implemented.
- The project has a solid approach, with a diverse and capable team.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The vehicle packaging looks straightforward and is sufficient for modeling before doing the full truck build. The selection for specialized tires, including steer tire optimization, is interesting. The development of simulations and full high desert proving ground inspires confidence that the hardware will work and move the field closer to commercialization. Thermal management was partially explained and looks useful. The Portland route and reference to past SuperTruck projects appear logical and look like good progress toward DOE goals. Just one or two pages of accomplishments would not show much effort, but the full overview of routes to cooling optimization and efficiency based on real-world routes all show significant groundwork for a successful project. The final review of initial safety work hits all the right areas, from the safety plan, to safety upgrades for facilities, to on-vehicle best practices for safety management.
- The project reports one budget period and 18% total complete. From the presentation, it appears that the groundwork is well laid to build the B-sample vehicle and start to validate the model results this year. Cycles of optimization in Budget Period 2 appear to be a key element.
- The project chose tires and provided a good rationale. The project also chose truck capabilities. The fuel cell will be 300 kW, and the battery is 100 kWh and 450 kW peak. Otherwise, the actual progress was only very generally described. The selection of the fuel cell and battery were drawn out only through questions. The need to protect proprietary information is understood, but this presentation was vague well beyond those of others in the industry.
- In powertrain optimization, the project mentioned increasing efficiency by operating at reduced power. It is not clear which driving scenarios are taken into consideration. It is not clear what Route 1 and Route 2 in the graphs are. It is not clear how 20% efficiency is achieved in Route 1 as compared to Route 2, which is 8%. It is unclear how reduced cooling is achieved. The project could consider making more progress on safety in coming years, as this is the top-priority topic. Design review at 30% is good progress, considering a start date of May 2022.
- The project is in early stages, but the plan seems to track closely with DOE goals and objectives.

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 great integration of partners. Michelin provided good input on steer tires. MAHLE worked on critical aspects of cooling and drivetrain needs. It was good to see analytics from the National Renewable Energy Laboratory and Oak Ridge National Laboratory, as well as workforce development through work with Oregon State University. The project is going beyond analysis with benchmarking parts with analysis partners. The work with Argonne National Laboratory (ANL) highlights the development of power batteries and cycles required for a successful fuel cell truck TCO. Finally, Linde will provide a compressed gas fueling trailer for testing.
- The work with Michelin on tires was the collaboration that was really discussed in detail in the presentation. It would be helpful to highlight modeling and analysis work. Much of this work was done with collaboration partners (national laboratories and universities), and this work can have a broad impact in supporting industry work on freight transportation. Those collaborations are listed in the summary slide but were not highlighted during the presentation.
- The project team is comprehensive and comprises leaders from industry, government, and academia.
- The project has good collaboration with partner participation that is well-coordinated.
- The project's partners include a truck maker and a truck buyer. It seems like they are probably offering valuable perspective, but it is not clear yet.

Question 4: Potential impact

This project was rated **3.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- A successful demonstration will really prove the capability toward fuel cells for heavy-duty long-haul trucking. The LH2 storage aspect for later in the project will be critical to working toward parity with diesel trucks at nearly 2,000 miles of range. The level of technical effort, engineering, and comprehensive partner engagement show that this effort will have a very high chance for success and will be incredibly relevant to DOE decarbonization goals and the use of hydrogen trucking.
- Assuming it achieves the stated targets, this project's impact will be great. A 600-mile range Class 8 truck with 6 miles per kilogram and diesel-equivalent performance would enable the heavy-duty market if the price is suitable. This is a market that would otherwise be hard to decarbonize.
- Reducing greenhouse gas and emissions in freight transport by 75% is an extremely important goal for the industry. If this can be done with TCO parity, it will have dramatic impact.
- The project supports good progress on LH2 in the future and also plans to study market strategy, TCO, and infrastructure.
- The project is very relevant to energy storage, including the use of LH2.

Question 5: Proposed future work

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

- The technical practicality of vehicle fueling with sub-cooled LH2 is not a sure thing, so the reviewer will watch this project over the next couple of years to see if it can be achieved. Hopefully, this area can be highlighted in future project updates. It would be pragmatic to have a backup plan so that unforeseen issues/delays do not delay the rest of the project. That said, the project plan over the next four budget periods appears to be well developed and sound.
- The future work to finalize the packaging is key to the final sizing of components. Cooling is an important challenge for these large 300 kW fuel cells with limited airflow. Durability is a key for these million-mile truck challenges, and the drive-cycle hybridization with the power-focused battery is critical. The close work with ANL will be important to showing market viability and the need for low-cost infrastructure.
- The project's progression to LH2 is really interesting and should offer many lessons learned to DOE collaborators.

- The remaining challenges are clearly defined with good planning. This is well done, with praise to the project team.
- The project offers very high-level future work only, essentially building, testing, and then redesigning for the final design.

Project strengths:

- The main strengths of this project are the background knowledge of Daimler with Freightliner, in-house proof testing of components, and the long history with compressed hydrogen and recent research and development (R&D) efforts with cryogenic storage.
- The project team is evaluating many things in a holistic approach. The project is very sound, and the reviewer looks forward to the results of the next phase.
- The project has a well-developed execution plan, and it appears that resources are in place to run the plan successfully.
- Powertrain optimization is a project strength. A more critical strength is achieving >600-mile range on a single fill-up.
- The project has a strong team with excellent, high-level goals.

Project weaknesses:

- It would be helpful to see more details about the output metrics that are expected of the B-sample phases and how they will work as input to the final demonstrator phase. Also, while the end-goal metrics (fuel consumption, range, payload, TCO, durability) are stated at a high level, it would be helpful to understand how the project will define success or next steps at the end of the project, as the results of those metrics will likely fall along a range and not all be 100%.
- The project has almost no data on methods or progress (aside from excellent readout on tires), so it is very hard to say whether needed progress is being made.
- Subcooled LH2 is a new technology, so there could be unknowns and unforeseen challenges. The project's safety needs more attention.
- It is not clear that targeting a 600-mile range offers a viable alternative for diesel Class 8 trucks.
- The project has no weaknesses at this time.

Recommendations for additions/deletions to project scope:

- Tire designs and compounds are important in electrified platforms, but perhaps this effort could track closer to DOE hydrogen goals by allocating tire R&D money to fuel cell systems. It is suggested that the project study sleeper cab noise, harshness, and vibration characteristics of the fuel-cell-powered system against traditional diesel powertrains.
- As much as feasible, it would be good to have a pathway to LH2 storage demonstration within this project. The infrastructure will be a lower cost and enable further flexibility in fuel cell cooling with a longer range.
- No changes are recommended. The scope is appropriate for the goals stated.
- There are no recommendations for additions or deletions to project scope.

Project #TA-057: High-Efficiency Fuel Cell Application for Medium-Duty Truck Vocations

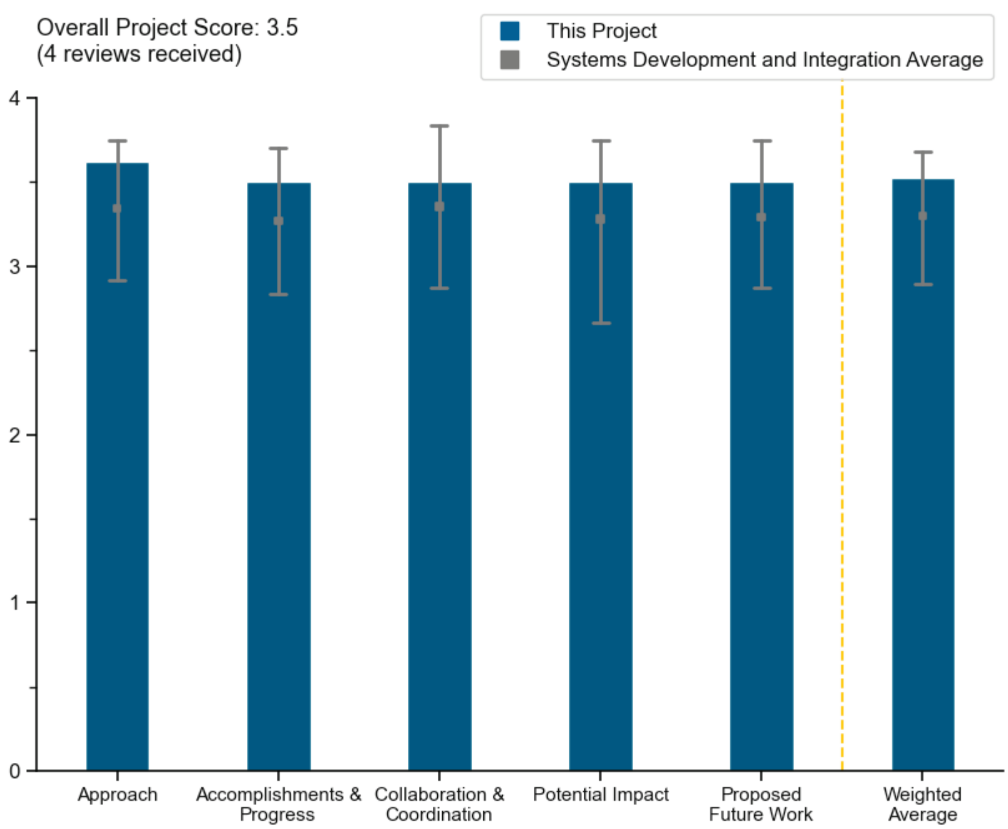
Stan Bower, Ford Motor Company

DOE Contract #	DE-EE0009858
Start and End Dates	3/1/2022–12/31/2026
Partners/Collaborators	FEV Group, National Renewable Energy Laboratory, Consumers Energy, Ferguson, Southern California Gas Company
Barriers Addressed	• Hydrogen infrastructure and cost • Commercial vehicle lifetime durability • Capability in extreme cold environments

Project Goal and Brief Summary

Ford Motor Company (Ford) is leading development of a zero-emission vehicle fuel cell propulsion system for Ford Super Duty® Chassis Cab vocation applications. Researchers will use modeling and simulation to design the technology, then construct the components and integrate them into pilot vehicles. The vehicles will be deployed to three fleet customers, who will demonstrate the technology in real-world environments. Using pilot data, the project team will evaluate fuel cell durability, usage, efficiency, refueling, and operating costs. In addition, researchers will conduct greenhouse gas (GHG) and environmental impact studies, as well as a full total cost of ownership comparative analysis against existing drivetrains.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 project is looking at efficiency, operating cost, and GHG impact relative to internal combustion engine (ICE) versions. There is a balance between the fuel cell following load and the battery following load and the fuel cell servicing the battery, but mostly the battery takes the transients and the fuel cell keeps it charged. The project has high power chemistry.
- The phased project plan has clear deliverables and metrics for each phase, with logical transitions between the phases. Also, the team earns kudos for clearly stating the go/no-go criteria for each phase.
- There is a sound plan and approach to project execution. It is early in the project, but the team seems to be technically capable of delivering as promised.
- It is not clear what the major contributor to 75% tank-to-wheel efficiency improvement was, and the project is asked to provide more details on overcoming the challenge on extreme cold weather operation. Details are needed on fuel cell, battery, and propulsion system operating strategies.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The project has specced out a 140 kW continuous power stack with a 350 kW peak, 800 V battery pack with 40 kWh capacity to help in towing. Three Type IV tanks hold 21.5 kg at 700 bar and 300+ miles with the same towing and same or better performance. The project has two substacks that share many gas conditioning parts to save cost. The project discovered that the worst case for fuel cell electric vehicles (FCEVs) can be different from ICE vehicles.
- On the performance attribute analysis, it is not clear exactly how the FCEV is providing better range than the 7.3 L gasoline engine. The project a has a detailed evaluation of the fuel cell thermal management system.
- The project is reported to have completed key milestones related to battery and thermal designs as evidence of being on track at this time.
- The project nests well with DOE goals to reduce GHG emissions without compromising vehicle performance.

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 fleet users and their assessment of the vehicles' performance will be especially important and is a unique aspect of this project. The next reports should focus on what data and evaluations will be gathered from the users and how those results will be used both before and after the end of the project.
- The project is smart to partner with a utility company. The use case is appealing. Ford could consider taking fabrication of fuel cells in-house in lieu of FCEVs.
- The project has good collaboration with partners that participate and are well-coordinated.
- The project has customers and subcontractors as collaborators, but it is not clear how much the customers are contributing to this project.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Adoption of FCEVs in this vehicle class will be a critical component of transitioning transportation away from fossil fuel. Many vehicles of this type are owned and used by "friendly" organizations (municipalities, utilities) that can collaborate on centralized, lower-cost fueling solutions, thus reducing one of the stated project barriers, which is a big opportunity for the project.

- Medium-duty has not gotten as much attention as heavy-duty but is an area where a large number of vehicles are sold and used. These hydrogen vehicles can provide the 24/7 requirements under which these classes of truck may be required to operate. These are all enablers for takeoff of a medium-duty hydrogen truck market.
- The project's potential impact is good, and most aspects align with the Hydrogen Program and DOE research, development, and demonstration objectives.
- The project is very relevant to hydrogen's use as an energy carrier.

Question 5: Proposed future work

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

- The proposed future work seems appropriate for the task at hand. More detail would have been nice, but there is enough detail provided to say the plans are appropriate and well-timed.
- The project structure has logical phases and steps with clear exit criteria and input expected from one stage to the next.
- The project seems to have a solid plan with achievable and meaningful go/no-go stage gates.
- More details on the safety plan could be provided.

Project strengths:

- The project presents as well planned, with appropriate resources engaged to execute. The project is targeted at moving FCEV technology into a key segment of the transportation industry.
- The project has a good engineering process on systems engineering development from vehicle- to component-level development.
- The project is conducting fantastic work. The reviewer is looking forward to the next phase of the project.
- The project has a strong team, a worthy target vehicle, and good partners.

Project weaknesses:

- The project has no obvious weaknesses. It would have been good to learn more about battery chemistry (rather than the answer given in questions, "energy power blend," which is as much about architecture as chemistry per se) so the cold start and life properties could be evaluated.
- It is not clear from the proposed future work slide that the vehicle configurations and usages for the fleet deployments are fully developed (last line on the slide). It would be helpful by the next review at least to highlight the process for figuring out those points and to show the status. For example, power takeoff usage in a boom truck could have significant power consumption and therefore significant impact on some of the project metrics. Snowplowing brings its own unique set of usage profiles and challenges.
- The project should look into electrification of the work truck's traditional hydraulic implements (e.g., booms and lifts) for increased efficiency and reduced system complexity.
- The project needs to show more key performance indicators.

Recommendations for additions/deletions to project scope:

- There are no recommendations for scope changes. This is a good project, and the reviewer is anxious to see future updates.
- There are no recommendations for additions or deletions to project scope.

Project #TA-058: Freight Emissions Reduction via Medium-Duty Battery Electric and Hydrogen Fuel Cell Trucks with Green Hydrogen Production via a New Electrolyzer Design and Electrical Utility Grid Coupling

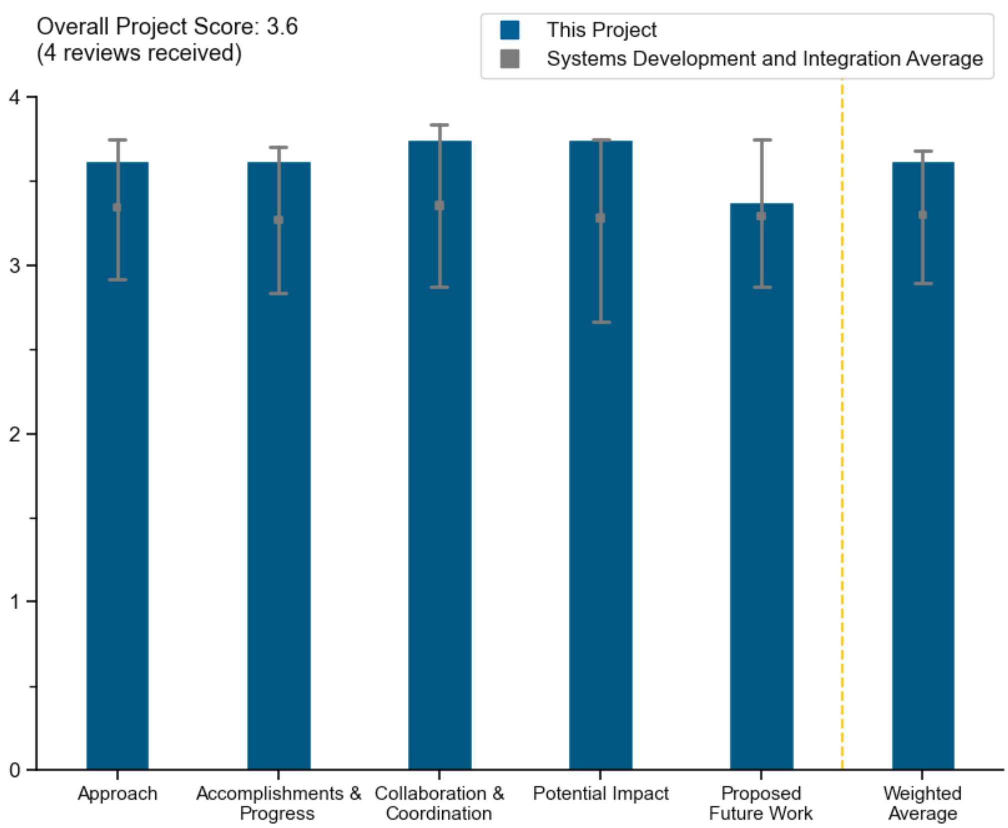
Jacob Lozier, General Motors LLC

DOE Contract #	DE-EE0009859
Start and End Dates	7/1/2022–6/30/2027
Partners/Collaborators	Argonne National Laboratory, Nel Hydrogen, Southern Company, Metro Delivery
Barriers Addressed	• Hydrogen fuel cost • Vehicle heavy-duty fuel cell system durability

Project Goal and Brief Summary

The project aims to showcase a significant reduction of 75% in greenhouse gas emissions while maintaining a competitive total cost of ownership compared to internal combustion engine vehicles in medium-duty (MD) trucks. The project's focus includes modeling, data analysis, and simulation of MD trucks to improve propulsion system performance and durability. The work also involves demonstrating advanced fuel cell and battery electric propulsion systems, establishing a hydrogen-centric microgrid for hydrogen fuel, and conducting equity analyses of the impact of zero-emission trucks on underserved communities. The project seeks to develop a low-cost electrolyzer and create an economically viable pathway for deploying charging and hydrogen-filling infrastructure at scale.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 makes sense. The comprehensive integration of the grid and renewable power sources with hydrogen production, fuel-cell-powered trucks, and battery electric vehicle (BEV) trucks is valuable for several reasons. Among them, the work will highlight the role hydrogen can play in balancing temporal mismatches between the availability of renewables and energy demand for transportation. The project will also be an opportunity to understand the relative strengths and weaknesses of MD trucks powered by hydrogen fuel cell and battery electric drivetrains in a real-world operational setting. Southern Company and Metro Delivery will find that the hydrogen fuel cell trucks work best in some situations and the BEV trucks work well in others. Including both drivetrain technologies may reveal the preferred fleet composition (fractions that are hydrogen-fuel-cell-powered and BEVs) for Southern Company and Metro Delivery, which would be a useful starting point as other companies explore the use of both technologies. Using power consumption data from an existing MD truck fleet is the logical starting point, and the use of simulation tools such as Autonomie for estimating fuel cell state of health degradation as a function of the anticipated power consumption profile is a good first stab at assessing the adequacy of fuel cells in this application. The real-world data should then confirm that and results from the rest of the simulation/modeling work going into the system sizing and integration analysis.
- The approach to performing work is well-thought-out and organized. The work is sequential and systematic, encompassing many organizations and following a logical flow. The project team has defined the problem well and set up a project to baseline and analyze data to ensure the project meets or exceeds predicted performance.
- The project has a strong approach that shows the team's expertise and knowledge in developing full-scale hydrogen-fuel-cell-powered systems.
- The project does cover some aspects of overcoming barriers, but it is not clear what measures are completed and what is planned. It would be helpful if the project could pinpoint barriers addressing points.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- Although it is early in the project, the goals outlined will track well with DOE goals. System demonstrations look to be relevant to workloads from real-world use.
- Accomplishments to date are as expected, based on the start date of the effort. Baselining has begun, which will set the bar for how much improvement this project delivers.
- General Motors (GM) seems to be moving forward at a reasonable pace.
- The mechanism preventing membrane and electrode damage factor is not evident.

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 with two companies that use the MD trucks on a regular basis, a national laboratory that has expertise in vehicle modeling and simulation, and an industry leader in electrolysis position the project for success. The collaboration between GM (expertise in BEV charging), Nel Hydrogen (expertise in electrolyzers), and Southern Company (expertise in electrical infrastructure) is a logical division of labor for the development of the microgrid that plays to each of the contributors' strengths.
- The project has exceptional collaboration and partnering. Working with well-established entities provides high potential for a successful outcome. The project has helped establish a new working relationship between two major companies, one of which is investing in new production capabilities near the lead performer, thus reaffirming the deep collaboration fostered through this effort.

- The project has close, appropriate collaboration with other institutions. The partners are full participants and are well coordinated.
- The project has a strong, collaborative team with plenty of experience.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has specific targets and high-level goals derived from the DOE targets. The project strives to answer questions on efficiency and applicability of fuel cell technology at a fleet level. Performance over baseline incumbent technology is extremely important for understanding what gaps still exist, how those gaps can be closed, and what additional work needs to get done.
- The project is well aligned with the Hydrogen Program goals. If successful, it should help pave the way for greater adoption of hydrogen-fuel-cell-powered MD trucks, which seems like a good target, given that such fleets can rely on central refueling/recharging infrastructure.
- The project is a great opportunity to showcase the next generation of GM's fuel cell technology. The lessons learned should be applicable to most ground systems using hydrogen fuel cells for power.
- The project has excellent impact since electrolyzer development is involved.

Question 5: Proposed future work

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

- The proposed future work is a logical extension of the current state of the project and, when complete, will carry the project closer to its goals. It would be helpful to understand in greater detail how the team plans to exploit the new electric vehicle powertrains to improve other aspects of these vehicles, for example, by electrifying auxiliary systems that are currently hydraulic. Perhaps such efforts are anticipated after 2024, when the early demonstration trucks will have been built.
- This reviewer is looking forward to seeing the technology in service.
- Future work is in line with continuing the progress set forth from the project objectives.
- The project needs to capture key performance indicators on the target or end goal for future work.

Project strengths:

- The project connects to real-world data for initial sizing and state of health modeling. The project is collaborating with companies that will use the trucks in real-world conditions. There is collaboration with organizations that have expertise in technology areas critical to the success of this project.
- Hydrogen export is a key project strength for the proposed systems. This could have a positive impact on future decisions made by fleet managers when considering investing in alternative fuels for individual duty cycles.
- The project has great partnership and a very large scope of work aimed at answering fundamental questions about performance and cost versus the current technology.
- Strengths include a detailed engineering process and an advanced fuel cell system.

Project weaknesses:

- It is good to see a focus on durability for this set of systems (this is not a weakness). Total cost of ownership will be a strong argument for or against this technology, and system downtime will be a critical factor influencing fleet managers.
- The project has a lack of scale. The scale of the current effort makes sense and is a logical first step. However, it will not reveal potential problems such as refueling/recharging bottlenecks associated with a fleet of vehicles that are all used on the same schedule. Building a larger number of trucks that more closely represent the way Southern Company or Metro Delivery would use a fleet of entirely hydrogen fuel cell vehicles and BEVs would reveal such infrastructure constraints, if they existed.

- Prototype fuel cells are being used in commercial fleet assets, which increases risk, both in performance and maintenance.
- The project's novel approach in durability tests needs better review for covering edge cases.

Recommendations for additions/deletions to project scope:

- The project could assess changes in driving/use patterns with the hydrogen fuel cell and BEV trucks compared to the existing diesel trucks. With the new capabilities and limitations (e.g., BEV range), it will be useful to understand how the trucks are used differently from the existing fleet vehicles.
- There are no recommendations for additions or deletions to project scope.

Project #TA-059: Medium-Duty Vehicle Total Cost of Ownership and Target Development

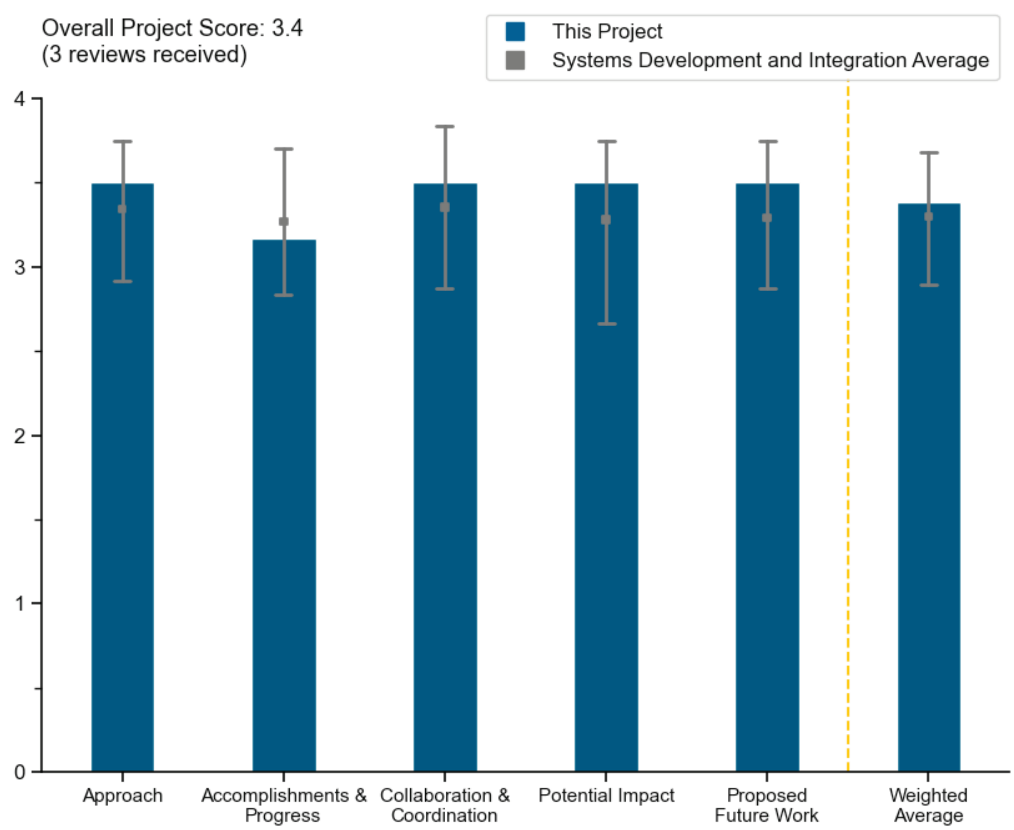
Ram Vijayagopal, Argonne National Laboratory

DOE Contract #	WBS 9.3.0.6
Start and End Dates	9/1/2021–8/31/2023
Partners/Collaborators	National Renewable Energy Laboratory, 21CTP, Strategic Analysis Inc.
Barriers Addressed	• Future market behavior • Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools

Project Goal and Brief Summary

The project's objective is to support the development of fuel cell electric trucks (FCETs) for medium-duty (MD) applications by evaluating their real-world performance and total cost of ownership (TCO). The project aims to identify the applications where FCETs have the most impact, quantify their energy consumption and cost compared to conventional diesel trucks, and determine the cost and efficiency targets needed for FCETs to achieve cost parity with competing technologies. The project involves conducting vehicle simulations, analyzing data from industry sources, and considering inputs from the Hydrogen and Fuel Cell Technologies Office (HFTO) and other stakeholders to inform target-setting and technology development activities. The analysis demonstrates that FCETs have the potential to be a viable solution for longer-range MD applications in the future, and they can provide a lower TCO compared to both diesel trucks and battery electric trucks, depending on the vehicle's range and operational requirements.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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.

- Argonne National Laboratory's (ANL's) approach to performing the work is outstanding. The project has a methodical evaluation of stakeholders and component suppliers. The vehicle performance is critical to projecting TCO and total energy consumed. Evaluating MD trucks is not straightforward and requires extensive review of real-world requirements and usage to have good results in modeling the performance. The real value is in comparing two types of powertrains between fuel cell hybrid and fuel cell dominant, which will depend on cost projections for batteries, fuel cells, and hydrogen storage.
- Generally, the project is well targeted. These are key questions to address for development of the medium- and heavy-duty (MD/HD) vehicle market. The scope is perhaps a bit broad, with the various vehicle types, but it is interesting to see how the different vehicle types may have different TCOs based on duty cycle, etc.
- Vast amounts of data from a variety of related topic areas add to the strength of outcomes in the context of this being a new area of development and availability of operational data. Preliminary TCO values are likely not the only parameters for the choice of battery electric vs. fuel cell electric, or a mix thereof. Particularly in the commercial application setting (versus commuting and travel in passenger vehicles), equipment functionality can be expected to play a major role as well.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- ANL has made excellent progress toward project objectives and DOE goals. The vehicle sizing and component requirements span a very large range, from Class 3 to Class 8 refuse trucks. The target of 45 mph may be too fast or two slow for some class vehicles within the seven applications.
- This is the project's first time reporting. It is valuable that a broad input approach was taken in a context where very limited operational data is available for the targeted MD/HD vehicle market to verify how accurate the modeling effort is.
- Progress so far is good. Final project results are eagerly anticipated.

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 range of collaboration between the 21st Century Truck Partnership (21CTP) and component suppliers is outstanding. The team has considered real-time feedback from stakeholders to adjust targets and to modify the modeling capabilities.
- It would be helpful to make references to DOE Vehicle Technologies Office (VTO) projects in the presentation to show the link to peer reviewers and audience members (as well as industry stakeholders reading reported outcomes). VTO is working on some of this. The project is missing MD/HD compressed natural gas vehicle information as an additional/supplemental benchmark to diesel. It would be helpful to have truck fleet operator input.
- There is some collaboration, but the work is pretty confined to ANL.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- ANL has showed an excellent comparison to batteries and fuel cells to help steer DOE investment priorities and to educate industries that are preparing for the transition to electrification and zero-emission trucks. The problem of optimization and limits of different technologies is very complicated in considering the true cost of electricity, delivered hydrogen, and cost curves as they begin to level out this decade. A key result is that, for a 270+-mile range, a fuel cell vehicle may be more economical, depending on the cost of hydrogen, electricity, and total miles per year. Hydrogen pricing has a big impact on the range, increasing to over 500 miles at $8/kg, showcasing how important it is to reduce the cost of hydrogen for Hydrogen Program goals.

- This is the first TCO project performed by a (more) neutral stakeholder. TCO provides valuable insights when it comes to cost/mile analysis of goods moved and, for example, the potential cost increase of consumer goods in the long term. When comparing vehicle technologies based on range and cost, assessment for battery electric (and fuel cell electric) needs to include weight and sizing limitations (slides 15 and 16).
- This is an analysis project that can speak to TCO, but it likely will not have much broader market impact in terms of technology validation.

Question 5: Proposed future work

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

- The listed future work items are very relevant: the role of degradation in TCO, future drive scenarios with more automated logistics management, and the use of FCETs in future freight movement technologies. There are more results and data from MD fleets, with increased information on real-world results from fuel cell performance and cost, as well as the emerging learnings from different storage technologies.
- The focus appears to be strongly on the vehicle side of the equation. Functionality of evaluated technologies appears not to be considered.
- There is a strength in terms of understanding durability requirements and cost implications for different vocations.

Project strengths:

- ANL's project strength is the clear results from fuel cost and how different technologies may be compared. The model's flexibility to enable many different inputs is also a highlight.
- The project is conducting an overdue and much-needed assessment. The broad approach and inclusion of data sources are also strengths.
- TCO analysis coupled with detailed technology assessment is a strength, along with assessment of several vehicle types with their unique requirements.

Project weaknesses:

- There are no particular weaknesses here.
- The scope does not include an assessment of the fueling infrastructure factor (at scale, not infrastructure scattered here and there for both FCET and battery electric truck technology options). Availability of operational data from MD/HD truck fleets is very limited. Functionality of assessed technology options in a commercial setting appears to be factor that is currently not included.
- The sheer quantity of drivetrains, technology offers, and pricing leads to a dilution of the message and how to interpret results. It would be helpful to focus more on real-world use cases to clearly show what technologies and which use case scenarios are most likely to need one technology over another.

Recommendations for additions/deletions to project scope:

- The project should evaluate whether 100,000 units/year is the appropriate production volume for all the vehicle classes/categories included in this assessment because several of these vehicle classes have a lower realistic production volume (for example, transit buses see approximately one-tenth of this number annually). The "functionality in commercial application" factor should be included.
- The project should provide clear use cases when more data is available from the MD hydrogen fuel cell truck use: storage technology options, hydrogen pricing, and updated fuel cell technology options.
- Perhaps some consideration for climate and gradeability, if possible, could be included.

Project #TA-060: Offshore Wind to Hydrogen – Modeling, Analysis, Testing, and International Collaboration Work

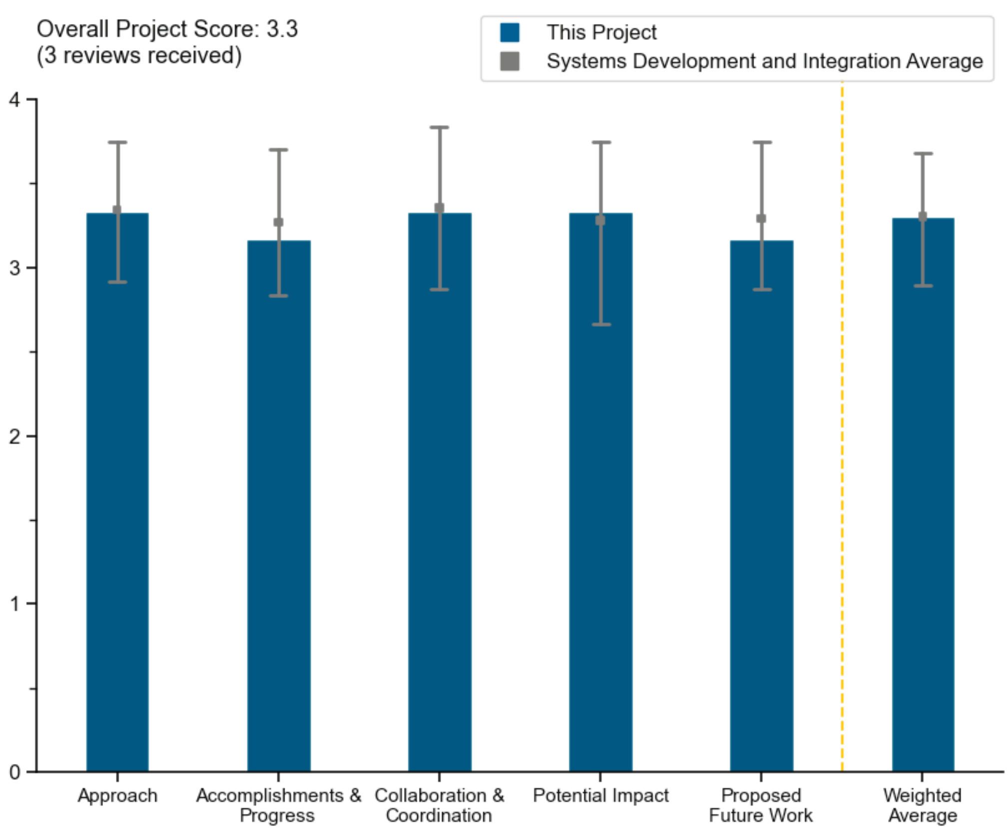
Genevieve Saur, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.15
Start and End Dates	1/1/2022
Partners/Collaborators	Netherlands Organization for Applied Scientific Research (TNO), Giner, Inc., GE Research, HYGRO, Plug Power Inc.
Barriers Addressed	• Renewable electricity generation integration • Capital cost • Footprint, size, and weight • Operations and maintenance • Control and safety

Project Goal and Brief Summary

A key barrier to industry adoption of hydrogen production using renewable energy sources is the uncertainty that the approach is economically viable. This project aims to better understand the economic viability of multiple system-level concepts to produce hydrogen from offshore wind, as well as test/validate control systems, in addition to electrolyzer performance under specific conditions for hydrogen production using electricity from offshore wind.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 reasonable and sound. The project employs a combined approach of modeling, experimental demonstration in NREL's test facility, and international collaboration, which is very good. Additionally, the approach of examining three specific techno-economic analysis (TEA) case studies to cover the main configurational options is a very good choice.
- The project aims to better understand integration of control systems and electrolysis with offshore wind. Optimizing the systems will help researchers to gain a better understanding of the most effective control schemes, and the modeling work is well supported with real tests.
- The comparison of three different strategies for offshore wind power to hydrogen is interesting and relevant. Although the direct electrolysis of ocean water is unlikely, it could be an interesting side case, as there are somewhat promising research efforts in this area. It would be interesting to better understand why project partner TNO Norway (Toegepast Natuurwetenschappelijk Onderzoek) is involved, as the labs have good TEA capabilities. Presumably, TNO has some additional insights around offshore wind concepts.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- So far, only modeling and preparation for the experimental portions of the project have been reported on. Capital cost results have been completed but not yet released. A top-level comparison between general TNO and NREL assumptions regarding specific cases has been made and is considered a worthwhile activity.
- Significant progress has been made in understanding cost-effectiveness in multiple scenarios and regions. Initial outputs have shown configurations that produce economic value through TEA. A test is needed for confirmation.
- The project is in the early stages, with no results presented. The reviewer is looking forward to the project outcomes.

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.

- Teaming with TNO is a solid choice. Partnering with Giner, Inc., General Electric (GE), and Plug Power Inc. for electrolyzer and wind turbine expertise significantly strengthens the project.
- There is very good collaboration between lab and industry. Outreach to the international community to look at regional impacts on the models provides significant value.
- The international exchange with TNO is interesting, and it is good to see there might be some good exchange of information with the European Union.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Off-shore wind represents a significant opportunity for low-cost renewable hydrogen. As there are no current offshore wind/electrolysis demonstrations, yet there is fundamental uncertainty regarding optimal configuration, this project is relevant and has high potential to aid understanding.
- This is a very interesting question to investigate. All sources for low-carbon hydrogen that can be brought to bear will be needed. The project is taking a likely avenue to relatively low-cost hydrogen, if carefully combined with electricity production and under the right conditions.
- Success here should provide greater insight into how system integration can be optimized for cost, resulting in broader deployment of the technology.

Question 5: Proposed future work

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

- The main future work task is conducting and analyzing the experimental results and is a high-value activity. The joint NREL–TNO paper is also a high-value activity.
- Proposed future work will continue to address issues identified and confirm the modeling with actual testing of the integrated systems.
- There are no real issues here. The project plan seems reasonable.

Project strengths:

- Teaming with TNO is a substantial strength. Combined modeling and testing in the NREL testbed is a strength. Evaluating multiple TEA case studies (in collaboration with TNO) is a strength. The list of key insights, options for reducing costs and uncertainty, and recommendations for improving the TEA are excellent.
- The project is researching a very interesting question, and the three production strategies seem well conceived.
- The project has strong collaboration with industry partners and the international community.

Project weaknesses:

- There could be a more explicit statement of the parameter that will be assessed (and modeled) as part of the experimental project, for instance, how response time is being measured (what the measurement is, exactly) and polarization curves. There should be more discussion of stack and system volume and whether it fits on an offshore platform.
- Overall project goals are a little unclear. Clarification is needed on the final objective functions/decision variables. The project seems focused mostly on operating expenses with some capital expense considerations but is pretty confined.

Recommendations for additions/deletions to project scope:

- Further analysis should be added to gauge whether the volume (and required stack power density) of the electrolysis system fits on an offshore platform. Low-cost, undersea hydrogen storage at a 40 m depth (to offset some of the pressure load [~bar] and reduce storage cost) is a good idea. Matching stack pressure to the storage depth is worth considering. Slide 22 refers to stating the cost estimation uncertainty for systems that do not yet exist, which is a worthy effort.
- The project should look at the internal rate of return for an offshore wind project and then see how the three hydrogen strategies impact that (positively or negatively) depending on the assumptions. The researchers should use "electricity only" as a baseline and see how hydrogen production moves the needle, instead of assuming the three hydrogen production cases. There is speculation that hydrogen production can improve the economics of offshore wind (at some hydrogen take-off price), but this project is a great opportunity to put a finer point on that (if it is not too much of an expansion of scope).

Project #TA-062: Validation of Interconnection and Interoperability of Grid-Forming Inverters Sourced by Hydrogen Technologies in View of 100% Renewable Microgrids

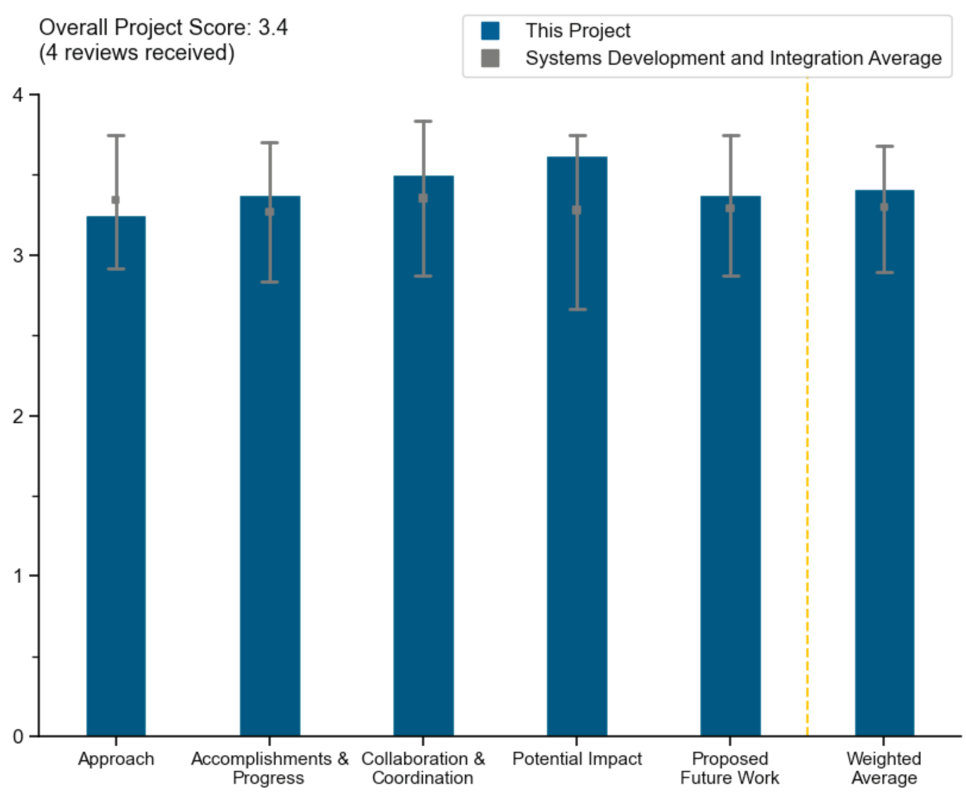
Kumaraguru Prabakar, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.16
Start and End Dates	1/1/2022–12/31/2024
Partners/Collaborators	Southern California Gas Company, University of California, Irvine
Barriers Addressed	• Intelligent electronics device capability description (ICD) file development and hosting in the public domain • First-of-its-kind power hardware-in-the-loop setup to run grid-forming inverter experiments • Complete power hardware-in-the-loop and controller hardware-in-the-loop integration with microgrid model • Complete test plan execution in hardware setup

Project Goal and Brief Summary

Grid-forming (GFM) inverters are increasingly important in distribution systems with microgrids. This project focuses on fuel-cell-coupled GFM inverters as potential assets. The project's goals include developing a testbed to evaluate updates to interconnection and interoperability requirements, leveraging existing assets for hardware-in-the-loop experiments, and accelerating industry adoption of GFM fuel cell inverters. The standardized sensing, operation, and control of these inverters will reduce installation costs and enable widespread adoption, making them an asset in distribution systems and microgrids. The project's outcomes will contribute to integrating hydrogen assets into the grid, reducing costs, and facilitating the market potential and scalability of GFM fuel cell inverters.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 started in 2022 and will be completed in 2024. The project will develop a testbed to evaluate and document updates to interconnection and interoperability requirements for GFM fuel cell inverters. This project will also create a hardware-in-the-loop setup to run GFM inverter experiments. The plan is reasonable and doable.
- The project takes a logical approach. The team could leverage work done by fuel cell companies—such as Bloom Energy, FuelCell Energy, and Doosan NA—that have stationary fuel cell systems installed and have dealt with grid connection and interoperability issues.
- The approach is well defined and aims to provide recommendations for updates to existing standards. This will help to standardize operation and control, plus reduce smart grid integration cost.
- There was a discussion around direct current (DC) coupling storage (i.e., batteries) with the fuel cell on the same inverter, which seems like an excellent concept. However, the power hardware-in-the-loop (PHIL) experiments appear to include only a GFM inverter connected to a fuel cell stack. It is unclear whether there are any plans to incorporate energy storage on the DC-coupled side of the inverter for PHIL testing.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- The team has completed Phase 1 of the project. The project executed a cooperative research and development agreement with Southern California Gas Company and a subcontract with the University of California, Irvine; completed the alpha version of interoperability codes; submitted an open-source software record and will make the technology available in the public domain after review; completed PHIL experiments with a GFM inverter; submitted a digest to the Institute of Electrical and Electronics Engineers conference to disseminate the methodology to run PHIL experiments with GFM inverters; and procured a microgrid controller to work with a Banshee microgrid model.
- Efforts appear to have been focused mostly on equipment procurement and installation. Hardware experiments were completed and shared with the community for test standardization.
- Draft interoperability codes were prepared and submitted. The project completed hardware-in-the-loop experiments and demonstrated a response of fuel cell to full load in <20 seconds.
- This project is about halfway through its intended duration, but costs incurred to date are less than 10%. It is unclear if this is in line with the expected budget.

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 includes the National Renewable Energy Laboratory, Southern California Gas Company, and the University of California, Irvine. This team can accomplish the goals laid out in the plan.
- Very good collaboration between the national lab, academics, and industry partners provides confidence that areas of test and exploration are well formed.
- It would be beneficial to have more collaboration with a grid operator, perhaps having a grid operator on the advisory board. Additional collaboration with fuel cell manufacturers/providers would be beneficial (Bloom Energy, Ballard Power Systems, Doosan NA, FuelCell Energy, Cummins, Inc., Plug Power Inc., etc.). Some of these have microgrid systems and systems that operate on the grid already.
- The partner list includes academic institutions, industrial organizations, and final end users but no inverter original equipment manufacturers. It is unclear whether there are any plans to discuss this effort with inverter manufacturers to ensure feasibility.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The efforts look to standardize test protocols and inform codes and standards. Output will inform manufacturers on how to optimize and integrate smart grids, with the intent of cost reductions. This standardization, along with development of codes for manufacturers to follow, reduces costs of system integration.
- Interoperability and interconnection costs can hinder adoption of new technologies. Current standards do not include fuel cells. Updating standards to include fuel cells will reduce installation costs and enable fuel cells to replace traditional generation on the grid.
- This project will propose updates to existing standards. If the proposed changes are accepted in these standards, the industry could be revolutionized, and these standards could break down the barriers for adoption.
- Inverter communication standardization is an important area, and this project appears to address this need well.

Question 5: Proposed future work

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

- Proposed future work will continue to address challenges and barriers. Standards will be made available for review and refinement, moving recommendations closer to final. Finalization of the controller integration will enable full testing of the experimental setup.
- The project will complete standards recommendations documentation and submit the document for review and dissemination in open-source. Interconnection is included. Proposing and updating the standards for integration should be the prime objective of this project.
- The proposed test plan appears to be sufficient.
- The open-source approach provides benefits.

Project strengths:

- This project incorporates several important relevant stakeholders required for GFM fuel cell inverter technology. The feedback from these industrial partners will be valuable in guiding the project. Being able to evaluate the response of these inverters in a microgrid simulation will provide good data on how the inverter would respond in real-world scenarios.
- Very strong collaboration ensures that setup, equipment, and test plans have been thoroughly vetted. This provides great confidence that the approach and results will have validity to the community.
- This is a very beneficial project, as standards are a major hurdle for integration.
- The project addresses important issues of grid connection and interoperability.

Project weaknesses:

- Incorporating feedback from inverter manufacturers would be valuable for better understanding how the proposed changes to the standards could be implemented.
- Collaboration with fuel cell companies is limited.

Recommendations for additions/deletions to project scope:

- DC coupling storage behind the GFM inverter would be valuable. The current PHIL allows for testing of alternating current (AC)-coupled storage, which is definitely valuable. The inclusion of DC-coupled storage may change some of the control paradigms around the fuel cell.
- The project should add collaborations with existing stationary fuel cell companies (Bloom Energy, FuelCell Energy, Doosan NA, Plug Power Inc., etc.).

Project #TA-065: Total Cost of Ownership Analysis of Hydrogen Fuel Cells in Off-Road Heavy-Duty Applications – Preliminary Results

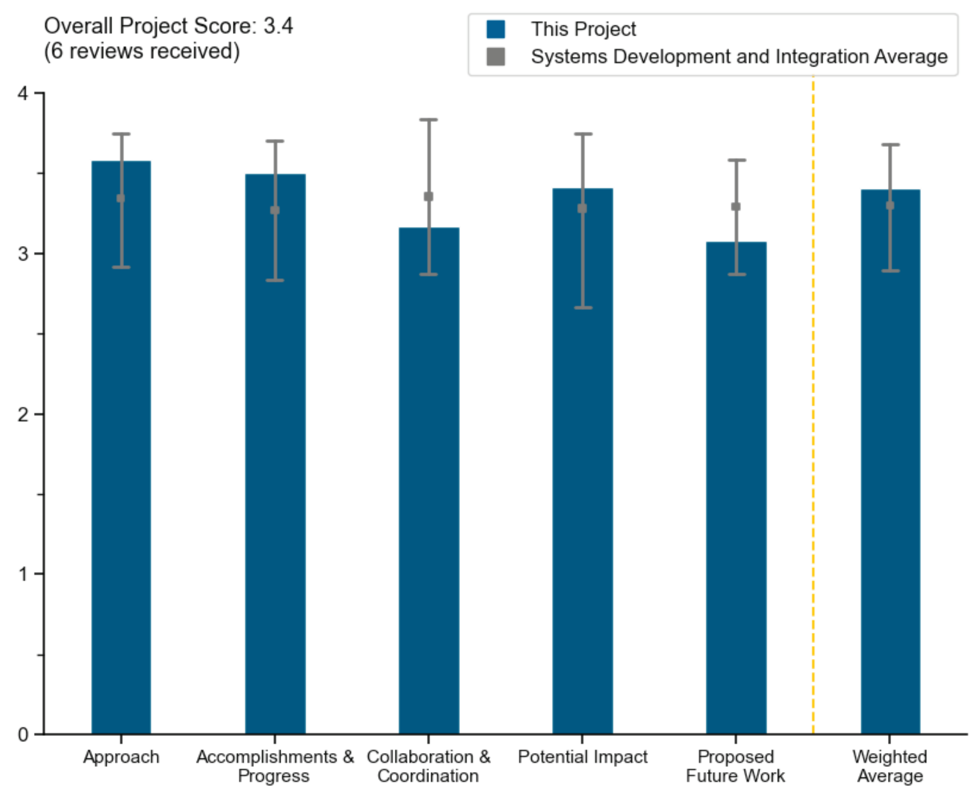
Rajesh Ahluwalia, Argonne National Laboratory

DOE Contract #	WBS 9.3.0.6
Start and End Dates	10/1/2020–9/30/2022
Partners/Collaborators	Collaborations (industrial companies contacted for feedback): AGCO Power, Caterpillar, CNH, Dawnbreaker, Empire Tractor, First Mode, Fortescue, John Deere, Komatsu, Volvo Trucks
Barriers Addressed	• System cost • Efficiency • Thermal management • Life cycle assessments

Project Goal and Brief Summary

Construction, mining, and agriculture equipment is the largest contributor to off-road greenhouse gas (GHG) emissions within the transportation sector. This project will determine the fuel cell and hydrogen storage performance needed to make fuel cells in off-road vehicles economically competitive with more commonly used technologies, such as diesel engines. Fuel cell systems being developed for heavy-duty trucks will be adapted for tractors, wheel loaders, and excavators; for example, systems will be resized for power requirements, and degradation will be reduced through voltage clipping. Researchers will determine the total cost of ownership (TCO), considering the uncertainties of critical powertrain design (e.g., degree of hybridization), parameters (e.g., vehicle miles traveled), and driving cycles. This project has the potential to pave the way for a green fuel alternative to power the nonroad sector.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 assumes a representative haul route and then evaluates the performance metrics of fuel-cell-powered hybrid electric haul trucks, which is reasonable. It is analogous to the use of urban and highway drive cycles to characterize the energy performance of passenger vehicles, because while use of a representative haul route will not exactly duplicate a specific scenario, it should have sufficient detail to permit the comparison of powertrain technologies. The presenter made a convincing argument that the one-dimensional model employed here is sufficient for capturing the essential features of drivetrain performance, in particular, the amount of fuel consumption, since that plays a significant role in determining the cost of ownership. The "simulate and compare" approach is appropriate here in part because the existing trucks already have hybrid electric powertrains, so the only changes are the replacement of the engine/rectifier/diesel storage with the fuel cell/power electronics/hydrogen storage, which is a well-bounded change. The use of the heat exchanger to place an upper bound on the size of the fuel cell system makes sense, given the relatively lower operating temperature of the fuel cell compared to the existing diesel engines.
- Argonne National Laboratory (ANL) showed an outstanding approach to the difficult challenge of developing a TCO model for off-road mining vehicles. There is a clear motivation for reducing GHG emissions from mining and showing how hydrogen fuel cells compare to conventional diesel powertrains at the scale required for large mining vehicles. ANL is incredibly detailed in the requirements and how they compare to fuel cell system status, ultimate goals, and current technology status. This shows where additional research and development is needed or what demonstrations should attempt to showcase. ANL showed a clear and concise approach in evaluating the hybrid power train, thermal performance, and liquid hydrogen storage required for equivalent performance.
- This is a comprehensive analysis based on thoughtful consideration of the issues for a fuel cell mining truck. Each aspect, vehicle, baseline diesel system, fuel cell, battery, heat rejection, and drive/duty cycle is defined with a focus on the key aspects.
- There is potential for the mining industry to adopt hydrogen for its equipment. This study is a great initial look into the conversion and can give insights for the industry.
- The project has a strong approach and knowledgeable principal investigator.
- The initial approach is acceptable overall. However, many assumptions are being made that need to be clearly stated. Fuel cell performance data models used are not representative of real-world fuel cells. Liquid hydrogen storage is being used without a validation that it will fit onto the vehicle used in the model. The methods used to hone in on a good system to model and baseline data capture are great and serve as a great start.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- ANL showed a clear accomplishment in down-selecting all aspects required for a comprehensive TCO assessment: technical equivalence, system configurations for hybrid fuel cells, and the fuel cell load-following system. The power demand is carefully chosen to meet all aspects of the drive cycle: grade, speed, and full power with regeneration accounting. This also highlighted the major challenge of rejecting heat in meeting the net power requirements. ANL provided an extensive comparison between the two systems and the system design rationale for exact kilowatts and kilowatt-hours required from the fuel cell or battery combination. The discussion for matching fuel cell durability and lifetime to battery capacity and degradation over a similar timeframe was a key result and accomplishment.
- Numerous accomplishments are cited, including definition of the market segment, consideration of duty cycle, heat rejection, and capital cost/TCO analysis.
- The project has already yielded useful conclusions regarding the suitability of hydrogen fuel cells for haul trucks from a cost perspective.
- The study gives a complete picture of TCO and will be used in the industry.

- The project shows favorable characteristics that fuel cells bring for mining applications.
- The data being produced to date is useful. However, more realistic modeling needs to be done based off fuel cell data in the real world.

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.

- ANL provided an outstanding list of collaboration partners, and it shows in the depth of detail in the TCO assumptions and the exact models of equipment under evaluation. Major players in mining equipment and mining operations were included in the comprehensive list of coordinating industrial companies.
- The group of collaborators is quite relevant to the subject matter and represents the industries that will be interested in the results. With these collaborators providing data, there is high confidence in the assumptions used in the analysis.
- While this is a fully ANL-internal analysis project, the ANL team was in discussions with numerous relevant industrial companies. This makes up for a lack of formal project partners.
- It would be helpful to understand more about collaborations with AGCO Power, Caterpillar, CNH Industrial, Dawnbreaker, Empire Tractor, First Mode, Fortescu, John Deere, Komatsu, and Volvo Trucks, including what inputs they provided and what impacts these key players had on the project.
- Several partners were contacted for feedback. However, no response was shown during the presentation. It was not clear how closely connected the project is to the various collaboration partners.
- The project seems to be relying on companies to supply feedback on the analysis, but those companies are not directly involved in the project.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project has a very high relevance and impact. The results clearly show that fuel cell cost dominates the TCO cost and that a fuel-cell-only system will be lower-cost without the battery range extender model. The final output including the very high dependence on hydrogen cost shows how critical it is that DOE focus on cost reduction of hydrogen delivered to mining vehicles vs. business as usual with diesel fuel. A key slide was the tradeoff between fuel cell cost to price of hydrogen. There is a clear correlation between fuel cell cost targets and how important input fuel costs influence the overall comparison.
- The mining industry is a cross between the transportation sector and the hard-to-decarbonize sector. Hydrogen has the potential to bring renewable energy to this significant contributor. GHG reduction in this sector will also reduce the contribution of GHGs from other sectors, as all other materials are originally produced from mining. This project gives insight for leaders in the mining industry to confidently decide the path forward.
- This was an excellent project, with clear goals to provide information and data that can be used and discussed as a way to keep the conversations about hydrogen fuel cell use cases moving forward. The impact is high, and this project has use for more refined data modeling.
- The project provides strong relevance to Hydrogen Program goals because haul trucks are used in fleets that can be supported by centralized refueling infrastructure.
- The project provides strong impacts on future decisions for fuel cell powertrains in mining applications.
- The project makes the argument that nonroad is 20% of GHG emissions within the transportation sector, and construction, mining, and agriculture equipment is >50% of nonroad GHG emissions. However, mining vehicles of this type (100+ ton dump trucks) are likely not large GHG emitters. The team may be correct, but the argument is not convincing. That said, the TCO reduction of the fuel cell vehicle is significant and would have an impact on GHGs in this sector.

Question 5: Proposed future work

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

- The proposed work is to continue ANL's input to the Mission Innovation efforts and explore the cost of fueling infrastructure for off-road, heavy-duty applications. This will be a key aspect of the fuel cost inputs and will be very welcome to the stakeholder community.
- The proposed continuation to study the refueling infrastructure required to support haul trucks is the next logical step, given that the current work suggests hydrogen-fuel-cell-powered haul trucks are economically feasible.
- The project proposed to investigate refueling infrastructure for off-road, heavy-duty applications next. This is a logical extension of the current project. This is a reasonable topic.
- The project is completed, so there are no further tasks, but a willingness for further work in the area was expressed.
- The project has concluded; however, the presenter states that the team is open to continued support.
- Funding does not seem available for future work.

Project strengths:

- The project addressed a well-defined problem with relevant input data and a clear methodology. Results were straightforward and easy to interpret in a useful way. The project showed strong relevance to the goals of the Hydrogen Program because haul trucks are used in fleets that can be supported by centralized refueling infrastructure.
- The overall approach, methodical and logical execution of the analysis project, and inclusion of the TCO comparison are major project strengths. The thoroughness of the battery discharge/efficiency analysis and battery sizing is also a strength, as is the generation of a power use cycle from a postulated vehicle drive cycle.
- The major strength is the depth of detail and analytic capabilities demonstrated by ANL. Other major strengths are the close coordination examples shown by the comprehensive list of stakeholders.
- The project identifies critical assumptions in the analysis and lays out the needed results into charts that are relatively easy to understand.
- The project exhibited great initial set-up and down-select on the baseline technology. The project also had great overall analysis and comparison data generation.
- TCO modeling for fuel-cell-powered mine haul trucks was completed, and data was presented.

Project weaknesses:

- The radiator/thermal system is based on the same (presumably frontal) area of the existing diesel truck. This is a reasonable starting assumption, but it may be that additional area/radiator size is possible. Truck original equipment manufacturers (Class 8) state that with prudent design, they can achieve a larger radiator area. A larger area may be obtainable on these large off-road trucks, too. On Slide 6, the $/kW values for various powertrain components do not have a basis shown. The values seem high, so lacking a specification of their cost basis is a particular weakness. In addition, it appears that the power cycle was derived from the vehicle duty cycle. Presumably, this is because actual power/drive cycle data was not available. Not using actual data is a weakness. In a back slide, it is stated that costs are based on a manufacturing volume assumption of 1,000 vehicles/year. Burying this assumption and not defending its validity is a weakness. Finally, the TCO comparison is very good overall, but there should be a diesel future to compare against the fuel cell ultimate. The diesel trucks will keep improving, just as the fuel cell vehicle is expected to improve.
- A sensitivity analysis should be completed (if one has not been done already) to understand how changes in the standard haul route influence the battery sizing and other characteristics of the fuel cell powertrain. It would be good to understand if, for example, the battery size varies linearly with the climb length and steepness, or if there is a “knee in the curve”—and at some critical value where a technological limitation comes into play.

- The results were presented in academic journals and to working groups, but an article in an appropriate publication for the mining industry would be of benefit.
- The team did not explain how this data is being used in industry or how further investigation could affect project results.
- The project is not representative of real-world fuel cell performance data and hydrogen storage volume requirements.

Recommendations for additions/deletions to project scope:

- Real duty and power draw data should be added to the analysis, and a future diesel truck should be added to the TCO comparison. The project should document some of the cost assumptions for the powertrain components.
- The project should add realistic fuel cell performance models and size the hydrogen storage that would realistically fit on the chosen platform. This data would be important to see how far the current technology is from meeting the required performance metrics of the baseline technology.
- Further communication to the mining industry could prove to be the difference between the results getting used in the industry and just staying in academic publications.
- The project is over, but it would be very interesting, pending industry interest, to explore operation at an altitude where cathode humidification is not available from ambient air.

Analysis, Codes and Standards – 2023

Analysis, Codes and Standards Subprogram Overview

Introduction

The Analysis, Codes and Standards subprogram aligns with priorities in the *U.S. National Clean Hydrogen Strategy and Roadmap* and performs enabling activities to inform research, development, demonstration, and deployment (RDD&D). The subprogram comprises two activity areas: Systems Analysis and Safety, Codes and Standards (SCS). The Systems Analysis activity area identifies priority markets for hydrogen technologies and assesses impacts. The SCS activity area informs safe design and operation of technologies and addresses regulatory and permitting challenges.

The Systems Analysis activity area funds crosscutting analyses to identify technology pathways that can facilitate large-scale use of clean hydrogen to enable decarbonization, advance environmental justice, and enhance energy system flexibility and resilience. To perform these foundational analyses, the subprogram relies on a diverse portfolio of both focused and integrated models that characterize technology costs, performance, impacts, and cross-sector market potential. These tools and capabilities are continuously updated and enhanced. New tools are also developed as needed.

Crosscutting 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, Advanced Materials and Manufacturing Technologies Office, Industrial Efficiency and Decarbonization Office, Office of Clean Energy Demonstrations, and others
- State and local government organizations
- Other federal agencies (e.g., the U.S. Environmental Protection Agency)
- Private sector companies
- International organizations.

In Fiscal Year (FY) 2023, the Systems Analysis activity area focused on user-friendly tools to characterize cost and emissions of real-world deployments, analyze cost and emissions of additional hydrogen production technologies, and incorporate hydrogen into energy market models to include hydrogen demand scenarios in strategic sectors to enable net-zero by 2050.

The SCS activity area supports research, development, and demonstration (RD&D) to improve the fundamental understanding of the relevant physics and 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 best safety practices and developing information resources.

In FY 2023, the SCS activity area focused on approaches to streamline permitting, resources on current codes and standards and safety best practices, and safety component research and development (R&D) (e.g., release behavior, sensors).

These crosscutting efforts support technology development and scale-up of hydrogen activities across the entire hydrogen value chain (production, delivery, storage, and end use), as well as across multiple industry sectors (transportation, grid integration and power generation, industrial and chemical industries, etc.).

Goals

The Systems Analysis activity area 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.

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

The key milestones of the Systems Analysis activity area are as follows:

- Develop models and analyses to support the implementation of the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law) and the Inflation Reduction Act. **(2023–2027)**
- Conduct state-of-the-art assessments of technology cost, performance, and value proposition to help guide the RDD&D portfolio. **(2023–2027)**
- Validate and refine models and tools to enable large-scale market growth, inform multisector coupling, and realize emissions reductions and jobs potential. **(2027–2035)**
- Characterize market barriers and opportunities for supply chain expansion and high-volume manufacturing. **(2027–2035)**
- Assess RDD&D and market transformation processes, policies, and progress across applications and sectors to enable system resilience, emissions reduction, and sustainability; and assess job potential, including impacts on disadvantaged communities. **(2035–2050)**

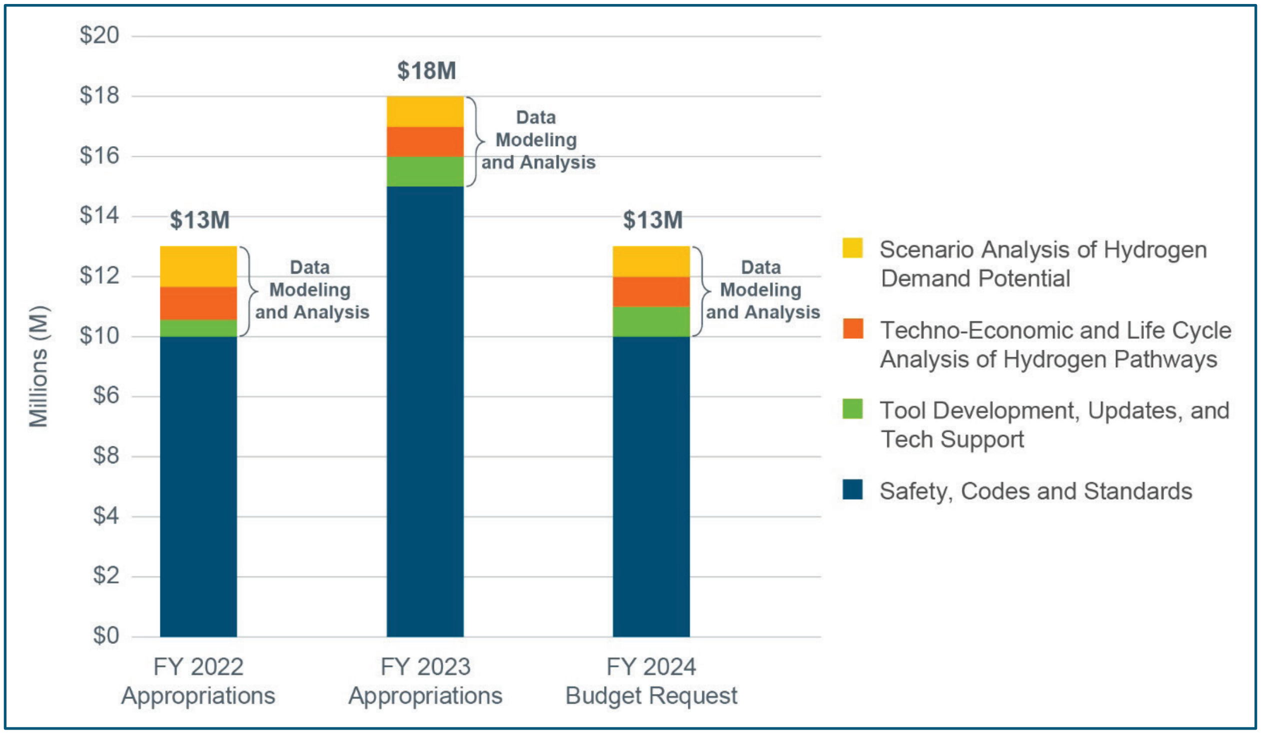
The key milestones of the SCS activity area are as follows:

- Identify ways to reduce the siting burdens that prohibit expansion of hydrogen fueling stations by using hydrogen R&D to enable a 40% reduction in station footprint, as compared to the 2016 baseline of 18,000 square feet, by 2022.
- Develop a 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.
- Ensure monitoring systems and data collection are in place for potential hydrogen and other emissions/releases and validate hydrogen sensor technology capable of parts-per-billion sensitivity, detection speeds of less than one minute, and <$1,000 annual operating cost.

Budget

The FY 2023 appropriation for the Analysis, Codes and Standards subprogram was $18 million. The budget for the Systems Analysis activity area is $3 million per year. The budget for the SCS activity area grew from $10 million in FY 2022 to $15 million in FY 2023, with new funding to support approaches to streamlining permitting for hydrogen deployments.

The FY 2024 budget request of $13 million includes $3 million for Systems Analysis activities and $10 million for SCS activities.



Annual Merit Review Results

During the FY 2023 Annual Merit Review, 23 projects funded by the Analysis, Codes and Standards subprogram were presented, and 16 were reviewed (a breakdown by budget category is shown on the right). The reviewed projects received scores ranging from 3.1 to 3.7, with an average score of 3.4. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Following are reports for the 16 reviewed projects. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Number of Projects Reviewed by Budget Category	
Tool Development, Updates, and Tech Support	3
Techno-Economic and Life Cycle Analysis of Hydrogen Pathways	1
Safety, Codes and Standards	
Codes and Standards Harmonization	3
Component R&D	3
Hydrogen Behavior and Risk R&D	3
Materials Compatibility R&D	1
Safety Resources and Support	2

Project #SA-174: Life Cycle Analysis of Hydrogen Pathways

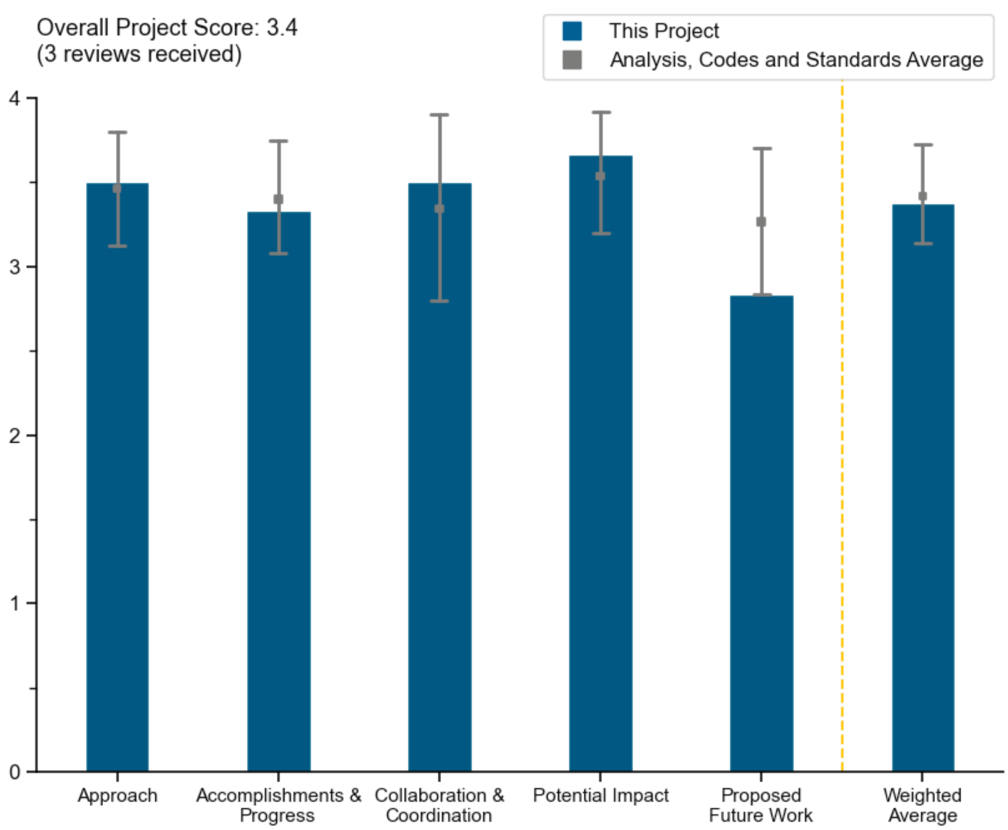
Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	WBS 5.1.0.6
Start and End Dates	10/1/2019
Partners/Collaborators	National Energy Technology Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools • Stovepiped/siloed analytical capability for evaluating sustainability

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 environmental implications of hydrogen production technologies. Argonne National Laboratory is collaborating on this project with the DOE Strategic Analysis Office, DOE Advanced Manufacturing Office, National Renewable Energy Laboratory, National Energy Technology Laboratory, and University of California, Irvine.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Analysis, 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 core of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) model incorporates all the latest science into a tool that can utilize operator-specific data to estimate emissions. The work done by Amgad Elgowainy and the project team focuses on creating modules and models that leverage the importance of the Inflation Reduction Act's 45V tax credit to the myriad of production technologies and configurations that could exist for hydrogen production. The project's work is essential and reflects why GREET was specifically included in the Inflation Reduction Act.
- The approach is in line to provide a real picture of the greenhouse gas (GHG) emissions using a unique tool and also allowing a comparable approach. To do so, the tool has to be freely available.
- GREET is a key foundational repository of emissions and energy contributions. This project is effective in building on GREET.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments achieved this year are very good, with development of an H_2 module user interface with simple process and outputs and the evaluation of electrolyzer capital expenditure (CAPEX) embodied GHG emissions. Following are a few comments on the presentation. Hydrogen produced from nuclear electricity is low-carbon but not renewable hydrogen. The CO_2 allocation method used for co-products should be clarified. In chlorine plants, there are inconsistencies regarding the use of water as input. It is surprising not seeing the impact of platinum group metals such as iridium and platinum on the GHG emissions for electrolyzers. The inclusion of H_2 in the gas global warming potential (GWP) is highly debatable. As H_2 is not a GHG, it is not to be considered as such, even if it has an indirect impact. The emissions of natural gas and methane remain the real problem. Moreover, for calculating the GWP, the latest equation adopted by the United Nations Framework Convention on Climate Change (UNFCCC) should be used, as this is now the Fifth Assessment Report (AR5) and not AR6.
- The project estimated GHG emissions for the byproduct H_2 from a chloralkali plant pathway. The project has built on past work to develop a large array of H_2 production pathways (for which energy and GHG emissions are compared). The project has also extended analysis to the autothermal reforming pathway and developed an H_2 module interface.
- The level of work is typically outstanding, but the project has opportunities to make the tool more policy-relevant.

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 simplified life cycle analysis (LCA) tool is a great way for non-regular users of GREET to understand the basics of LCA for hydrogen.
- GREET and the pathway analysis draw on a large range of domestic and international collaborators.
- Collaboration is adequate regarding the activity.

Question 4: Potential impact

This project was rated **3.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project's use of GREET will be significant, as it will impact the level of subsidies of hydrogen producers.
- Because of the large 45V tax credit, the potential impact of the project's work is almost impossible to overestimate.
- The models and pathway analysis will be widely used.

Question 5: Proposed future work

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

- Proposed future work is aligned with the project objectives. The project's inclusion of GWP of H_2 is highly debatable and should not be included before general consensus, based on scientific facts, is achieved. The possibility of taking CAPEX embodied emissions into account for all the pathways should be investigated. Achieving a full LCA is indeed the real approach to ensure achieving the climate targets.

Project strengths:

- The technical work and the level of detail regarding the LCA of hydrogen production technologies and potential end sources are unparalleled.
- The project has a long history, appears quite robust, and is already used by many people. The work is managed by experienced, highly skilled experts.
- GREET is foundational and a publicly available tool used by many groups for a wide range of applications.

Project weaknesses:

- There has been a good deal of debate around how to evaluate the indirect emissions from electrolytic hydrogen production, which requires accounting of a consequential-type analysis of the marginal impacts of a large electric load on a local grid. Since GREET is an attributional model, the project can utilize only defined resources (or a defined mix of resources) as emissions factors. However, depending on how eligibility is determined, there could be a good deal of variation as to what the "real" emissions impacts would be for a given project. Even a basic analysis of the impact of adding renewables based upon the project's Emissions & Generation Resource Integrated Database (eGRID) (even on an annual timescale or scaled up to an annual timescale) could have impactful policy implications for these types of projects. This is especially the case when attributing long-established low-carbon resources with little likelihood of being backfilled with commensurate generation technology (i.e., nuclear or large hydro). This is outside the traditional lines of GREET, but it could not be more important for the success of the 45V program.
- An H_2 GWP multiplier is not included in the analysis.
- There are no specific weaknesses to be reported.

Recommendations for additions/deletions to project scope:

- The project should add an H_2 GWP multiplier to the analysis. Electrolyzer embodied GHG can be presented as a combined value (stack plus balance of plant) and compared to batteries and photovoltaic panels (to put it in perspective).
- There should be some written analysis, reasoned discussion, or modeling that could attempt to address the significant potential indirect emissions impacts of 45V.
- The two main recommendations are not to include GWP of H_2 and to extend the model by including CAPEX embodied emissions for all pathways.

Project #SA-178: Cradle-to-Grave Transportation Analysis

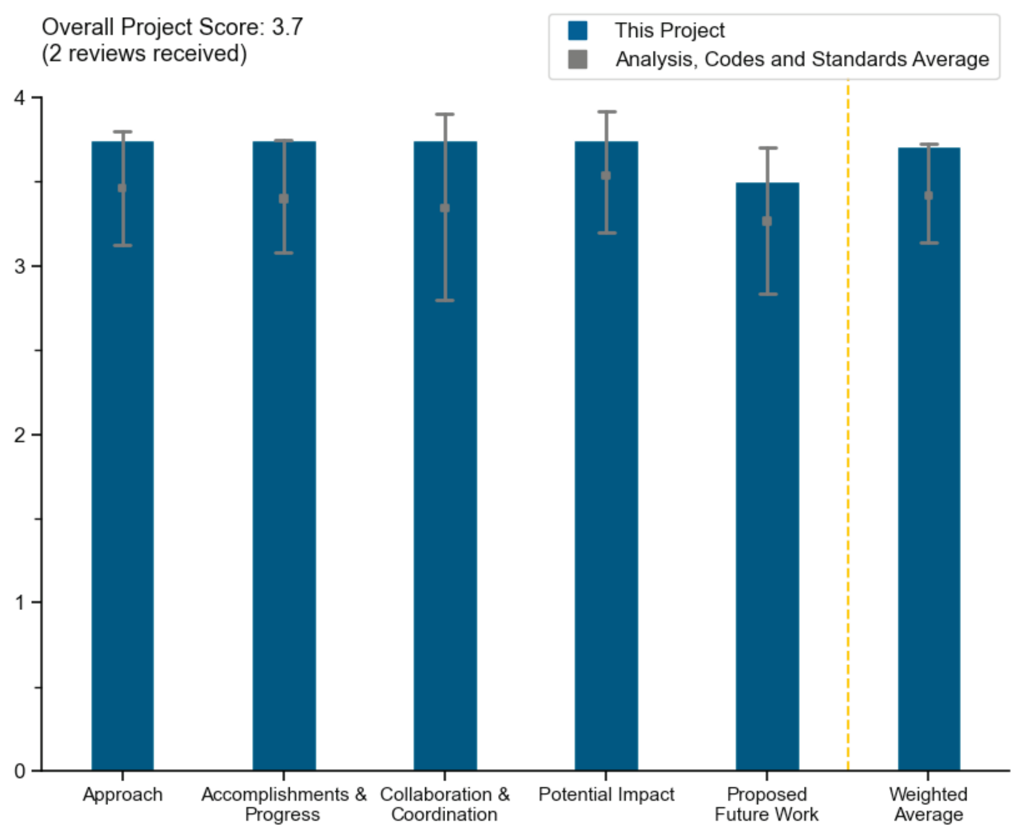
Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	WBS 5.1.0.6
Start and End Dates	10/1/2021
Partners/Collaborators	U.S. DRIVE Partnership's Integrated Systems Analysis Tech Team, Strategic Analysis, Inc., Argonne National Laboratory Autonomie Team
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 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 impacts of medium- and heavy-duty vehicles. 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 Analysis, Codes and Standards 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 **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach adopted is well aligned with the project objective to evaluate C2G economic and environmental impacts of fuel production and vehicle technology pathways.
- The level of detail provided is excellent.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments presented this year are of great interest and allow for expanding the range of vehicles considered in the GREET model. For the GHG emissions, it is not clear whether wheels and tires have been included, but they should be. It is expected to see different values of GHG emissions from tires, depending on the weight and the type of energy used.
- This project appears to bring multiple DOE goals together for a unified project, which could have very interesting future implications.

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 is a great opportunity and example of multiple types of collaborative work between different parts of DOE. Contract management should allow these types of collaborations.
- The level of collaboration appears correct for this project.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The usage of GREET has a significant impact in the choice of transportation from an economic and environmental point of view and for the level of potential subsidies. It is thus important to develop a transparent and reliable tool.
- It may be interesting to observe how deployment and actual C2G impacts take hold as state mandates for Advanced Clean Fleet regulations are implemented.

Question 5: Proposed future work

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

- The project should consider drayage and drayage-type trucks and how those operations, duty cycles, and configurations may be different from other Class 8 long-haul or box trucks. The project should also look at zero-emissions transportation refrigeration units and any sort of parasitic or related loads associated with transport refrigeration unit trucks, trailers, and containerized trucks.
- The future work corresponds to the need to evaluate the total cost of ownership, which is usually the main decision driver.

Project strengths:

- GREET is a tool that has been developed over many years with many users. It appears quite robust and is continuously improved upon with these kinds of projects.
- The project has a strong level of detail and consideration of the types of vehicles involved.

Project weaknesses:

- The project should consider drayage and drayage-type trucks and how those operations, duty cycles, and configurations may be different from other Class 8 long-haul or box trucks.
- There are no specific weakness to mention.

Recommendations for additions/deletions to project scope:

- Regarding fuel production, a full life cycle analysis approach, including capital expenditure embodied emissions, should be developed.

Project #SA-181: Global Change Analysis Model Expansion – Hydrogen Pathways

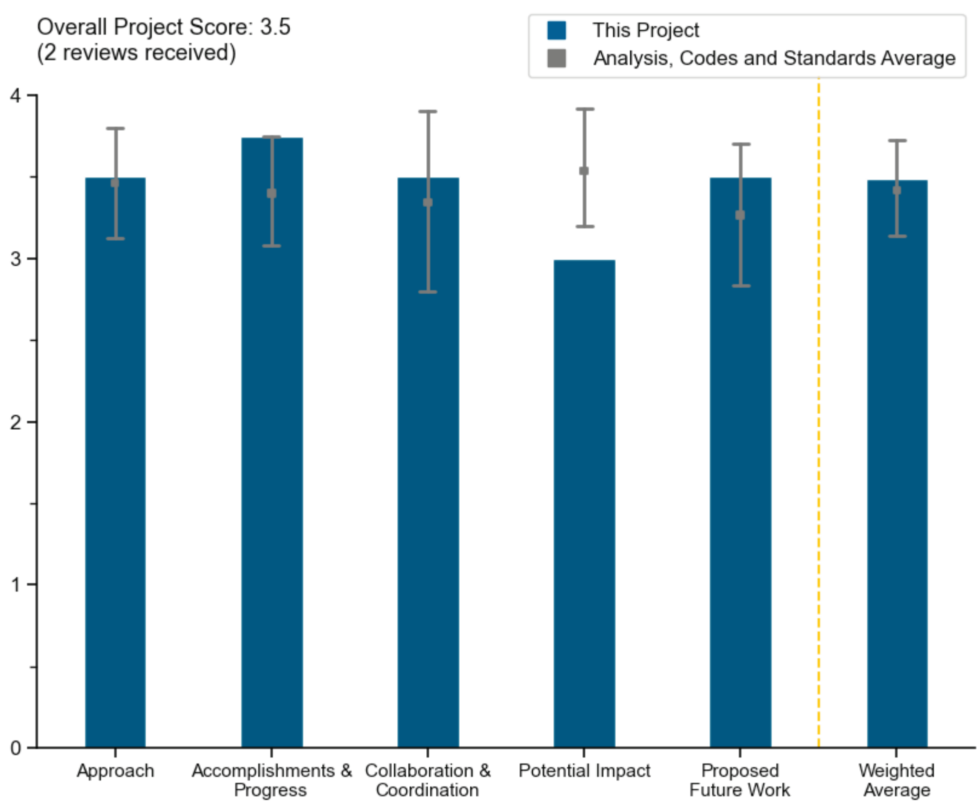
Page Kyle, Pacific Northwest National Laboratory

DOE Contract #	WBS 5.2.0.107
Start and End Dates	05/1/2021–10/31/2023
Partners/Collaborators	Argonne National Laboratory, National Renewable Energy Laboratory, University of Maryland
Barriers Addressed	• Complexity of modeling structures • Large number of assumptions to be reviewed • Consistency with ongoing Energy Efficiency and Renewable Energy research into these topics

Project Goal and Brief Summary

This project seeks to add a hydrogen module to a configuration of the Global Change Analysis Model (GCAM) in an effort to improve hydrogen representation in the tool, which allows researchers to explore the interplay of energy, agriculture, and climate systems. The work will include analyses of various hydrogen technologies to offer insight into their role and importance in facilitating system-wide emissions mitigation. By updating cost, performance, and emissions mitigation information on hydrogen production technologies, the project aims to increase hydrogen consumption in the industrial, transportation, refining, and building sectors, helping them to achieve decarbonization goals.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Analysis, Codes and Standards 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 **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Overarching objectives and barriers are generally well defined, and the project also appears fairly feasible. Despite the complexity, model updates are straightforward in their objectives and feasibility. The one piece that seems to require further attention and clarification is the "Value of Technology" analysis of hydrogen technologies in emissions mitigation. This objective is of utmost importance and cuts to the core of the foremost challenges concerning hydrogen. It is difficult to see from the materials offered how this analysis has been conducted and how identified strengths and weaknesses were laid bare by the test case.
- The project has a good approach for updating hydrogen in GCAM, which has long been needed.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and DOE goals.

- The project update makes a significant leap in the development and contemplation of hydrogen in GCAM/MiniCAM.
- There appears to be good progress on expanding hydrogen end uses, production, and transmission and distribution (T&D) options and incorporating updates in the public model version.

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 is necessary for this type of model development, and it is great that the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) team at Argonne National Laboratory and the National Renewable Energy Laboratory were included, and hopefully a sustainable pipeline for adding updates was established for implementing technology changes.
- Collaboration lacks sufficient information to provide a fine-grained response. However, based on the list of partners, there appears to be solid collaboration and coordination with academic and other DOE labs.

Question 4: Potential impact

This project was rated **3.0** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Considering the use of GCAM in Intergovernmental Panel on Climate Change reports and high-profile climate studies, including the U.S. Long-Term Strategy, the project's effort has significant importance in bolstering the evaluation of hydrogen in supporting U.S. and global climate goals and informing the Hydrogen Program and DOE research, development, and demonstration (RD&D) goals. However, the "Value of Technology" analysis will be a key component in determining the effectiveness of this effort in supporting DOE goals to target hydrogen deployment in high-value applications where it does not compete with more efficient solutions. There is little information on this analysis as of now, which makes it challenging to evaluate the degree to which this project supports DOE hydrogen programs and goals.
- The potential impact is difficult to gauge, as GCAM is extremely complicated and there are very few consumers who understand the specific nuances within the model. Ideally, there was contemplation and clear justification for how the baseline scenario was modeled with uncertainty and to highlight what or how parameters could be changed to reflect different baselines or specific model runs.

Question 5: Proposed future work

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

- The categories identified as future work are sensible, notably the addition of hydrogen emissions and their greenhouse gas (GHG) impacts. This is a key shortcoming in current models that may lead to major climate-damaging misfires in hydrogen deployment. That said, there appear to be two key missing categories:

    - Continuous refresh of the techno-economics of hydrogen end uses, including compared with clean energy alternatives. It is critical that GCAM remain at the frontier of hydrogen analyses by reflecting advancement in clean energy solutions to keep supporting the most cost-efficient pathways to net-zero.
    - A more fine-grained representation of hydrogen production pathways, notably various operational frameworks for electrolytic hydrogen. Those include variability of operations with renewable electricity availability and baseload, or close to baseload, operations.

  Those issues are the core of the 45V clean hydrogen debate and will remain key considerations in determining the highest-value proposition of hydrogen deployment for grid and economy-wide decarbonization.
- The proposed future work is important to capture and should be implemented soon and updated as the science of the radiative impacts of hydrogen are developed.

Project strengths:

- This is a project with utmost importance, considering the widespread use of GCAM in high-stakes climate and technology modeling, as well as the substantial interest in hydrogen as a climate solution. The expansion of hydrogen end uses and T&D technologies appears to be in the right direction, and plans to incorporate hydrogen emissions and their GHG impacts would position GCAM to be at the cutting edge of hydrogen modeling.
- The project’s strengths include interaction with other DOE research, as well as updates to the model and contemplation of the modern hydrogen sector, hydrogen production types, uses, etc.

Project weaknesses:

- The “Value of Technology” analysis will be a key indicator of this project’s effectiveness in supporting a fine-grained examination of hydrogen’s highest value proposition for decarbonization. The project provides little information in the materials presented on this piece, which poses some difficulty in determining the project’s value. Furthermore, it is key that in future work the techno-economics of hydrogen production and end-use technologies, as well as those of alternative clean energy solutions (e.g., direct electrification), be periodically updated to capture the continuously evolving nature of climate solutions. This is necessary to ensure that DOE’s Hydrogen Program and RD&D programs writ large support the most cost-efficient decarbonization pathways and avoid costly detours.
- The project has no real interactions with the conventional hydrogen market of petroleum refining or chemical production, as well as the more discrete impacts on renewable diesel or electro-fuel production. There could be important impacts as these technologies develop or if there are significant differences in the crude slates, which could significantly alter conventional hydrogen demand. Also, when hydrogen is used for the vehicles distributing the hydrogen to stations should be contemplated.

Recommendations for additions/deletions to project scope:

- The project should provide a periodic update of the techno-economics of hydrogen production and end-use technologies, as well as those of alternative clean energy solutions (e.g., direct electrification), to capture the continuously evolving nature of climate solutions. The project should include a more fine-grained representation of hydrogen production pathways, notably various operational frameworks for electrolytic hydrogen. Those include variability of operations with renewable electricity availability and baseload, or close to baseload, operations. The project also has an opportunity for public comment on the upcoming paper on the value of hydrogen technology in emissions mitigation.
- The project should have better interaction for renewable diesel production, especially in fossil fuel refining, considering its outsized demand.

Project #SA-186: Updates to National Energy Modeling Systems to Include Hydrogen Module

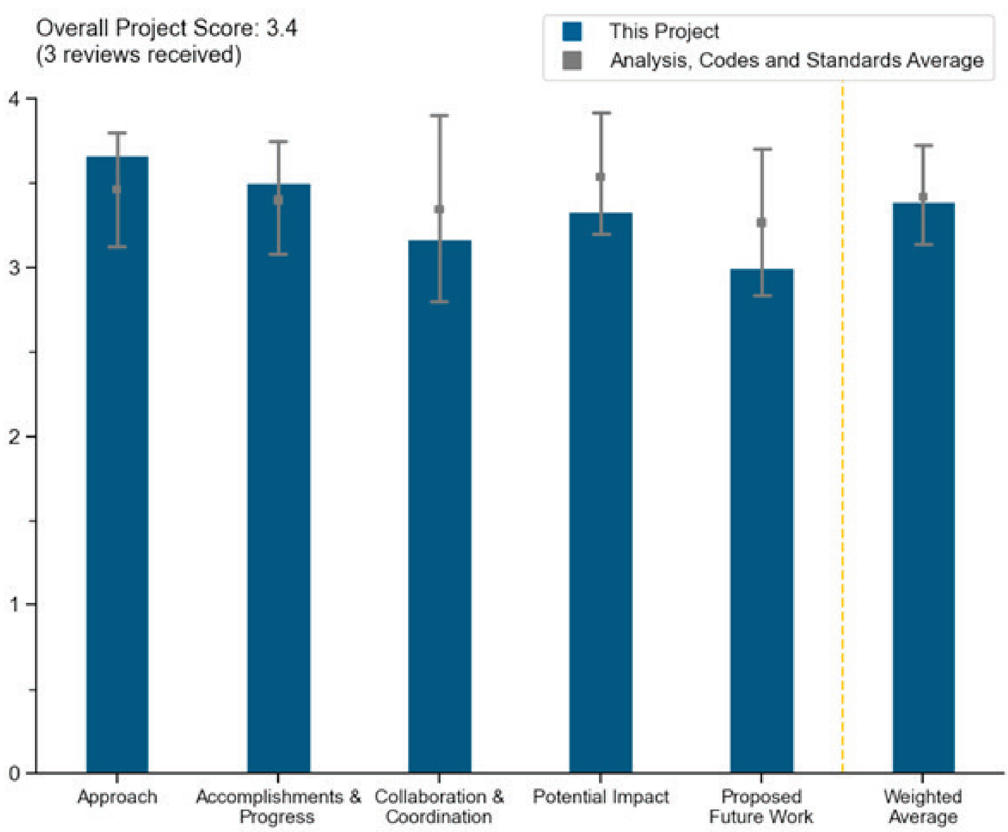
Michael Schaal, OnLocation, Inc.

DOE Contract #	38574
Start and End Dates	4/1/2022–12/31/2022
Partners/Collaborators	Office of Fossil Energy and Carbon Management, U.S. Energy Information Administration
Barriers Addressed	• Broad scope of changes needed across many sectors of the model

Project Goal and Brief Summary

This project aims to enhance the representation of hydrogen production, transportation, and storage in the National Energy Modeling System (NEMS). The project will add additional hydrogen demand representations to NEMS and increase the range of technology trade-offs available in low-carbon scenarios using NEMS. This project will review how existing U.S. Energy Information Administration (EIA) cases result in changes in the projection of future hydrogen supply and demand within an integrated area of the U.S. energy economy. The work will contribute to an understanding of which policies and technological advancements result in differing levels of hydrogen production and consumption.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Analysis, Codes and Standards 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 overall approach using the Advanced Interactive Multidimensional Modeling System (AIMMS) seems good. The addition of different modules for multiple uses of hydrogen is also good. However, the project may need to include some work around the hydrogen capacity expansion needed to support these industries.
- Project objectives are clearly defined. The progress on implementing a hydrogen market module and expanding the range of hydrogen end uses across sectors furthers the goal of enhancing hydrogen's representation in NEMS.
- Adding hydrogen to NEMS makes sense and could provide some interesting results or expose modeling constraints.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The project appears to contemplate the interactions of hydrogen throughout the economy and is working well to combine equities throughout DOE for examining how hydrogen can contemplate many programs.
- The project is making excellent progress toward the stated goals.
- While progress concerning incorporating a hydrogen market module (HMM) and expanding hydrogen sectoral end uses appears to be robust, it is difficult to determine how robust assumptions and model structures are from the materials offered for review. However, the categories implemented are sound and offer solid foundations for periodic improvements.

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 has great collaboration with national laboratories and is jointly funded by several offices. The project needs to make sure to include original equipment manufacturers for each sector that is modeled to ensure that the latest and greatest performance projections of hydrogen use are included. There are also several other significant economy-wide modeling efforts, such as from the Electric Power Research Institute (EPRI) Low-Carbon Resources Initiative expanding the EPRI Regen model, with which the project should collaborate.
- The reviewer does not have sufficient information about collaboration and coordination to provide a fine-grained response. However, based on the list of partners, there appears to be solid collaboration and coordination with federal agencies (EIA) and DOE programs. There seems to be missing collaboration with non-government entities, notably academics. DOE should encourage OnLocation to extend review and input opportunities to non-government entities, especially as NEMS is widely used by a diverse set of stakeholders, including non-governmental organizations and the private sector.
- The project is a research collaboration for many offices at DOE, and rightfully so.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward goals and objectives.

- Considering the central use of NEMS in government and non-government energy projections, in addition to its unique ability to endogenously assess the impact of various policies on hydrogen deployment trends, this effort has significant importance in bolstering the evaluation of hydrogen in supporting U.S. and global climate goals and in informing the Hydrogen Program and DOE research, development, and demonstration (RD&D) goals. However, absent thorough test cases where the model updates are demonstrated to enable an examination of the techno-economics of hydrogen relative to other clean energy solutions, it is difficult to assess the extent of the project's value. A thorough techno-economic comparison across clean energy solutions, and an endogenous evaluation of their merits in supporting climate goals, will be critical in determining the effectiveness of this effort in supporting DOE goals to target hydrogen deployment in high-value applications where it does not compete with more efficient solutions. There is little information on those capabilities in materials offered for review, which makes it challenging to evaluate the degree to which this project supports DOE hydrogen programs and goals.

- The project is conducting highly impactful work that undergirds strategy decisions for a variety of stakeholders.
- The impact is difficult to judge because few consumers fully understand the complexity of NEMS and, in particular, specific modules. The hope is that there is enough thought into the base cases and uncertainty bounds to help more inexperienced consumers (say, at EIA) take something useful from this tool.

Question 5: Proposed future work

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

- The plan to include granular temporal pricing in the representation of electrolysis is very sound and should be highly encouraged, as this will be a key factor in determining the economics of electrolysis and its interaction with the grid and broader economy. This issue relates to the core of the 45V clean hydrogen debate and will remain a key consideration in determining the highest-value proposition of hydrogen deployment for grid and economy-wide decarbonization. OnLocation should be encouraged to periodically update the techno-economics of hydrogen production and end-use technologies, as well as those of alternative clean energy solutions (e.g., direct electrification), to capture the continuously evolving nature of climate solutions. This is necessary to ensure that DOE's Hydrogen Program—and RD&D programs writ large—supports the most cost-efficient decarbonization pathways and avoids costly detours. OnLocation should also be encouraged to include estimates of hydrogen emissions linked to various production, transport, storage, and end-use options. The climate impact of hydrogen emissions is a key component to ensure that we do not misfire with DOE and private hydrogen investments and slow down climate progress.
- Proposed future work was not covered in the presentation; however, it seems that adding competition between sectors and the development of more modules would be future work.

Project strengths:

- NEMS brings a unique ability to endogenously examine the techno-economics of various clean energy solutions and policy impacts on technology deployment, and together with the substantial interest in hydrogen as a climate solution, that ability bolsters this project's importance and value. The HMM and added end uses appear to be in the right direction, and plans to incorporate granular temporal electricity pricing would support a fine-grained and robust evaluation of the interactions of electrolysis with the grid and broader economy. Additionally, the HMM would enable a much more robust examination of its optimal value for economy-wide decarbonization.
- The project offers explicit hydrogen supply and demand scenarios, contemplation of many hydrogen technologies, and interactions between parts of DOE to integrate complicated technologies into NEMS.
- The project has a comprehensive approach with multiple end uses.

Project weaknesses:

- Test cases assessing the ability of the enhanced model to robustly compare across clean energy solutions on the basis of techno-economics will be a key indicator of this project's effectiveness in supporting a fine-grained examination of hydrogen's highest-value proposition for decarbonization. There is little information in the materials presented on this piece, which poses some difficulty in determining the project's value. Furthermore, it is absolutely key that in future work, the techno-economics of hydrogen production and end-use technologies, as well as those of alternative clean energy solutions (e.g., direct electrification), be periodically updated to capture the continuously evolving nature of climate solutions. This is necessary to ensure that DOE's Hydrogen Program—and RD&D programs writ large—supports the most cost-efficient decarbonization pathways and avoids costly detours.

- It is not clear how much elasticity (elasticity around transient or based on delivery infrastructure) is built into the models.
- The project has no clear interaction with liquid fuel production.

Recommendations for additions/deletions to project scope:

- The project should include hydrogen emissions across the value chain and their greenhouse gas impacts. Additionally, the project has an opportunity for public comment on the representative/test results of net-zero pathways examined with the enhanced model. A periodic update of the techno-economics of hydrogen production and end-use technologies, as well as those of alternative clean energy solutions (e.g., direct electrification), is encouraged to capture the continuously evolving nature of climate solutions.
- It would be interesting to learn whether there are interactions between the hydrogen module and the liquid fuels module as, depending on the slate of crudes for petroleum or the introduction of more biofuel or electro-fuel technologies, there could be significant differences in hydrogen demand (as liquid fuel refining is the highest consumer of hydrogen).
- The project should focus more on decisions between sectors (i.e., pinch analysis of the highest value of climate-neutral carbon) and collaboration with EPRI, etc.

Project #SCS-001: Component Failure Research and Development

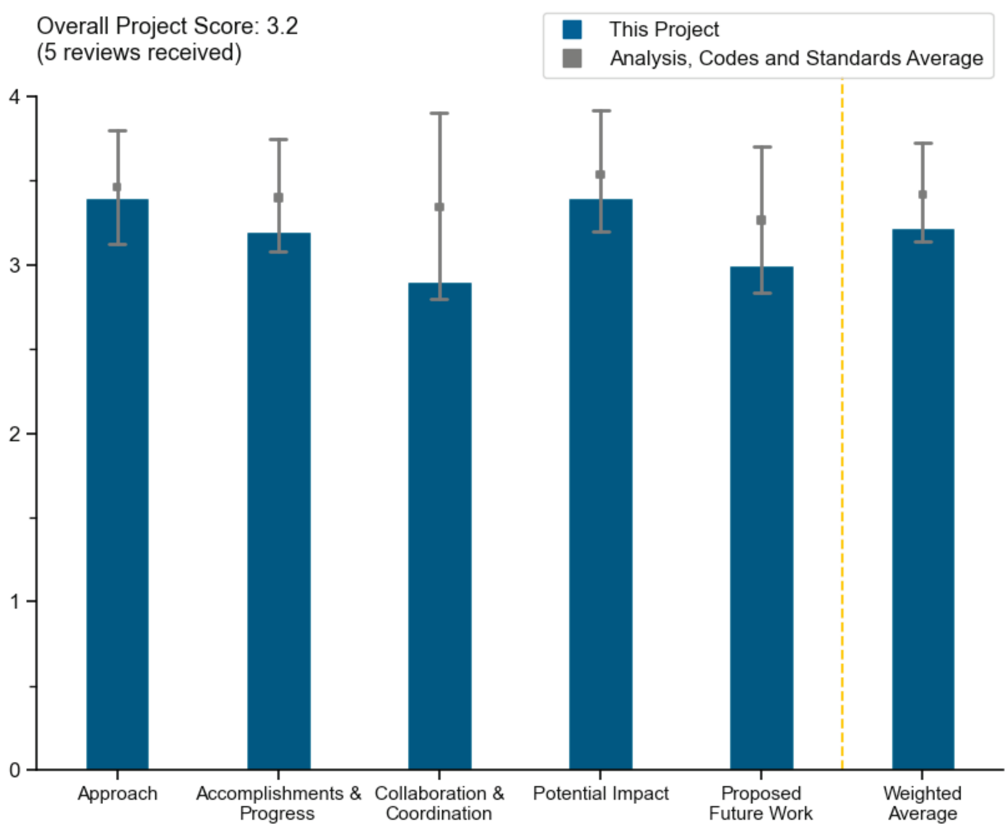
Kevin Hartmann, National Renewable Energy Laboratory

DOE Contract #	WBS 6.2.0.502
Start and End Dates	10/1/2018
Partners/Collaborators	University of Maryland, A.V. Tchouvelev & Associates Inc.
Barriers Addressed	• Safety data and information: limited access and availability • Safety not always treated as a continuous process • Insufficient technical data to revise standards

Project Goal and Brief Summary

The project aims to establish a scientific basis for risk and reliability analysis in hydrogen systems by integrating data collection, model development, and stakeholder engagement. To achieve this, the project focuses on deploying the Hydrogen Component Reliability Database (HyCReD) to track hydrogen-specific component failure rates and failure modes, understand leak behavior and size for different components and failure modes, and introduce new models and data into quantitative risk assessment (QRA) and prognostics and health management (PHM) for hydrogen systems. The project seeks to improve the reliability, safety, and cost-effectiveness of hydrogen systems through reduced downtime, enhanced understanding of hazards associated with leaks, and application of new models and data in risk assessment and system maintenance.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Analysis, Codes and Standards 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 stated project approach does an excellent job at laying the groundwork to achieve the project deliverables. The pathway is very reasonable and sound; it includes developing a component reliability database, developing an experimental means of quantifying typical failures modes (leaks), and then devising new models to support QRA of hydrogen systems.
- The project's approach to overcome barriers in safety data is clearly being addressed by the implemented methods. The project's collaboration with the University of Maryland seems well integrated and connects well with the DOE Hydrogen Program activities.
- The project problem and goal are clearly defined and understood. The project's tool will address critical barriers in the hydrogen industry.
- The ability to assess and capture hydrogen system component reliability is relevant, and work is advancing.
- Using modeling for QRA and PHM and using the Leak Rate Quantification Apparatus (LRQA) for leak rate and Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) to assess hazards is a good approach. However, the gaps seem to be lack of failure data.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The development of the HyCReD approach is an excellent accomplishment. The principal investigators shared subsequently that the database entry process was simplified to allow for the maximum uptake of useful information while at the same time minimizing the effort from the individuals providing the information. Given the project goals, this deliverable was critical. The use of existing failure information from H2Tools was also noted and should provide some good information for the effort.
- The HyCReD tool demonstrated significant accomplishments in this Annual Merit Review. The performance indicators are well defined and demonstrated through the examples shown.
- The team successfully compiled a database with existing information. To get more input, the user-facing interface should continue to be enhanced to allow the inputting operation to be simpler. Also, the tool should allow periodic uploads of large datasets from users.
- The HyCReD database would help with lessons learned and enhancing codes and standards. However, lack of failure incidences limits the database. More outreach is needed, and one hopes that more data will become available in the future.
- The project milestones and go/no-go decision points are not specified, so it is difficult to assess details. Qualitatively, work to date is relevant and comprises progress toward the overarching project goal.

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.

- There is good collaboration within the project team, which includes a well-rounded group of experts from the national laboratories and subject matter experts A.V. Tchouvelev & Associates Inc., and a call was made to support the failure incident database (HyCReD), but perhaps more coordination is necessary with groups such as the Center for Hydrogen Safety and the Hydrogen Safety Panel (HSP). Perhaps a presentation to the HSP is in order for the next meeting (which is in the October timeframe in Washington, DC).
- The project has great collaboration with a university, a private institution, and a government entity (National Renewable Energy Laboratory [NREL]).
- Collaboration between NREL and the University of Maryland is noted and productive. There are some concerns about industry engagement to populate the incidents going forward that might require different collaborations for project success.

- Further coordination and collaboration are needed with hydrogen facilities and the HSP. The incidents on components could also be included in the H2Tools database so all the information is available in one place.
- The project's tool needs significantly more partner engagement and input from operating companies to be successful.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project targets a strong need within industry to support QRA, given the lack of available (credible) leak data to support such risk assessments. The project provides an excellent use case, showing how the deliverables could support the safe implementation of hydrogen enclosures. Such enclosures could be relevant beyond stationary applications and could be relevant for mobile (tube trailers and fueling stations) and onboard vehicle systems (and rail, marine, and aviation applications where enclosures may be employed).
- Much of the existing hydrogen equipment is used near the maximum limits of its design. High pressures, pressure cycling, and temperature cycling of components is a difficult use case that causes significant reliability challenges in hydrogen equipment. This issue is problematic for hydrogen station operators and for the consumer who is affected by the poor reliability of stations. The project's database has the potential to highlight challenges that are faced by many organizations in the hydrogen industry.
- The impact of the project is demonstrated through identifying failure incidents and improving safety, codes and standards to prevent the events from occurring in the future. The project's model was done for compressed natural gas (CNG) vehicles through the Clean Vehicle Education Foundation, initially, and is now maintained by NGVAmerica. The project's database has been a good resource for safety standards development for CNG vehicles.
- This project has great potential to advance progress in obtaining very important data to greater reliability and in meeting DOE goals.
- The work is relevant and can help address DOE objectives. Solving the external engagement challenge will be critical to scaling up real-world impact.

Question 5: Proposed future work

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

- Collaboration with HSP, NREL, and hydrogen facilities to validate HyCReD and determine leak hazards is important. Also, quantification of the effects of hydrogen leaks within enclosures would be good for standards development. U.S. regulations on this matter may also need to be considered (https://www.reginfo.gov/public/do/eAgendaViewRule?pubId=202304&RIN=2127-AM40).
- Making the database able to be used by all is a critical next step for the project and seems feasible.
- The plan for future work is logical and relevant. More future focus on external stakeholders would be an important addition.
- The stated proposed future work activities present no issues.
- The project has no clear path forward to gather operational information. The project could engage industry organizations to introduce the tool and gain buy-in from the management of operating companies. Also, equipment standards organizations (such as the CSA Group) may be interested in supporting a tool that monitors performance of components during operation.

Project strengths:

- The project is well stocked with subject matter experts and is well organized in its approach to achieving the mission. The development of the HyCReD database is well executed, and the ensuing utility will support industry objectives.
- Hydrogen equipment has significant reliability challenges. The project's database will be a valuable tool for combining the influence of the entire industry to identify weaknesses in equipment reliability and performance and will encourage improvements in design.

- Validated tools such as HyRAM+ are already available for evaluating hazards from component failure. HyCReD could be a repository of component failure incidents that could help manufacturers and improvements to safety standards.
- The project uses a scientific basis for risk and reliability analysis that will significantly improve safety data.
- Viability of the concept has been validated. Good collaboration exists between partners.

Project weaknesses:

- The project has no major weaknesses. The project could engage more with industry and other organizations (CSA Group, HSP, etc.) to support HyCReD.
- Data of this kind is hard to find and clearly document. Although the project is making a great effort to do this work, it may be data-limited.
- There needs to be more coordination with hydrogen facilities and other hydrogen research communities to get component failure incidences in the field. Also, the project needs to coordinate with H2Tools to include HyCReD information so that all failure incidents are available in one place.
- The project’s major weakness is the lack of industry involvement. There are several potential incentives that could be utilized for contributing to this tool, and the tool could also be mandated as a part of funding opportunities. Industry involvement is key for success of the tool.
- The potential for limited impact at scale without more effective modes of incident input should be considered and addressed.

Recommendations for additions/deletions to project scope:

- The project proponents are strongly urged to explore expanding the project scope to include mobile applications (tube trailers and mobile fuelers) and onboard vehicle systems (heavy trucks, trains, ships, and aircraft) in which QRA forms an integral part of the hazard and risk assessment of the fuel cell electric vehicle system. For vehicles, for example, the process is embodied in design failure mode and effects analysis and functional safety assessments per International Organization for Standardization (ISO) 26262. This project could support an improvement implementation of these assessments.
- One issue obtaining a good deal of attention is blending hydrogen into natural gas supplies in Canada, Europe, and elsewhere. The project’s work might not lend itself to assessing elevated risks associated with introducing hydrogen into distribution and equipment designed only for natural gas, but it would certainly increase the relevance of the work.
- The project could evaluate how the Offshore and Onshore Reliability Data (OREDA) databank was structured to gather operational information.

Project #SCS-005: Research and Development for Safety, Codes and Standards: Material and Component Compatibility

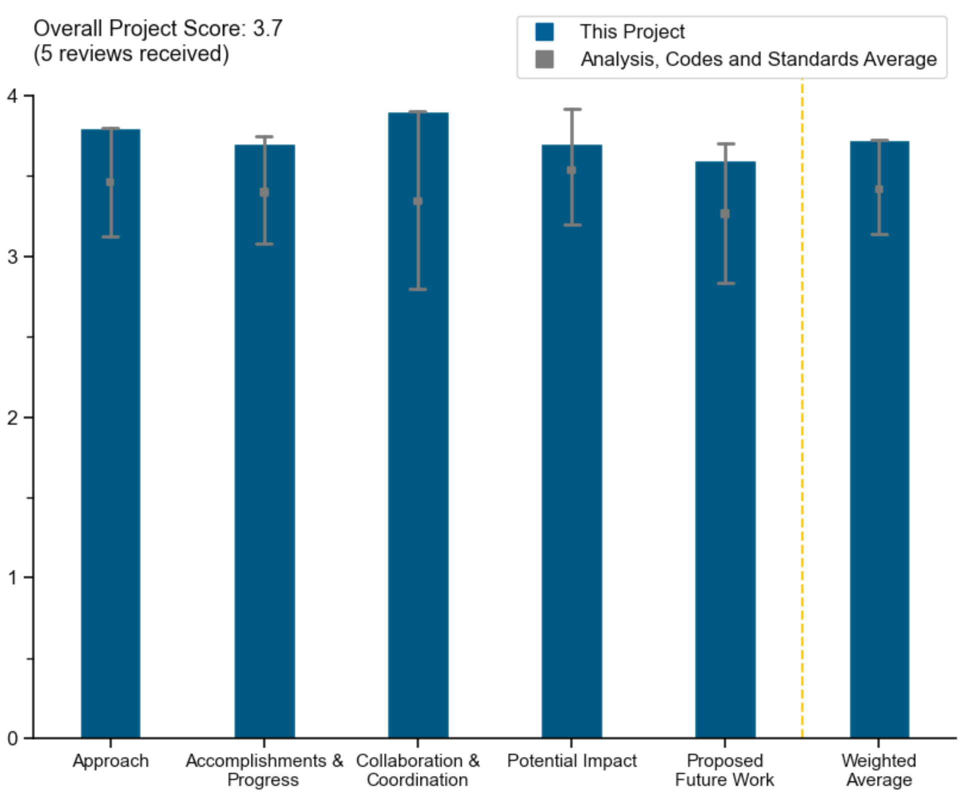
Joe Ronevich, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	CSA Group, American Society of Mechanical Engineers (ASME), SAE International, International Organization for Standardization (ISO), FIBA Technologies, Inc., Tenaris Dalmine S.P.A., JSW Steel, Swagelok Company, NASA White Sands Test Facility, Hexagon Digital Wave, Luna Innovations Inc., National Institute of Advanced Industrial Science and Technology (AIST) – Tsukaba, International Institute for Carbon-Neutral Energy Research (I2CNER), Materialprüfungsanstalt (MPA) Stuttgart, Korea Research Institute of Standards and Science (KRISS)
Barriers Addressed	• Safety data and information: limited access and availability • Consistent regulations, codes, and standards needed 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 Analysis, 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.

- As the project has progressed, different aspects of testing continue to be investigated. The current approaches of examining fatigue/fracture at different locations and orientations within "thick-walled" vessels is not fully understood. Similarly, it is not well understood if a correction factor should be applied to previous data for low-pressure applications (rather than extrapolation from worse-case data determined from high-pressure tests). Both efforts/approaches demonstrate this project is continuing to make progress and refine its previous work.
- Infrastructure advancement for hydrogen transport is a needed element to support climate goals. The project's approach addresses extending use of pipeline materials for gaseous hydrogen transmission as specified in ASME B31.12 code cases. The work advances the technical basis for fatigue design rules and test methodologies.
- The project approach is understandable and can easily be explained to those of us for whom materials testing is not a core expertise. The project also has the very practical objective of informing standards that will simplify the testing of equipment in hydrogen installations (the ASME code case for pipe evaluation).
- The project's goals are clearly identified, and the barriers have been addressed. Additionally, the project is sufficiently designed and easy to follow.
- Both general and specific testing approaches are well described and aligned with project goals.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- The project has made valuable contributions. It reduces uncertainty about the uniformity of fatigue and fracture properties and shows that fatigue and fracture in thick-walled pressure vessels can be independent of orientation and location. The project also provides a technical basis for code modification to allow pressure correction of fatigue design curves. The project demonstrates simple relationships to reduce testing burden for structural integrity assessment of hydrogen pipelines. In addition, test methods have been developed to characterize hydrogen effects on component fatigue.
- As a result of the refinement described in Question 2, both approaches yielded accomplishments, and the team's progress answered the nuances; fatigue and fracture do not depend on orientation of the crack within the thick wall of a vessel, and there is a correction factor that can be applied depending on stress intensity factor. This project has performed well.
- Although it has been in process for a very long time, the project has produced some clear scientific basis for understanding fatigue crack growth behavior in metals used for piping and components.
- Multiple slides demonstrate specific technical accomplishments and real-world impacts (application). Data charts are excellently annotated to point out data conclusions.
- There appears to be continual progress, proven by the status given on the project's milestones; however, this reviewer has little knowledge of material and component compatibility and cannot confidently state whether the project has adequately demonstrated progress toward addressing critical barriers to achieving DOE goals.

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.

- Given its longevity, the project has a breadth of collaborations/partnerships in various areas within the industry (e.g., standards development organization [SDOs], industry, and even international engagement). Engagement with international entities is crucial since international harmonization is a challenging yet vital endeavor.

- Collaboration is noted for research peers, code experts, and industrial groups. Data is well distributed and peer-reviewed. This effort demonstrates the outstanding quality and value of Sandia National Laboratories and its personnel.
- The project has good partnerships. The project has a good mix of industry, government (domestic and foreign), academia, and standards organizations.
- The range of SDOs, industry, and research partners is impressive and lends much credibility to the work.
- The project's collaboration and coordination are conducted with the right SDOs, industry partners, and international institutions.

Question 4: Potential impact

This project was rated **3.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project is crucial for the advancement and commercialization of hydrogen technologies. Also, engagement with international entities is crucial since international harmonization is a challenging yet vital endeavor. Such harmonization will significantly advance progress toward DOE research, development, and demonstration goals.
- The project relevance is clearly defined in slide 4 but could be amplified to qualify how this project fits into the overall high-level DOE Hydrogen Program goals and further advancement toward successful industrial hydrogen applications.
- The impact of the project will ensure that codes and standards are supported by the best information and made available to industry in a timely fashion to support development. In turn, the work is coordinated with international partners.
- The project would make testing/certification of materials in hydrogen service more clear-cut, quicker, and less costly and has great implications for industry.
- The team's work is leading the way on material embrittlement data.

Question 5: Proposed future work

This project was rated **3.6** for effective and logical planning.

- The future work described is useful, but it is unclear how much of it can be accomplished if the (20-year) project ends in September 2023.
- The co-principal investigators and the team are clearly building on past progress/achievements and plan to further develop their research.
- The project continues to refine and update existing methodologies of understanding material issues. The proposed future tasks are equally worthwhile and needed.
- The project's presentation clearly identifies barriers and qualifies them against the project scope to be completed and practical additional scope in the future.
- The proposed future work will continue to address barriers.

Project strengths:

- The project benefits from consistent and extremely knowledgeable investigative personnel who are well embedded in codes and standards organizations, as well as industrial groups. Project data will be extremely valuable in furthering industrial design and future codes and standards. The summary on slide 18 is outstanding in providing a high-level project description and results.
- The project uses a methodical approach to capture important learnings and has disseminated those learnings widely, particularly into ASME.
- This project continues to address industry and standards issues with focused effort by top researchers.
- The project is leading the world in gathering hydrogen embrittlement data for various metals.
- The project has an excellent history and diverse partnerships.

Project weaknesses:

- The project slides were missing safety planning and issues and mitigation. Since the poster slide presentation has key administrative and project data, an actual developed poster would have been more communicative at the poster session, rather than simply printing out the slides and mounting them on the poster wall. Diagrams and photographs of test process flow and equipment would have been more valuable. The project's key charts could be reproduced with several high-level bullets explaining impacts to industry and codes and standards.
- The project should expand upon/provide more information on the informational resources mentioned in the "Proposed Future Work" section and its plan to disseminate information on materials and component compatibility to the industry and the public.
- The project has taken a very long time to complete.

Recommendations for additions/deletions to project scope:

- It is recommended that the project consider evaluation and interface of past incidents involving piping and equipment fatigue failures in hydrogen service. Generalized data is readily available on H2tools.org and through the Center for Hydrogen Safety. The examples, along with other industry/working group input (e.g., NASA), may identify key incidents that could qualify future direction of testing scope and prioritize effort.
- The scope is defined primarily to advance hydrogen pipeline development, and this is being adequately addressed. However, expansion of the scope to include the evaluation of bulk metallic glass materials for use in hydrogen components could further serve hydrogen infrastructure advancement.
- Most of the data gathered to date is for thick-walled vessels. While this benefits large storage and gas line installations/industry, many newer applications use thin walls and tubing of various thicknesses (not typically considered thick-walled). Perhaps some future work could be to start determining whether these thin-walled systems demonstrate any different results from hydrogen exposure. Furthermore, this project could develop guidance for how to apply the materials data gathered to thin-walled systems.
- The project should probably look at the proposed future work and see whether there is a focused future project that can be defined from that. Then, the project team could close out this project and start a new one.
- The project should proceed and continue with its planned future work.

Project #SCS-010: Research and Development for Safety, Codes and Standards: Hydrogen Behavior

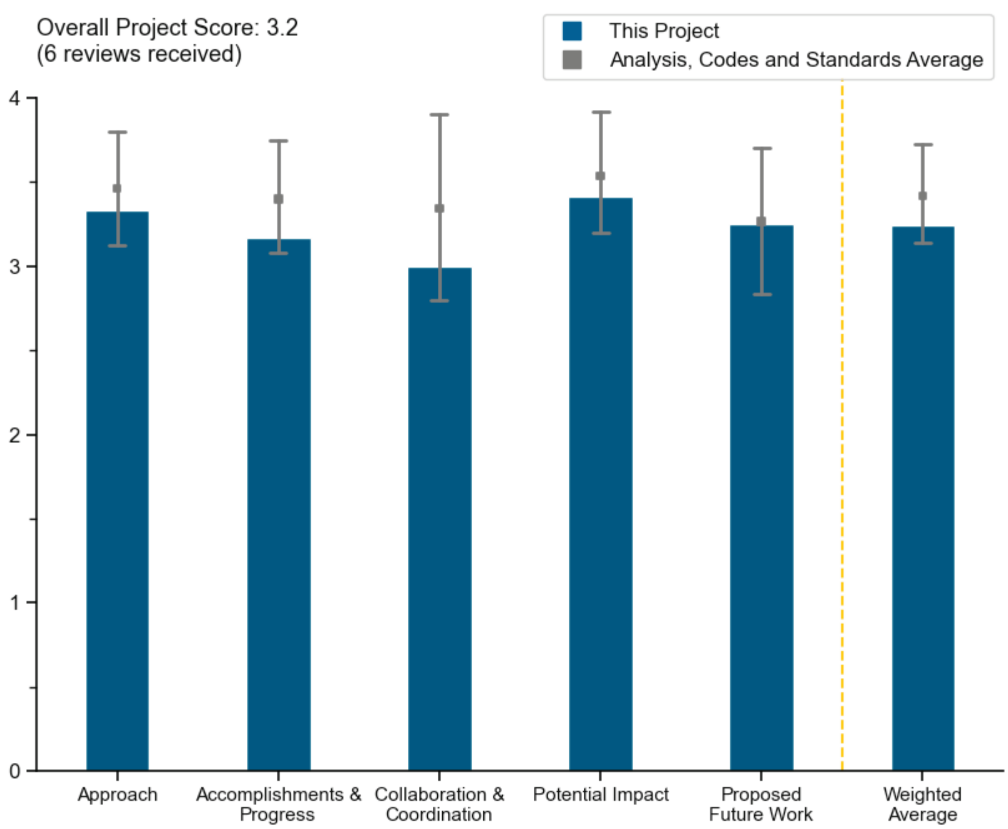
Ethan Hecht, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	National Renewable Energy Laboratory, Chart Industries, Inc., Air Products, National Fire Protection Association (NFPA) 2 Technical Code Committee
Barriers Addressed	• Conduct research to generate the valid scientific bases needed to define requirements in developing regulations, codes and standards • Enable the safe deployment of new hydrogen technologies

Project Goal and Brief Summary

Sandia National Laboratories 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, dispersion, 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 regulations, codes, and standards (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 Analysis, Codes and Standards 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.

- Proactive RCS efforts were initially (1990s) stymied by insufficient physical data and models to support safety codes. DOE has, over the previous years, funded engineering studies to remedy this issue and continues to address needs. The efforts have yielded good results for safe handling of pure gaseous hydrogen media. Now, attention is logically focused on the technically more challenging work of liquid hydrogen media and a new topic of focus, hydrogen–methane blends. The current focus of RCS efforts is well justified. The complaint that more could have been done sooner is tempered by noting that, in years past, reasonable focus was applied at the time, given the technical challenges and the funding available.
- This project is part of a coordinated activity with two other projects that feed each other and complement each other to facilitate deployment of technologies. It is clear that this work is essential to address three major areas where further development is needed. It is clear how it fits into the bigger SCS picture.
- This project is timely and has industry support. The approach to conduct experiments needed to validate numerical models and to impact the codes and standards development process is necessary as the industry moves from one form of hydrogen to another.
- Much work is needed to model liquid hydrogen applications/spills/releases. This project has this goal in its sights and continues to make progress in this and many other areas.
- The work is relevant and demonstrates a practically driven approach to illuminating safety measures for hydrogen use.
- Overall, the project has a good approach to executing various activities with good laboratory capabilities.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments presented include the following: the technical justification for National Fire Protection Association (NFPA) 2 (Hydrogen Technologies Code) liquid hydrogen (LH2) bulk storage setback distances has been formally documented, a generalized tunnel safety analysis has been developed, a physics model for the Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) is under development, a quantitative risk assessment (QRA) sensitivity analysis has been conducted for factors that drive distances to risk metrics, and a Python software backend has been made available for users to add their own software processing to HyRAM+. In addition, modeling of LH2 pool behaviors in HyRAM+ is under development, and actions to address reviewer comments from the previous year are in progress. These efforts are on focus to address barriers to RCS implementation.
- This project is making progress with the data (and funding) available. During the Annual Merit Review presentation, it was discussed that the model was validated with only a single data set. More data sets (which the team is working toward) will greatly improve the confidence in the model results.
- Specific milestones and go/no-go decision points are not identified, so it is difficult to assess progress toward specific goals in detail. Qualitatively, significant progress has been demonstrated on relevant technical issues, including the revisions to the 2023 edition of NFPA 2. Recognition and awards for the project are noted and demonstrate accomplishments.
- Several accomplishments are outlined in the presentation, and it seems like the project is successful. A few of them seem to need more data to be of additional value to the community. Nonetheless, significant progress is demonstrated.
- Modification to the NFPA 2 requirements is a valuable accomplishment.
- Outside of the LH2 activities to support the 2023 NFPA 2 publication, it is not clear how the additional activities support DOE goals.

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 participating organizations includes adequate collaborations with national laboratories, industry, and national and international standards organizations.
- The current partners (National Renewable Energy Laboratory [NREL], Chart Industries, Inc., Air Products, and the NFPA) are great. There are also many other LH2 users whose data could be beneficial for this project; the team could reach out to them to get more data (NASA, U.S. Department of Defense, other industry LH2 users and producers, etc.).
- There are decent collaborations, but the reach is actually much broader and was not brought out within the presentation.
- There is strong coordination with key industry partners. With the growing interest in large-scale deployment, however, these types of projects can benefit from greater industry involvement.
- Collaboration through the NFPA 2 committee is indicated. However, this seems to be an area where the project could improve and involve additional institutions.
- Collaboration with NREL is noted. Revising codes and standards has been accomplished and requires effective collaboration with external stakeholders and committees.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project has a very high potential impact toward meeting DOE research, development and demonstration goals and objectives. The LH2 modeling and separation distance determination is very much needed for siting LH2 systems. The results from this modeling/validation will enable this team to work closely with SCS bodies to update LH2 separation distances for improved station siting.
- The existing code requirements are restrictive and could translate into higher costs. With the growing interest in decarbonization of various industries, this project will have direct impact on specific code requirements and provide supporting data for a smooth rollout of small- and large-scale hydrogen infrastructure.
- The impact of the work extends NFPA 2 standards on bulk LH2 setbacks and improves HyRAM+ modeling capabilities. Progress has occurred on analysis of hydrogen hazards due to hydrogen vehicles in tunnels, LH2 pool and gas blend modeling within HyRAM+, and sensitivity modeling within HyRAM+.
- The work on hydrogen blending with natural gas is highly relevant and can be impactful going forward as the physical phenomena are understood and brought forward into hazard mitigation methods.
- The fundamental data being generated by this project is making a large impact in advancing the understanding of hydrogen behavior and will be useful in so many applications.
- It is unclear where the impact will end up with regard to the LH2 pooling and blending activities.

Question 5: Proposed future work

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

- It is important to advance the HyRAM+ capabilities for LH2 pool modeling, QRA specifications for green-hydrogen–natural-gas blends, and a generalized tunnel safety analysis framework.
- This project has a clear focus on future work; there is an undeniable need for real-world data to improve the existing models.
- The proposed future work is essential to improving this model validation.
- Future work seems effectively planned and will continue to be of extreme value.
- The proposed future work is reasoned and relevant.
- It was hard to understand how the proposed future work will be utilized and continue to support the SCS subprogram and broader hydrogen community.

Project strengths:

- One strength is the persistent effort to address RCS needs with state-of-the-art engineering research. A second is the continued follow-through to incorporate the findings in HyRAM+. The presentations identify where in-depth reporting and analysis can be found.
- This fundamental research will enable and answer many questions regarding hydrogen behavior. The scope and approach are being used to investigate several areas of interest and need in the community.
- Project strengths include a track record of successful scientific progress, delivery of practical results, tangible progress in the form of code revisions, and relevant topics including hydrogen blending.
- The results produced by this project benefit NFPA 2 by improving the siting of LH2 applications.
- This project is timely and will be critical to the hydrogen infrastructure rollout.
- The project has strong capabilities.

Project weaknesses:

- Correlation of research to how the results will impact the hydrogen community was lacking. With the integration of risk, the coordination and collaboration activities are much broader and stronger than presented. Also, it was hard to understand the relevance of the project activities outside of the NFPA 2 LH2 support.
- More defined plans to engage more broadly with external partners might provide extended benefits.
- This project could benefit from expanding the network of collaborators.
- Real-world data is needed to best validate the models.
- Additional data for validation of models is needed.

Recommendations for additions/deletions to project scope:

- The only recommendation is to continue to pursue the research agenda and collaboration with RCS stakeholders. One technical recommendation is for pooling research to develop a metric that can identify when pooling behavior might pose a hazard of condensing and entraining air products with LH2 (the persistent LH2 drip scenario).
- As the team moves into the test phase, it would be wise to develop a process for tracking any leaks or issues to then be able to feed that data on component failures into HyRAM+.
- Continuing to work with the code development organizations and expanding on the validation efforts are both necessary.
- The proposed future work is an appropriate template for expansions.

Project #SCS-011: Hydrogen Quantitative Risk Assessment

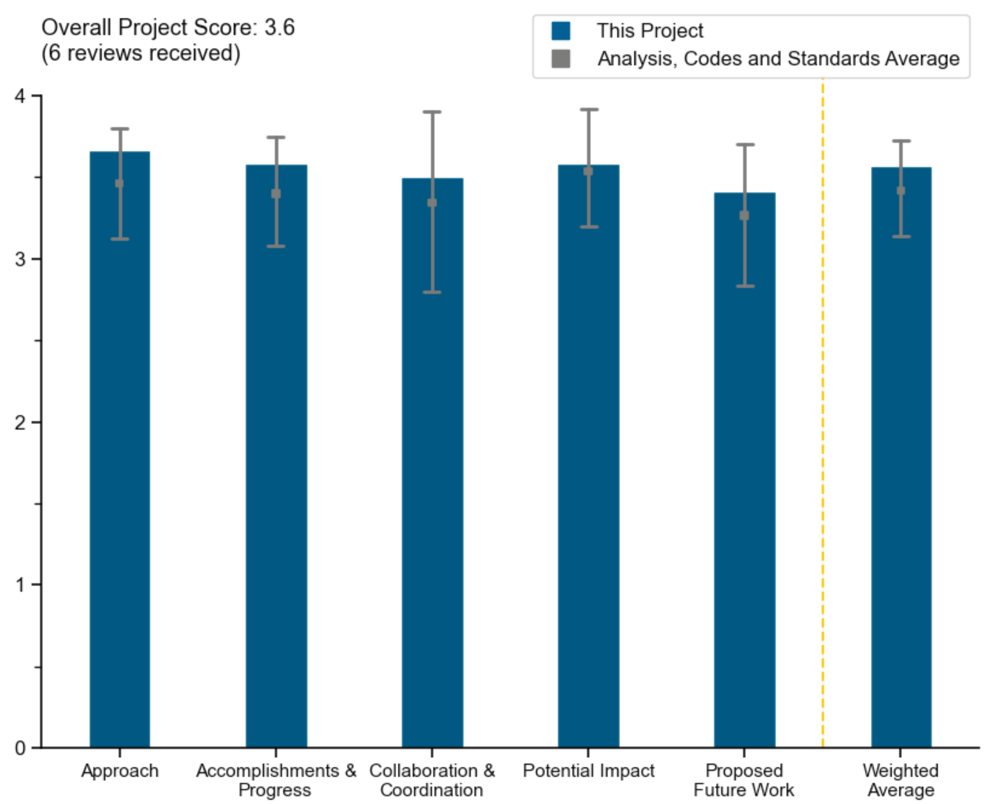
Ben Schroeder, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	Westinghouse Air Brake Technologies Corporation (Wabtec), Chart Industries, Inc., Hexagon AB, Hexagon Digital Wave, Air Products, Pacific Northwest National Laboratory, National Renewable Energy Laboratory, Argonne National Laboratory, HySafe, Sims Industries, National Fire Protection Association (NFPA) 2/55, U.S. Department of Transportation Tunnel Jurisdictions, International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), International Electrotechnical Commission (IEC), International Organization for Standardization (ISO), International Energy Agency (IEA)
Barriers Addressed	• Risk-informed codes and standards • Safe deployment of new hydrogen technologies • Harmonization of hydrogen standards

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 safety regulations, codes, and standards (RCS) for emerging hydrogen technologies. Sandia National Laboratories (SNL) will develop and validate hydrogen behavior physics models to address targeted gaps in knowledge, build tools to enable industry-led codes and standards 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 Analysis, Codes and Standards 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 approach is a strong blend of experimental, analytical, and computational work. The development and dissemination of tools and scientific safety information requires this type of multi-modal approach. The approach also includes projects to develop information for RCS, with a particular focus on National Fire Protection Association (NFPA) 2 safety distances for liquid hydrogen (LH2) bulk storage, and some tunnel requirements. This direct safety, codes and standards (SCS) development is a larger portion of the work (slide 6 and several accomplishments and plans) than the approach (slide 5) indicates for SCS-011 scope. While the approach is sound, it is questionable whether this applied standards work is the best use of the national laboratories. The DOE national laboratories are world-renowned for developing scientific tools and capabilities that industry cannot develop. It seems that model and tool development and credible information dissemination are better uses of the DOE laboratories than near-term work on harmonization of standards and continued revision of safety distances.
- Given the historical loss of rationale to past codes and standards for hydrogen use, this work is critical. The development of physics-based models promulgated in application packages for developers to use is an excellent strategy for promoting the use of risk-informed analysis. The findings from this activity inform RCS work and promote harmonization with international partners.
- The project is comprehensive, from modeling to implementation, which is extremely important for the overall hydrogen industry. The use of “real-world data” is an essential part of this work and for improving the standards.
- The Hydrogen Risk Assessment Models (HyRAM) toolkit is being used by various other DOE projects. This is a great tool for QRA in hydrogen facilities, tunnels, etc.
- Promoting and enhancing modeling tools to advance codes and standards development is critical to rolling out hydrogen infrastructure and avoiding unnecessarily conservative and costly requirements.
- The overall approach and relation with the other ongoing projects are excellent and very well explained.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- Finally, there are updates to bulk liquid storage setback distance requirements. Work continues on the complicated real-world issues of hydrogen release in tunnels, with engagement with the Massachusetts Department of Transportation. A newer area of focus concerns hydrogen blends. Work to clarify what factors present the greatest risk will be helpful to developers, as will providing a means (Python) for users to perform custom work with the HyRAM software. Work on modeling LH2 pool spill behaviors will be an important addition to HyRAM and, given recent initiatives for enormous storage facilities, will be a critical safety tool.
- The work in tunnels (i.e., looking at different tunnel structures; moving to blow-down, not constant release) to make the scenarios more “realistic” is very positive and will aid in helping the authorities understand the scenarios more completely. The work in hydrogen blends, especially modeling true natural gas mixtures and hydrogen–natural-gas mixtures for HyRAM, is forward-thinking and a great use of resources.
- The Python package for simplified use by others is helpful. The progress on tunnel safety is good, and the work with Massachusetts may open the path for other states to follow.
- Considering the complex and various components of the project, the accomplishments are outstanding.
- The most notable scientific accomplishments this year are integration of new features to handle hydrogen blends, the new standalone Python package, and integration of new validated LH2 pooling models. The progress on the QRA algorithms is surprisingly limited and unbalanced, given the maturity of the physical behavior models and the amount of effort spent on the applied work. The sensitivity analysis overlooks the key aspect of risk mitigation, the system design choices. The QRA algorithms need more development. On the work to develop the tunnel safety analysis framework, the results provided are too vague to determine what progress has been made. No framework was presented; there are no details on the scenario variants

being modeled or the thermal–mechanical analysis tools being used, nor were there details on how any facet of the work has been validated.

- Direct impact on code modification, acceptance of hydrogen technologies, and reduced potential cost through developing models and numerical tools are critical to a smooth technology rollout. These efforts, however, could have more defined start and end dates where the work is closed out and new projects are started to best track the specific project progress.

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 ample collaboration across the industry and the standards development organizations. The input from users, which has led to changes/improvements, is useful and should be highlighted more in future presentations, demonstrating the feedback loop.
- SNL has collaborated with facilities, states, and other research organizations, and the tools they develop will be used by others for safety standard development and risk assessment.
- The demonstrated impact on NFPA 2 highlights the existing coordination and collaboration for this project. There is opportunity for more industry input and engagement, as more data is needed for further validation.
- The project has an excellent, well-rounded list of collaborators. It is unclear what support is being offered to the 40+ users of HyRAM+ (Hydrogen Plus Other Alternative Fuels Risk Assessment Models). The principal investigator indicated the team did not make systematic collection of user feedback a priority. The most recent user guide on the HyRAM website is from HyRAM 2.0.
- The project has great partnerships, but it could benefit from feedback from users.
- The collaboration and coordination appear adequate for this activity.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The impact is of utmost importance in furthering the hydrogen industry through quality safety codes and standards. SNL is an invaluable resource in this respect. The work in tunnels has involved not only public entities but private tunnel owners, helping them to understand hydrogen uses/properties, etc., which is a key first step in furthering the hydrogen economy. Unfortunately, the grassroots efforts are still very much needed, and although this is likely secondary to the planned approach, it is helpful and needed.
- This project provides a rigorous scientific and engineering basis for the assessment of risk in hydrogen systems, which informs RCS activities. The development of models for hydrogen behavior and their incorporation into HyRAM for users comprise an excellent outreach program and are important contributions.
- Developing scientific models and bringing them into a freely disseminated tool such as HyRAM+ is an excellent and high-impact way to reduce numerous DOE-identified barriers, especially the development of risk modeling tools and the need for scientific research and dissemination of scientific information to enable SCS both near- and long-term. However, direct SCS development is a larger portion of the work, and making revisions to RCS is not the long-term, high-impact work that DOE laboratories are uniquely positioned to create.
- This work has brought, and continues to bring, focus to the underlying and realistic technical requirements for codes and standards development.
- The tools are being used by other DOE programs to assess QRA. This tool would help with hydrogen infrastructure development and the use of roads, tunnels, and bridges by hydrogen vehicles.
- The project is essential to understanding risk and preventing safety issues.

Question 5: Proposed future work

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

- The tool needs to be enhanced for QRA of LH2 and different gas blends. Also, the work on tunnels and other safety matters regarding liquid pooling and hydrogen flames is needed.
- The work on tunnel risks and liquid pool risks (especially for large spills) must continue. Recent proposals for use of geologic storage will also require analysis.
- As the industry explores different forms of hydrogen for storage and utilization, it is good to see that the existing models are expanding to reflect those trends.
- The proposed future work is relevant and needed to progress the overall program.
- The proposed future work for this year is aggressive.
- There appear to be no specific plans for developing important aspects of the QRA, which is surprising, given the task name. QRA requires probabilistic models, logic models, failure causes, and data, in addition to consequence models. SNL has made great progress on the development and validation of the hydrogen consequence models and leak frequencies within HyRAM+. However, a large part of QRA involves development of the causal logic models, such as fault trees and cut sets, that enable QRA experts to obtain nuanced scientific insight into the causes of failure and how to prevent it. The current project appears to be well positioned to enable this, but this does not appear to be a focus of recent or future work. The QRA capabilities need to be more than consequence models. Version 5.0 of a QRA toolkit should have modifiable fault trees, at a minimum.

Project strengths:

- The entire project is a strength and is imperative to the advancement of the hydrogen economy. The credibility that SNL brings is extremely valuable.
- The project expands on previous work. Many of the recent accomplishments highlight the correlation to previous efforts. Collaboration, industry involvement, and end users are demonstrated.
- The project has well-thought-out research, with set goals and milestones, that forms a cornerstone for other DOE activities regarding the hydrogen economy.
- The project's scientific modeling capabilities are complemented by both experimental and computational experts.
- The project includes essential modeling to ensure risk assessment.
- The impact on RCS and outreach efforts is important and should continue.

Project weaknesses:

- The challenges and barriers are heavily bent toward applied analysis for near-term codes and standards needs rather than research and development. It is surprising that the capabilities of a national laboratory are doing applied, near-term work rather than being focused on further development of enabling tools for industry to do the applied analysis. The project has a lack of peer-reviewed publications. The future work does not address limitations in the QRA technique implementation in HyRAM.
- Although a good amount of work and progress showcased in this presentation is an expansion on previous work, it is important to know when to close one project to start a new one and whether those previous efforts met their respective goals.
- Validation is important, but the project's lack of data might be an issue. The collaborative approach will be key.
- It is not clear what emphasis in work is needed. It is important that funding for this work continue.
- The reviewer can identify no weaknesses.

Recommendations for additions/deletions to project scope:

- The project's work has primarily revolved around addressing risks from hydrogen behaviors and potential consequences for combustion. However, risks from materials selection in hydrogen systems is less clear from a QRA perspective. SNL does provide relevant materials data regarding embrittlement, and Pacific Northwest National Laboratory has research into the behavior of polymers exposed to hydrogen. Designers are constantly trying to find improved materials solutions, and many are not well-informed regarding hydrogen issues. This may be an area where QRA work can play a role both in clarifying risks and for outreach to users.
- The only recommendation is to highlight the user feedback and how that plays into the overall updating/improvement of HyRAM. Otherwise, it is important to maintain a pulse on the industry to make necessary updates/improvements to the project. The fact that SNL is very involved in industry codes and standards should keep that feedback loop active.
- The project should expand user support, efforts to validate the information and models used, and data collection for leak frequencies.
- The project could benefit from broader international collaboration, such as the work on tunnels.

Project #SCS-019: Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources

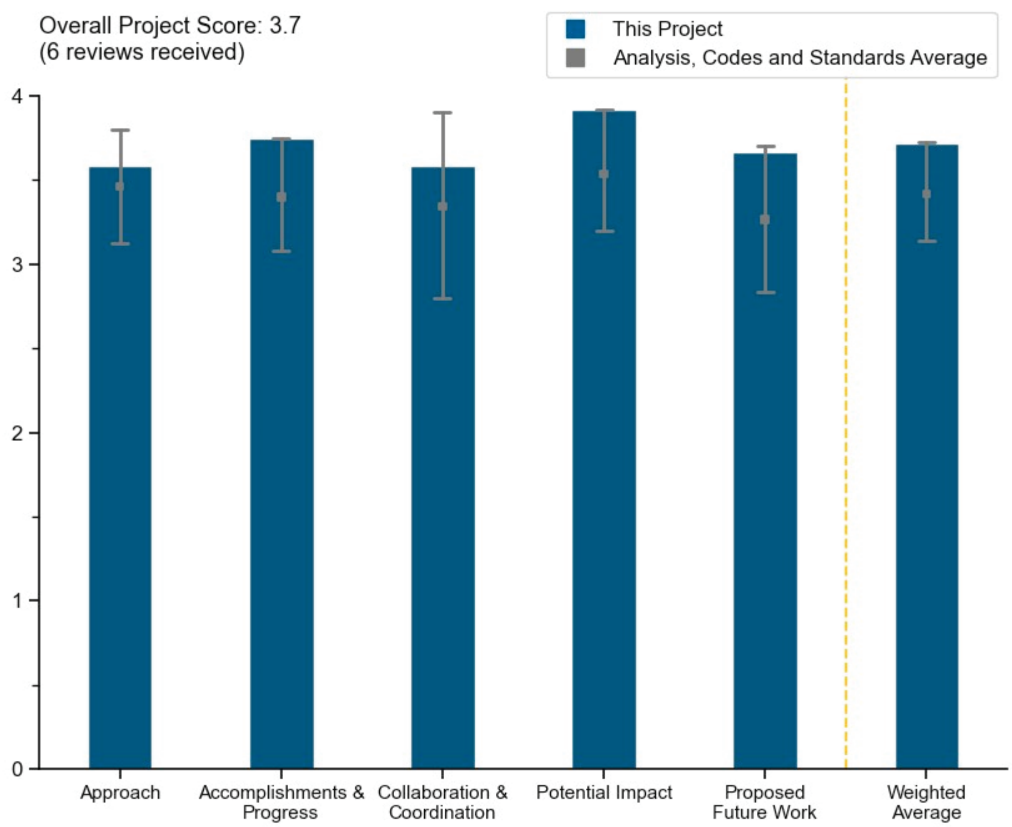
Nick Barilo, Pacific Northwest National Laboratory

DOE Contract #	WBS 6.1.0.702
Start and End Dates	3/1/2003
Partners/Collaborators	California Energy Commission, American Institute of Chemical Engineers' Center for Hydrogen Safety
Barriers Addressed	• Safety not always treated as a continuous process • Limited access to and availability of safety data and information • Lack of hydrogen knowledge by authorities having jurisdiction

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 is captured and added to the growing knowledge base of hydrogen experience to share with the hydrogen community, with the goal of preventing future safety events.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Analysis, 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.

- Congratulations are due to the project team on winning the Hydrogen and Fuel Cell Technologies Office's Safety, Codes and Standards award at the 2023 Annual Merit Review; the award is well deserved. The HSP, and now also the Center for Hydrogen Safety (CHS), are perfectly aligned to the needs of DOE and to the needs of the international hydrogen community, as witnessed by responses to the safety portals in place.
- The HSP, hydrogen safety tools, and first responder training are essential for deployment of hydrogen vehicles and other technologies. The approach of disseminating information on hydrogen to researchers and potential hydrogen facilities is important. Some of the courses and educational materials available are useful for safety standards development.
- The project has grown over the stretch of two decades, which is highlighted by the quantifiable metrics presented. The focus to promote safety is critical, and this project has grown in reach by partnering with key organizations and establishing global structure.
- With several years in the making, the project has an excellent approach to bringing hydrogen safety to the world.
- The project objectives and many critical barriers have been clearly identified and are being addressed. The project could be improved by expanding the approach regarding the two noted barriers on data. Access to and availability of the safety data and information are limited, and the project has insufficient technical data to revise standards. Fully addressing these barriers may require new approaches to obtaining data that has been difficult to obtain from industry experience.
- The barriers are clearly identified, and methods to address them are explained. However, the project might benefit from mapping against other existing ones to help gather more support. There is also a significant amount of information, as well as a number of activities, and explaining how the topics are prioritized could be useful.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and DOE goals.

- Significant measurable progress has been made, particularly with the HSP. The streamlining of the HSP review process is notable. Regarding safety knowledge tools and first responder training, one focus of the project is on the cooperative research and development agreement with the American Institute of Chemical Engineers (AIChE). Pacific Northwest National Laboratory (PNNL) transferred its first responder hydrogen safety training resources to AIChE to enable broader access to online and in-person training resources. It would be helpful to see metrics, if there are any, to measure how effective this has been. The project could consider including this in the presentation next year.
- While the initial focus was to ensure safety across all DOE-funded projects, throughout the last couple of decades, this project has expanded to become a critical part of all projects, including those outside DOE. While not mentioned in the slides, the adoption in other countries and in multiple languages highlights the success of this project.
- HSP accomplishments include various project plans, hazard analysis, training courses, an incident management guide, and incident investigation. Hydrogen Tools (H2Tools) provides lessons learned from incidences, best practices, and relevant codes and standards. These tools have been used worldwide by many. The first responder training by HSP is very useful. There are currently problems with first and second response for electric vehicles, and it looks like CHS is ahead of the game for hydrogen vehicles.
- This project continues to grow, providing outstanding accomplishments and progress toward implementing safety as a continuous process in hydrogen deployment in the environment. The addition of AIChE has proven to be a fantastic resource and is proving that in the seminars, training, and sessions it has been hosting.

- This project has accomplished outstanding metrics and established several pathways to gain know-how in hydrogen safety.
- The objectives are clear, and progress is well demonstrated.

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.

- By nature, this project maintains excellent collaboration and coordination with other institutions. The relationship with AIChE has helped to foster these collaborations. A question was posed during the presentation to elucidate the relationship with the International Association for Hydrogen Safety (HySafe) and the International Conference on Hydrogen Safety (ICHS). The response was that, by agreement, ICHS focuses on pre-normative effort, while CHS focuses on the applied part of the problem. As a result, CHS is frequently invited to provide a presentation at the ICHS meetings, and vice versa.
- The project continues to grow in the number of reviews and amount of data-sharing throughout the last couple of decades. Even more noticeable is the collaboration and partnering with relevant organizations to promote broader reach, real impact, and global adoption.
- This project has successfully coordinated with many organizations. To fully utilize the value of the safety information, the safety know-how should be shared with companies and standards organizations. Industrial gas companies hold a significant amount of operational experience in hydrogen, and these companies develop best practices for safety and safety standards through organizations such as the Compressed Gas Association and European Industrial Gases Association. There is currently little overlap between this project and these standards organizations, and this relationship should be improved to achieve the goal of this project.
- The project's existing partnerships are strong. The project may benefit from expanding partnerships to organizations that could provide access to incident and accident data. Also, the project could consider new partnerships that may be needed to accomplish the HySCAN tool development presented. To be able to drill down into applicable codes and standards, access to these copyrighted documents may be necessary. The project team should elaborate on this project next year.
- Collaboration is essential for this project and is well established.
- HSP/H2Tools and CHS outreach and collaboration are very good.

Question 4: Potential impact

This project was rated **3.9** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project excels at what it is intended to do, which is provide a safety resource to the community. Moving the safety panel to AIChE and combining that with CHS was an outstanding move. The Center provides the visibility, training, and tools necessary to accomplish the goal. The value is easily discerned when the "progress by the numbers" is considered on slides 12 and 23.
- The most important aspect of the hydrogen industry is safety. This project has done a superb job of collecting safety information, analyzing safety information, and utilizing the information to prevent accidents.
- Program and subprogram presentations emphasized the importance of safety, codes and standards to a higher degree this year than in years past. This project is well aligned with those goals and supports and advances those objectives.
- The project is critical, particularly the HSP part. It has become an essential expertise for new projects.
- The active sharing of safety data and the promoting of a safety culture in all projects are advancing the goals and objectives of the DOE Hydrogen Program and subprogram.
- This project would help with safe deployment of hydrogen technologies and garner public confidence.

Question 5: Proposed future work

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

- The project expanded to support California with its critical fueling infrastructure and is now looking at expanding to further include translating material into other languages for international dissemination. This is an important piece to promoting safety globally, as well as the alignment of the HSP for the launch of hydrogen hubs and the mentoring process to gain more talent.
- As hydrogen technology is introduced, HSP, H2Tools, and CHS are needed. There needs to be outreach to first responders for training and for standardized emergency response guides.
- This reviewer looks forward to seeing the continuation of this work, as it is crucial for the hydrogen industry.
- Progress, focus, and deliverables are outstanding; the project should stay the course.
- The proposed future work is well aligned with the needs of the industry. However, it could be of benefit to better explain the procedure in place to exchange knowledge and experience with other organizations around the world and how it translates in existing (or new) codes and standards.
- Continuing activities is important. Plans to expand, such as "deploy additional best practices on new and uncovered topics," are vague. The project should elaborate on these next year, with consideration to new collaborations that may be necessary.

Project strengths:

- The HSP has become a key advisory group for many new hydrogen projects. The new process in place to review proposals is an excellent improvement. The project resources created are essential. The trainings have become well recognized and aligned with the industry needs.
- The presentation covered a multitude of activities that are important to achieving DOE goals in safety, codes and standards. The project allows suitable flexibility to make measurable progress.
- The project's strength lies in the collective knowledge of experts and the pursuit of aggressive metrics to promote safety across all hydrogen projects.
- The project is well-thought-out and is needed for deployment of this new technology and for public acceptance.
- The project is clearly the best on the planet. It is a real gem for the global hydrogen community. The team is encouraged to keep it up.
- The project has an amazing body of work around hydrogen safety.

Project weaknesses:

- The portal may not be clearly updated, as some of the references are not exactly aligned with existing documents. It is unclear how the new HySCAN tool will work. During the presentation, it was specified that it will focus on National Fire Protection Agency (NFPA) 2 first. The project should reference accordingly once the page goes live.
- The project covers so many useful activities and tools, with too much to cover in a single presentation. The project could consider splitting HSP and H2Tools into separate presentations in the future (as evidenced by the speed of the presentation and number of questions). The project's data needs remain a barrier.
- There is opportunity to advance codes and standards in the hydrogen space, particularly in infrastructure. While it has a successful track record and it is a critical part of all hydrogen activities, the impact of the HSP, the various training curricula, and safety data could be further promoted.

Recommendations for additions/deletions to project scope:

- The answer to the document review given in slide 18 does not address one critical point the reviewer mentioned in the review. It was recommended that "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." No reference was seen on slide 18 to going "outside" the organization during the review process. It is critically important to seek a "fresh pair of eyes" on documents that the general public will see and potentially use. If someone from outside the organization is not available to perform the review, then a person inside the organization who is distant from the creation of the product/document should be used as an independent set of eyes.

- This project should increase the focus on liquid hydrogen (LH2) safety because there are many LH2 sites being installed and operated near the public.
- The project scope is very large and may benefit from a longer time presentation for future Annual Merit Reviews.
- HSP could help promote advances in codes and standards to establish new and technically sound requirements.
- The project could include standardized emergency response guides and rescue sheets so emergency responders know where to look for different types of incidences.

Project #SCS-021: National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory

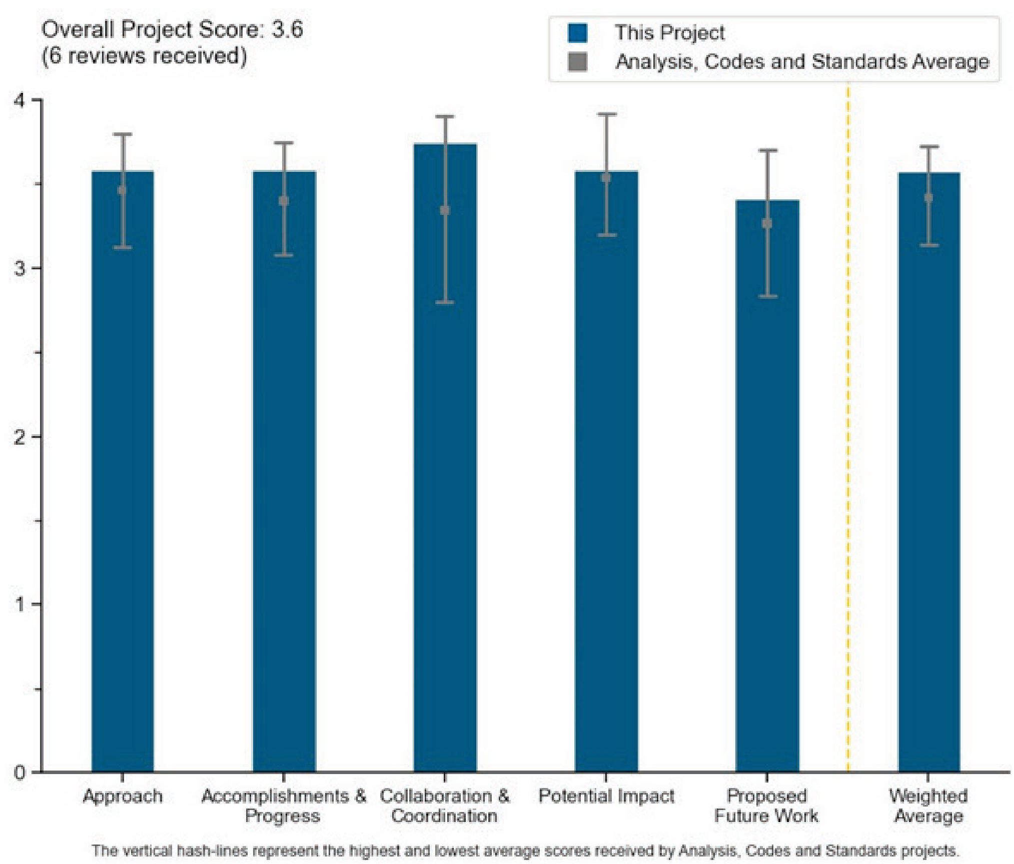
William Buttner, National Renewable Energy Laboratory

DOE Contract #	WBS 6.2.0.502
Start and End Dates	10/1/2010
Partners/Collaborators	AVT and Associates, Element One, Inc., University of Maryland, KWJ Engineering, Inc., Los Alamos National Laboratory, Shell, Amphenol, California Air Resources Board, GTI Energy, Electric Power Research Institute, Paulsson, Inc., Renewable Innovations, Boyd Hydrogen, LLC
Barriers Addressed	• Insufficient technical data to revise standards • Insufficient synchronization of national codes and standards • Limited participation of business in the code development process

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, regulatory agencies, 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



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.

- Because of hydrogen behaviors, improvement in detection technologies is still critical for monitoring safety and environmental concerns. The mission of the NREL Sensor Testing Laboratory is important for development of a national hydrogen infrastructure. The current focuses of the project are appropriate for national needs (early detection, trace-level detection, fuel blends, wide-area networks, modeling, etc.). In addition, the laboratory stands in as a "standards" lab for evaluating the true capabilities of new detection technology. The experience and findings from this lab are shared with regulations, codes, and standards (RCS) groups.
- The project goals slide is a great summary for the value of this project; "secondary greenhouse impacts" should not be used as a factual statement (the word "potential" should come in front of that phrase). The way the principal investigator said it was more accurate and less accusatory: "...losses along the value chain that impede market acceptance." The ability to do parts-per-billion detection for emissions monitoring for profitability is a realistic concern, as opposed to potential environmental impact, which is to be determined and might be secondary to the financial incentive for preventing leakage.
- The project has a multipronged approach to advancing sensor technology for improved safety and control and is conducting excellent work.
- The project continues to excel and is highly productive, producing excellent results, including new sensors; mentoring young scientists; and collaborating with a broad range of collaborators. It is simply outstanding.
- The project is sufficiently flexible to be able to identify and implement specific research and development (R&D) activities that support DOE and project goals.
- This effort does not appear to be a traditional DOE project in the sense that it has a single focus and mission; rather, it is a funded test facility and staffing that address multiple issues related to hydrogen detection technologies. As such, the approach will vary with the individual tasks assigned to the lab, and for the tasks reported this year, the approaches seem perfectly sound.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- Accomplishments for this period are appropriate and include upgrading the laboratory to address questions involving fuel blends, validation of sensor nets and trace detection technologies for emissions monitoring and quantification (for both open air leakage and fuel exhaust), and detection of contaminants. The work has included evaluation of sensors for cold hydrogen releases and evaluation of indoor leak scenarios.
- The project continues to remain aligned with the goals and needs of the DOE Hydrogen and Fuel Cell Technologies Office and especially the Safety, Codes and Standards subprogram element. Sensors are key components of all installations of hydrogen technologies, when properly deployed, and this project provides the background and support to ensure the appropriate and safe deployment of sensing technologies. The project excels at all the DOE performance metrics.
- This work started with "how well do sensors work" and has progressed to how to use them properly. The model validation for larger applications, such as hydrogen–natural-gas blends and manufacturing, is relevant and needed. While there is attention to the environmental concerns of leakage, care should be taken not to raise this to the top of the priorities to call unneeded attention to an issue that may not be an issue or may be of little consequence. Realizing that any potential issue should be addressed/resolved, there should be caution as to how much weight is given to each (i.e., a financial incentive not to lose molecules is warranted, versus an outcry—from those unfriendly to the industry—about an unknown "harm"). Any results/data that can be applied should be, but perhaps as secondary. Hydrogen sensors and monitoring is always important for safety and economic reasons, both from a leakage and hydrogen fuel quality perspective.
- The project has made really good progress toward the DOE goals, especially the great pivoting to cover timely topics such as blended fuels and hydrogen emissions, which have recently become a naysayer sounding bell against fuel cell electric vehicles (FCEVs). In this latter issue, it is great to see the national

laboratories doing productive work to address this head-on. The need for venturing into particulate analysis/testing is questionable. Regarding the choice of this issue as a course of study/focus, it is not clear where the facility gets its recommendations for future work. Greater effort must be made to ping industry for critical needs as they relate to the core expertise of the facility.

- The project has multiple accomplishments that seem to be demonstrating the success of the project and advancement of technology.
- This project demonstrates progress in detection and sensor equipment validation, but application to new markets may potentially require new approaches.

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 continues to maintain an active mentorship aspect to the project. Indeed, several of those being mentored moved on to be hired by NREL as staff. This project also maintains a well-constructed collaboration/coordination activity. This is outstanding.
- Collaboration is broad and well represented. The new sensor technology being demonstrated with GTI Energy and at the Advanced Research on Integrated Energy Systems (ARIES) facility is a great example of working with industry in R&D.
- The project's collaboration and coordination are impressive. The intern involvement is nice to see, as this is educating our future workforce.
- Existing collaborations are very appropriate, and there continues to be effort to expand collaborations to support implementation of sensors and new and emerging applications.
- This project continues excellent interaction with RCS groups, industry, academia, and international partners.
- The project has a fantastic list of collaborators and coordination efforts, but it would be good to do more focused feedback loops with industry. As the list is rather large, the non-academic, research, and other institutions far outnumber industry.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This work is spot on, advancing the safe deployment of sensing technology relevant to the application at hand. The project has been developing wide-area monitoring for the detection and location of leaks at large facilities over the past few years, which is a focused activity driven by H2@Scale. This is well done. This capability will also find application in quantifying leaks into the atmosphere to understand the secondary effects on climate and the primary effects on the commercial need to quantify fugitive leaks. A leak to the atmosphere represents molecules one cannot sell. Again, this is outstanding.
- The facility and this work product are critical to the success of the hydrogen industry. Safety is paramount, and the rapid, reliable, efficient detection of hydrogen releases is directly linked to safety and the ensuing success of the industry. All of the accomplishments achieved this year are noteworthy, with only minor regrets for a wish for re-focus, as indicated elsewhere in the review comments.
- Using the onboard vehicle sensors as an example, this is important, and there is more work to be done, as demonstrated by an audience question around "what can be done to prevent sensors from being poisoned by environmental conditions" (or, say, a truck pulling into a paint facility). Care needs to be taken in how the data is presented. That said, there is certainly valuable work being done, such as the SAE International paper on qualifying sensors for onboard vehicles.
- The project and the efforts of the laboratory include assisting technology developers, validating technology developments, identifying issues and directions for their solutions, and providing critical communications to the sensor development community and to RCS developers.
- A reliable sensor can make all the difference in a hazardous scenario. The project's work has the potential to help prevent many incidents.

- The project focuses on mitigating releases and addressing process control, which are both important to ensuring safety as more hydrogen projects are deployed.

Question 5: Proposed future work

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

- Advanced methods of detection are needed and will aid the industry. The way the project's work is presented in the slides is very positive and forward-looking.
- The project continues to expand upon needs that will benefit the industry. The project seems sufficiently flexible to address many of these needs, albeit with significant challenges, as described in the presentation.
- Progress, focus, and deliverables are outstanding; the project is encouraged to stay the course.
- The project's future work seems feasible and well-focused on overcoming barriers.
- The scope of the test facility and experts should be broadened to include automotive/onboard hydrogen sensor technology.
- The project should work on detection regarding hydrogen release behavior, active area monitoring, and specialized needs in emerging markets. Low-level detection still requires support by the laboratory.

Project strengths:

- The hydrogen sensor laboratory is clearly a much-needed resource for DOE and industry and should be expanded and supported to address even more topics. All project accomplishments listed for this year are well delivered and demonstrate the high caliber of the facility and experts there.
- The project is concentrating on the overall safety and economic drivers for sensor development and improvement. Improving the safe implementation of all hydrogen systems is nothing but positive.
- The project addresses key aspects of hydrogen detection and risk mitigation. Learnings are shared with codes and standards development organizations.
- The NREL sensor laboratory continues to perform relevant and critical work on a multitude of topics. This reviewer hopes that this can continue.
- This work is essential to the hydrogen community and will help enable the hydrogen economy's progress.
- This project is clearly the best on the planet and is a real gem for the global hydrogen community. The team is encouraged to keep it up.

Project weaknesses:

- It is difficult to optimize a project when the applications are a moving target. Having said that, it is appropriate that this project has the flexibility to make progress on established objectives, while also exploring solutions for new and emerging applications.
- The accomplishments for this project are not easily measured, nor does the future work outline metrics by which success of the project can be measured.
- The project is not as aggressively funded as one might hope.
- The project has no obvious weakness but should expand the scope a bit—and keep up the excellent work.

Recommendations for additions/deletions to project scope:

- The project should consider onboard "vehicle" hydrogen detection technology, especially in light of the expanded end uses for FCEVs, including Class 8 trucks, rail, marine, and aviation. Following are some topics for future consideration:
    - Pursue/develop a mock functional safety assessment for onboard vehicle hydrogen release monitoring, and show how the safety concept of the vehicle design drives the Automotive Safety Integrity Level (ASIL) rating of the sensor and the electronics that report the sensor results to the operator. Then select and test specific sensor designs/technologies to confirm the performance and ASIL rating.

    - Examine how poisoning of the hydrogen sensor affects performance and what mitigating factors could be employed to improve performance. This recognizes that the “vehicle” is never stationary and could come into contact with various airborne chemicals.
    - Evaluate hydrogen sensor technologies that can be employed inside the FCEV exhaust, where the sensor must operate in hot, wet environments.
- Related to sensor placement and the quantitative risk assessment (for Hydrogen Risk Assessment Models [HyRAM]), the project could produce a report/white paper for a less technical audience—a document with solid resources/references that can be used in project packages and readily absorbed by those reviewing said projects. The report or paper could potentially be a safety resource on other public websites and perhaps is already being considered.
- One area that the laboratory is probably aware of but has not mentioned specifically as a topic to investigate has to do with sensor development that uses “artificial intelligence” or “machine learning” in conjunction with analyzing what real time arrays detect. It is not clear how this technology works and what the claims of developers are with this technology. As with any other attribute of detection, what this technology delivers should be subject to evaluation and testing.

Project #SCS-022: Fuel Cell and Hydrogen Energy Association Codes and Standards Support

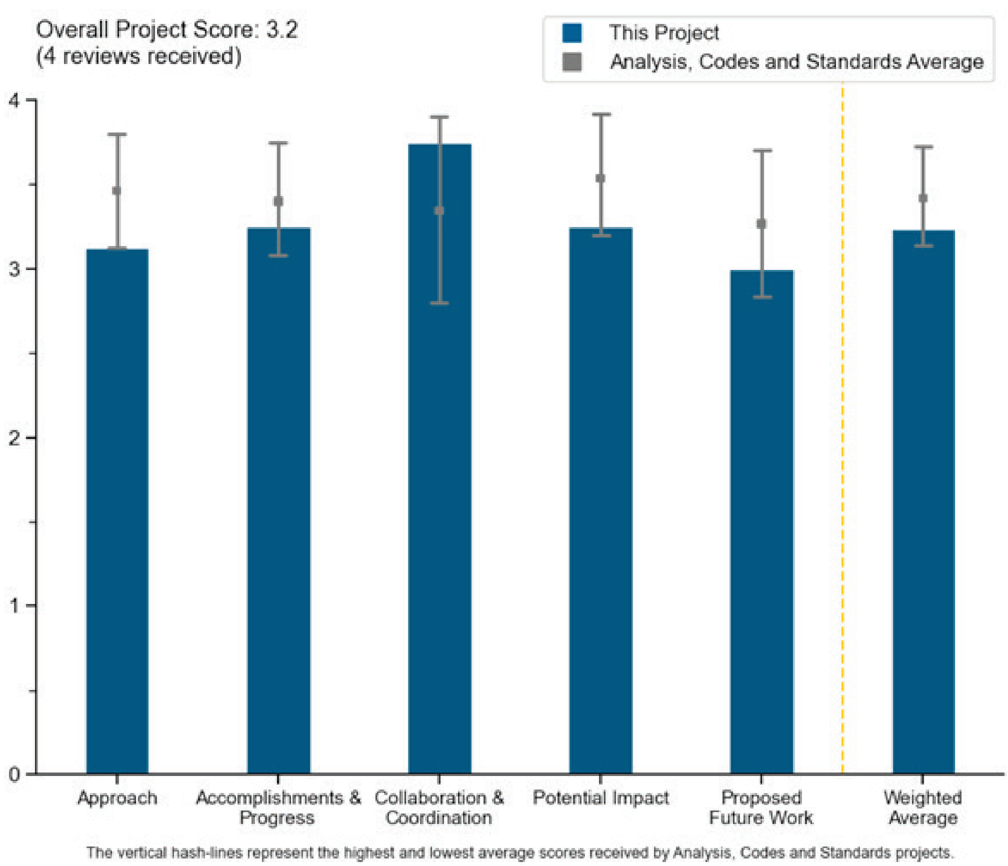
Karen Quackenbush, Fuel Cell and Hydrogen Energy Association

DOE Contract #	DE-AC05-00OR22725
Start and End Dates	05/05/2021–01/31/2023
Partners/Collaborators	National Hydrogen and Fuel Cells Codes and Standards Coordinating Committee, Pacific Northwest National Laboratory, Oak Ridge National Laboratory
Barriers Addressed	• Need for consistent regulations, codes, and standards to enable national and international markets • Insufficient synchronization of national codes and standards • Limited participation of business in the code development process

Project Goal and Brief Summary

The goal of this project is to facilitate widescale adoption of fuel cells and hydrogen energy systems through the development of consistent regulations, codes, and standards (RCS) that incorporate industry best practices. 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



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.

- In coordinating standards, it is critical to engage industry, assess needs, harmonize requirements, interact closely with stakeholders, and disseminate information in a timely manner. This project continues to successfully achieve these tasks.
- The approach supporting the DOE effort is greatly detailed. The chart on slide 7 is extremely valuable in displaying the vast interfaces involved with the project. The Approach: Coordination and Outreach slide (slide 9) also provides excellent approach details, while the use of working groups amplifies the continued value of the project effort. One approach area is unclear. FCHEA appears a very valid industry group, but it is unclear whether there is an end point to the formal project, what would demonstrate success, or whether there is a plan for FCHEA to be fully funded without DOE project support. It would be valuable to describe FCHEA's vision. Slide 27 is valuable for evaluating the "Matrix." The track changes approach is extremely valuable.
- It is difficult to discern the plan for this work based on the poster and responses to reviewer questions. The approach to Barrier J (Limited Participation of Business in the Code Development Process) is the strongest element. The approach to Disseminating Safety Information is reasonable, although there could be more specificity about the quality and sources of information used in newsletters. The approach to the Development and Harmonization of Regulations, Codes and Standards is not clearly articulated in the poster, and it is unclear how the project will make an impact on barriers. The key aspects of the approach are coordinating working groups, creating a newsletter, and updating various websites. The project would benefit from a clearer articulation of the project goals, plans, and milestones and a narrower scope to allow more effective progress on Barrier J.
- The approach is fine for the stated goals, but the question is really about whether the goals are particularly relevant at this point. This effort has been underway for a long time, including prior to 2021, and it is not clear that it is a critical part of the codes and standards effort. There are many organizations that have similar roles.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The overall application to DOE goals was described. Five slides detail accomplishments of both overall interfaces and working groups. The scope of activities is very broad, supporting the challenge of interfacing with national and international codes and standards. Multiple backup slides (35–40) were provided that qualify scope activities against DOE goals with prescriptive details. Data indicates a very strong project interface with DOE planning.
- Significant progress continues to be made in various working groups, website hits, code updates, and coordination with stakeholders.
- The volume of work is evident, but it would be good to see more articulation of what efforts are taken to ensure the output is high-quality and meaningful. It is difficult to identify which aspects of the approach are FCHEA activities versus codes and standards committee activities versus the Pacific Northwest National Laboratory (PNNL) activities versus the activities of the FCHEA member companies. The monthly discussions are an important activity, and FCHEA pulls together a large number of participants—this is commendable. However, this accomplishment is diluted by vagueness about what is being achieved and by whom. The newsletters and fuel cell standards database contain large volumes of information, but they are not archival and do not appear to be curated; the website has a good deal of information that is out of date or completely missing. Additionally, it would be helpful to see more articulated accomplishments from the FHCEA work (versus the accomplishments of the code committees versus PNNL versus the member companies).
- There are specific accomplishments, but these are anecdotal and/or tactical actions and are not as much on a strategic level to harmonize global codes and standards. For additional value, this project should take the lead on some specific needs or issues and drive them to conclusion, rather than being more reactive.

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 heart of a successful project effort involves integration with a wide variety of industrial and laboratory partners. The project highlights this collaboration from the very beginning of the presentation and continues with this theme throughout the presentation. Successful transition of data to the PNNL H2Tools.org website is an example of direct collaboration. Discussion with project personnel indicates a desire to increase knowledge and utilization of this data for improved application, with future work qualifying potential scope. Added details of how the project has and will interface with key safety organizations involved with codes and standards review (e.g., the Hydrogen Safety Panel and Center for Hydrogen Safety) could be expanded to provide interface specifics, including possible future transitions. The technology transfer effort detailed in slide 24 is noteworthy.
- This project collaborates exceedingly well with members who represent the full global supply chain, including universities, government laboratories and agencies, trade associations, fuel cell materials, component and system manufacturers, hydrogen producers and fuel distributors, utilities, and other end users. A tremendous amount of coordination between stakeholders occurs thanks to this project's continued involvement.
- FCHEA has many member companies and a network of contacts within the codes and standards organizations.
- This project pulls together an excellent, industry-focused team with an exceptional list of participants.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- At this stage of the industry, the project is critical to new technologies for synchronization of codes and standards development. Integration value is especially qualified in the backup slides, while the overall FCHEA working group effort directly supports safe advancement of hydrogen technologies. Codes and standards will always lag technological development, so the project effort will always be valuable. It is anticipated that as the hydrogen industry and codes and standards mature, along with the completion of DOE goals, the potential impact of this integrating project will lessen.
- All large-scale commercialization starts with standardization of components and hardware. This effort is entirely needed and must be continued to achieve DOE target goals.
- The most effective work is for overcoming Barrier J, Limited Participation of Business in the Code Development Process. It is unclear how the project is advancing progress toward "Conduct R&D to provide critical data and information needed to define requirements in developing codes and standards" or progress toward "Ensuring that best safety practices underlie research, technology development, and market deployment activities supported through DOE-funded projects." Adding more research engagement would improve translation of research into industry best practices. Slide 22 shows that FCHEA membership is almost entirely industry. To improve on these barriers where progress is limited, it is recommended that the project find a way to engage more research groups, academics, small businesses, and consultants that have expertise complementary to that of the medium and large companies that are already members of FCHEA.
- The accomplishments are not particularly impactful or relevant to specific DOE Hydrogen Program goals. While there are a number of useful tools managed by the project, it is not clear whether there would be a discernable impact if this project went away. For example, the six proposals to National Fire Protection Association (NFPA) 2 would have still happened; they would just have been submitted by someone else. It is not clear that FCHEA was a driving force behind important changes that otherwise would have not moved forward.

Question 5: Proposed future work

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

- The proposed work identified is absolutely needed. As always, the hard part is getting everyone's time to work on these codes and standards.
- The Remaining Challenges and Barriers slide, along with Proposed Future Work and backup slides, provides a detailed, logical, valid, and compelling basis for future effort. One area that could be improved

is documenting and demonstrating specific approaches for the thrusts of "Work with…" and "Continue to..." noted on slide 18. Backup slides to document FCHEA vision and strategy would be valuable, specifically addressing how successful the Association has been and why its approach will be successful in addressing the challenges generally described in slide 33.

- The future work is not clearly articulated. It is difficult to identify the activities and goals for many of the working groups. It would be prudent to consider narrowing the scope and focusing on developing higher-quality work products where the FCHEA team has differentiating strengths, rather than to take a scattershot approach to so many goals.
- The work proposed is very general in nature, without specific goals or metrics. There are not specific actionable items that show clear benefits above and beyond the ability of individual FCHEA members.

Project strengths:

- Strengths include past transition effort, establishment and continued management of the Regulatory Matrix, key working groups, extremely strong collaboration, and very knowledgeable and passionate project personnel.
- The project serves as a forum for new entrants to possibly better understand the hydrogen codes and standards arena and make contacts. Management of the Codes and Standards Database on H2Tools.org is also useful for the industry.
- This project has a tremendous amount of coordination and connecting of industry and RCS bodies, and this project does this very well.
- There is excellent coordination of industry stakeholders, as evidenced by number of member companies.

Project weaknesses:

- There is a lack of excitement or specific new activity to sustain the project long-term. Comments are made about participating in numerous activities, but just participation and monitoring is not enough to make a difference in many of these forums. Being a consensus organization of numerous parties who are already participating in the codes and standards process does not lend itself to effectiveness. This is reflected in the relatively static number of visitors, unique visitors, and pages viewed. Doing the math seems to imply that visitors are not returning on a daily or weekly basis to use the tools, information, and websites actively as a go-to location for additional information.
- The work appears ad hoc. A clearer plan, objective, and set of metrics are urgently needed. Lack of publications and presentations in scholarly or archival venues is a significant weakness. Peer review of the information is an important next step to consider, even if it means allocating additional resources. Ensuring high-quality, trustworthy information is critical. The poster does not effectively communicate the work and accomplishments.
- The project lacks prescriptive details for addressing challenges.

Recommendations for additions/deletions to project scope:

- Because so many members have such busy schedules, it is difficult to show major (and quick) progress on certain standards developments. This is not a weakness of this project, however. Perhaps something could be created to show who an action is assigned to, something that has outward visibility, in order to pressure/shame the action owner into making progress. One other recommendation could be to introduce or emphasize (via the working groups) the concept of hydrogen users needing to create and track incidents, leaks, and failures and report them back to DOE for incorporation and improvement of quality risk analysis tools such as the Hydrogen Risk Assessment Models (HyRAM).
- The team should emphasis quality work over quantity of work. The codes and standards database is important, but some information is significantly dated, the website does not indicate when the information was last updated, and the information is extensive but does not appear curated. A more systematic, curated approach would provide more trustworthy information.
- The project could consider whether the work should be paid for directly by FCHEA rather than requiring DOE funding. If the work is valuable, the industry should be willing to pay for it.
- Clarification of high-priority RCS would be valuable to qualify scope applied to challenges and future thrust and focus.

Project #SCS-028: Hydrogen Education for a Decarbonized Global Economy (H2EDGE)

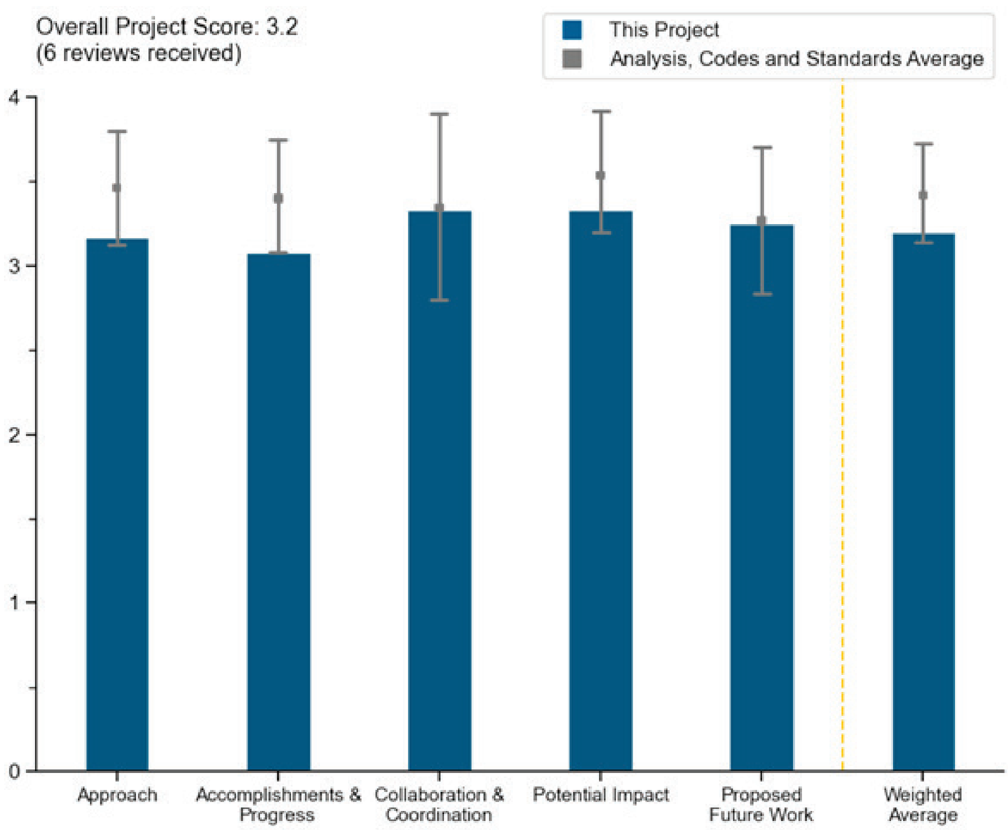
Eladio Knipping, Electric Power Research Institute

DOE Contract #	DE-EE0009253
Start and End Dates	10/01/2020–03/31/2025
Partners/Collaborators	GTI Energy, Oregon State University, University of Delaware, University of Houston
Barriers Addressed	• An increasing need for well-qualified professionals for the growing hydrogen economy

Project Goal and Brief Summary

As an emerging field, the hydrogen industry faces the challenge of mobilizing an experienced workforce—a critical need in which safety must be emphasized. This project establishes the Hydrogen Education for a Decarbonized Global Economy (H2EDGE) initiative. H2EDGE enhances workforce readiness by collaborating with industry and university partners to develop and deliver training and education materials, including professional training courses, university curriculum content, certifications, credentials, qualifications, and standards for training. H2EDGE will establish regional university hubs and an affiliate university network to train the workforce for the hydrogen economy. Professional short courses and university curricula will focus on the four pillars of the hydrogen industry: production, delivery, storage, and use.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Analysis, 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 being taken to educate both industry professionals and university students seems like an excellent way to reach the right people in the community. This work is critical to try to respond to the demand for well-trained professionals for the growing hydrogen economy.
- The project has a very good approach to building a wider curriculum on hydrogen across the partners. Overcoming the retirement of the principal investigator does not seem to have slowed progress based on the team's approach.
- The approach of initially focusing on four-year schools; moving to two-year colleges and trade workers is perhaps difficult. Given the large scope (spanning the entire value chain), one could see building the curriculum at the trade and two-year colleges initially and building it up for the four-year schools. However, the train-the-trainer approach may work well in this top-down model, and working with and through the Low-Carbon Resources Initiative (LCRI) may make it easier. Another aspect is the consideration for not just catering to those who have the means to attend the four-year colleges but building the workforce and giving the opportunities to those from disadvantaged communities, concurrently.
- This project is focused on increasing the number of well-qualified professionals needed for the growing hydrogen economy. This is a big job, and this project is an important step to achieving the objective. Ultimately, much more will need to be done to effect wide-scale deployment of educational opportunities.
- The overall approach is good. It is, however, very ambitious to look at university curricula and professional trainings in parallel.
- Professional short courses are a plus and have been a need for some time. Affiliate networks at four-year institutions seem interesting, but it is not clear how this will promote and increase the workforce.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- It is great that the project is engaging with the Hydrogen Safety Panel (HSP) to ensure safety is in all materials. The first professional short course was delivered recently (May 31, 2023, Intro to Basic Hydrogen Science), and an electrolyzer course is coming in July 2023 from Electric Power Research Institute, in person at the Institute's offices; other courses that are in development are to be delivered in the fall. The hope is that the expansion of courses delivered via webcast and/or self-paced online training happens relatively soon, given the timing of the project.
- Accomplishments outlined in the presentation demonstrate success in beginning to develop content and educate a number of individuals. The hands-on lab experiments course in the university seems like it could be very successful in truly making an impact on students through first-hand experience assembling and using fuel cells.
- Several courses have been developed, have been reviewed by the HSP, and are being deployed. Capstone projects are underway that help meet specific needs.
- Overall, the project is moving in the right direction and answering the overall objectives.
- The project milestones and go/no-go decision points are not specified, so it is difficult to gauge specific progress toward project goals. Qualitatively, development of offerings across the universities is a noted sign of significant progress, and the courses span the sciences and business. A clearer articulation of how ideas and best practices will be shared and scaled for the maximum impact would be helpful.
- Progress and execution are decent, but additional efforts should be made to get the material out and gather feedback, especially for the short course.

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.

- Collaboration is outstanding. The project seems to be involving the right types of institutions and plans to continue to grow in this regard.
- There appears to be very good collaboration in place, particularly with other universities.
- There is good collaboration and coordination. It was mentioned that the advisory board has expanded to 16 members, but it is not clear whether the board provides a good snapshot of the relevant stakeholders. From the presentation, it is very heavy on the utility member side.
- Partnership with universities and industries is good. but the project could benefit from partnerships with other technical schools. For example. other resources might be needed, especially for the professional courses. Use of STEM/STEAM (Science, Technology, Engineering, [the Arts], and Mathematics) schools may help to find high school students. The support of social justice might include training after incarceration.
- Overall, there is great collaboration with the academic community; students are generating relationships with organizations such as national laboratories. The industry collaboration, as well, seems solid, although there are no educational institutions on the advisory board.
- Each of the partners is doing work that is relevant, but practical collaboration toward scaling results is not evident.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Developing strong technical content in a way that engages people and educates students and professionals could make an enormous impact and significantly advance the hydrogen economy.
- If both the university curriculum and the professional trainings are successful, this project will be key for the future of the hydrogen landscape.
- The project is an important early step toward accomplishing DOE goals and objectives.
- The work to build academic curricula is important, and progress is being made. The effort to include a focus on historically black colleges and universities (HBCUs) is noteworthy and great. For maximum impact of the DOE grant, it would be good to see how the individual universities' efforts will be shared and scaled up. A gap that does not seem to be addressed at all is occupational training, which will be a critical aspect for success. Not all workers in the hydrogen economy will be from four-year universities. This occupational training is especially relevant for workers potentially displaced from other established jobs by increased hydrogen deployment.
- While the advisory board has grown from 7 to 22 members over the past few months, and there are 18 industry participants who will nominate universities in their jurisdictions to develop curricula, the overall scope is wide, and there is a risk of there not being enough resources or the project being spread thin, as it is reaching broadly across the industry. The impact has the potential to be huge, but again, given the scope and the timing, it is a huge reach.
- There could be relatively good impact, but the focus on workforce development should be more on the two-year or trade schools. Additional efforts under other opportunities could quickly overshadow this effort.

Question 5: Proposed future work

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

- Proposed future work seems ambitious, as there are many topics outlined that the project is planning to address. However, the plans set forth seem logical and indicate the work could be effective.
- The proposed future work presented reflects important next steps to achieve objectives.
- Future work, including the roadmap, is worthwhile.

- Proposed future activities are good, but the right stakeholder feedback might not be aligned correctly to maximize impact. Also, it would be nice to understand who is developing the curriculum and how is it vetted.
- The proposed future work is well aligned with the objectives of the project and clearly explained. It is, however, quite broad and may benefit from extra support and prioritization.
- Much is going on in the future work, so hopefully there are plenty of resources available to get it all done, and done with quality. There is no lack of enthusiasm, to be sure.

Project strengths:

- This topic is essential, and creating a network of universities would benefit the hydrogen sector overall. Supporting the workforce by reaching out to the industry is an asset. Interesting coursework is proposed on the business aspects of hydrogen.
- Education of the current and future workforce is a key piece that will need to take place to ensure the hydrogen economy can continue to grow and be a safe environment for everyone involved. The knowledge this project will pass on could make a significant impact.
- This project includes key partnerships to design and implement courses to lead to workforce development. Future work identified is appropriate and necessary for success.
- The project is creating an industry gap assessment to allow focus on which trade associations to work with to strengthen the program.
- Strengths include a strong network of universities and good industry partnerships, development of new curricula, and a worthwhile concept.

Project weaknesses:

- There are concerns for maintaining and updating the training content. Continuous funding might be a challenge in the future. Marketing and announcements should be further developed to help advertise to the broader community. There are already gas fitters who have skills in natural gas areas; there is a need to connect with the workers and unions. It could be done by looking at other skilled trades—e.g., construction, plumbing, electrical—and studying their recruitment strategies.
- There are no well-defined metrics by which one can see what the full scope of the project will be. There are no measurable metrics that tell if the pace of the project is right. The scope is too wide for the project to truly be successful; it would need time beyond the life of the project.
- Project weaknesses have, for the most part, been identified and are addressed in the future work description. Expanding partnerships and marketing courses are very important.
- Weaknesses include overall publicizing of the programs and availability and lack of academic institutions on the actual board.
- Opportunities to expand scaling, industry partnerships, and occupational education are noted.

Recommendations for additions/deletions to project scope:

- The scope is fine. The reviewer looks forward to seeing progress on the proposed future work at future Annual Merit Reviews.
- In the future, discussion could include how the maintenance will be updated/kept fresh with the most recent information/resources (i.e., through the subject matter experts at LCRI, GTI Energy, and the universities). Working with the HBCUs is great, but the project should also include other target communities (Native American, for example) and other under-represented groups. The project should include information on tracking and metrics of the outcomes of these courses (who and how many get jobs, and where).
- The project team could consider narrowing down the scope to pieces of work that can be accomplished, potentially focusing on a few areas of expertise.
- This is a large project that would benefit from a clear workplan and priorities.

Project #SCS-030: MC Formula Protocol for H35HF Fueling

Taichi Kuroki, National Renewable Energy Laboratory

DOE Contract #	WBS 8.6.2.1
Start and End Dates	10/1/2021–9/30/2023
Partners/Collaborators	Frontier Energy Inc., ElDorado National, GTI Energy, Luxfer Gas Cylinders, New Flyer of America, South Coast Air Quality Management District, Sunline Transit Agency, Southern California Gas Company, Shell, Trillium
Barriers Addressed	• Lack of a publicly available and verified high-flow fueling protocol for H35 medium- and heavy-duty hydrogen-powered buses and trucks

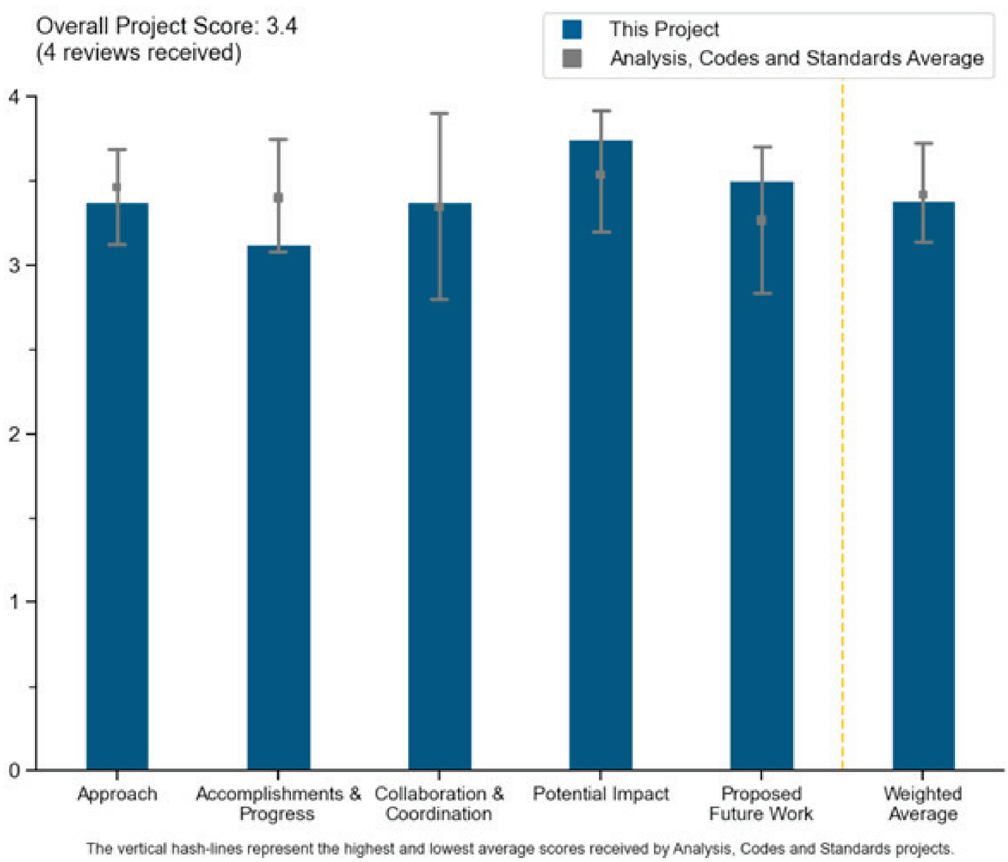
Project Goal and Brief Summary

The project aims to develop a validated H35HF[1] MC Formula[2] fueling protocol for medium-duty (MD) and heavy-duty (HD) buses and trucks, with the goal of standardizing fueling procedures. The protocol will be reflected in SAE J2601-2, and the National Renewable Energy Laboratory's (NREL's) hydrogen fueling model, H2Fills, will be upgraded for H35 MD and HD fueling and made publicly available. The project team has conducted surveys, integrated survey results to define boundary conditions, upgraded H2Fills for protocol development, and started implementing the MC Formula control logic in NREL's HD dispenser for protocol validation testing. The project seeks to address the need for a standardized fueling protocol to enable the growth of the hydrogen market and prevent potential issues with incompatible vehicle designs and the lack of accessible H35 stations.

[1] Refueling hydrogen at a high flow (HF) rate to an onboard pressure of 35 MPa (H35).

[2] A method that allows a hydrogen refueling station to directly and accurately calculate the temperature at the end of the filling in a hydrogen tank.

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 approach is well structured and well defined and suggests an excellent chance of achieving the project goals. The three main themes to discern boundaries, develop the model, and validate the fueling maps are well suited to a successful outcome.
- The project clearly states its goals and objectives and identifies remaining challenges and barriers. Furthermore, the project provides methods to overcome such challenges and barriers. Lastly, the layout of the project's approach is easy to follow.
- This project is well-thought-out, although it is not yet complete with only three months left. The German contract seems to be the rate-limiting step in supplying the component validation thermal masses needed to complete this work.
- The approach will work to meet the objectives of the project. It will be important that additional real-world testing be completed prior to standardization in SAE J2601.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- The project is proceeding on its stated pathway and making progress. However, there was no mention of how the barrier to controlling the dispenser flow/pressure will be resolved, especially since it is listed as not being capable with existing hardware.

- The project clearly delineates its excellent progress toward objectives, categorized by themes. However, some incomplete items in “Theme 3: Validation testing” lack expected timeline dates.
- Themes 1 and 2 are complete, although it would be preferable if more information could be provided regarding the results of the Theme 1 surveys. It is unclear why this information was not shared in the presentation. More results should be presented, rather than indicting tasks are complete.
- The progress for this work is good but not excellent. The progress of the German contract was scheduled to be completed in April 2023. At the time the view graphs were due, that work had not yet been completed. Presumably it has been done, or will be done soon, so this project can finish its work by the close of this fiscal year.

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 collaborators are perfect for this work. It also appears that a concrete active line of communication is maintained. This should yield transparency and excellent working environments. The reviewer anticipates that this project will be successfully completed by the end of Fiscal Year (FY) 2023.
- This project has a comprehensive list of industry partners. Additionally, the project demonstrates excellent participation capabilities by meeting with partners bi-monthly and having such partners provide data and feedback.
- This is an excellent group of project partners that can provide adequate guidance and credibility to the work for 35 MPa fuel systems. Bi-monthly meetings are more than adequate.
- The partners seem to be mostly aligned with the bus industry, so it is possible that the fueling protocol will be tailored more to that industry at the risk of negatively affecting other markets. Additional partners in other industries could provide additional perspective.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- On completion of this work, the United States will have a number of protocol fill tables based on the MC method. The MC method has gained recognition over the past couple of years as a fill protocol based in science. It has been recognized by SAE J2601 and hence used for light-duty vehicle filling. Moving this to the MD and HD vehicle filling protocol will be enormous in accelerating the development of the fueling infrastructure.
- The ability to broaden fueling infrastructure to allow any MD/HD vehicle to safely fill at stations that meet a standard protocol will help enable broader acceptance of vehicles. Consistent specifications for H35 MD/HD vehicles have been challenging, thereby leading to difficulty with specifying hydrogen fueling stations for these markets. This project could have a significant ability to improve safety by making these specifications clearer for consistent operation.
- This project is of much value since a publicly available and verified high-flow fueling protocol for H35 MD and HD hydrogen-powered buses and trucks does not exist. The project goal of developing a protocol has the potential to significantly advance progress toward DOE research, development, and demonstration goals and objectives.
- An HD high-flow fueling protocol for 35 MPa fuel systems is greatly needed, and this project is poised to deliver the results that can be fed into fueling protocol standards development activities immediately. It is not clear whether the stated SAE J2601-2 standard is the intended target, as it is understood that this effort would be incorporated into SAE J2601-5.

Question 5: Proposed future work

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

- The future work activities are as required per the project plan, with the final and most critical deliverable being the creation of language to allow the incorporation of this work product into industry standard SAE J2601-2 (or possibly J2601-5). This is an extremely valuable project to the industry.
- This project is scheduled to be complete by the end of FY 2023. Assuming that happens, the proposed future work is appropriate.
- This project has effectively planned its future in a logical manner by incorporating future goals.
- The future work mentions adoption within SAE J2601-2 but does not describe how that will be done or whether the project team has developed consensus within that team that this work will be adopted. The partners are primarily related to bus fueling, so the protocol might not gain broad support unless a plan is in place. In addition, limited testing at one site might be insufficient to lock into a standard. Additional testing might be needed first.

Project strengths:

- This project is to develop several filling tables to fill MD and HD vehicles derived from the MC method. These tables will be validated using NREL's hardware. This is a good project aimed at building and deploying fueling protocols to enable the rapid development of the fueling infrastructure for MD and HD vehicles. It is very nice work.
- The project strengths include a well-defined approach and timely deliverables. The end result will be extremely valuable to the industry in that it will fill a critical industry need. The project team members are extremely well qualified, and the test facility is top-notch in support of the project objectives.
- The ability to standardize the bus and fueling specifications will reduce some of the confusion (and as a result, safety issues), which will enable better adoption of hydrogen-powered vehicles. If a reasonable common specification can be developed, then this will be a major step forward.
- The project is filling in knowledge gaps regarding codes and standards and has the potential to guide stakeholders in the hydrogen space (e.g., standards development organizations, code development organizations, and industry).

Project weaknesses:

- The results of a lowest common denominator approach might result in raising the cost/complexity of H35 fueling stations if the new tables become a minimum requirement. In particular, the difference between Type 3 and Type 4 tanks at H35 can result in significant differences in fueling time or precooling temperature. This may have unintended consequences in other markets.
- There are very limited weaknesses to this excellent effort. Perhaps it would be good to see the results of the initial Theme 1 survey (sanitized for anonymity) to justify the approach. In future presentations or reports, it would be great to see more of the actual deliverables, as opposed to merely listing that tasks are completed. Other than that, this is an excellent effort.
- The only weakness found is the inability of the German firm to deliver on its contract. This could be a supply chain issue, and it could have already been resolved.
- The contents of the survey used to define protocol structure should be provided.

Recommendations for additions/deletions to project scope:

- A barrier is listed that existing hardware might not be sufficient to meet the developed H35HF MC protocol. If so, then it is premature to advance that in SAE J2601 unless that issue is resolved first.
- The project should proceed and continue with its planned future work.
- There are no recommendations for increase or decrease in scope.

Project #SCS-031: Assessment of Heavy-Duty Fueling Methods and Components

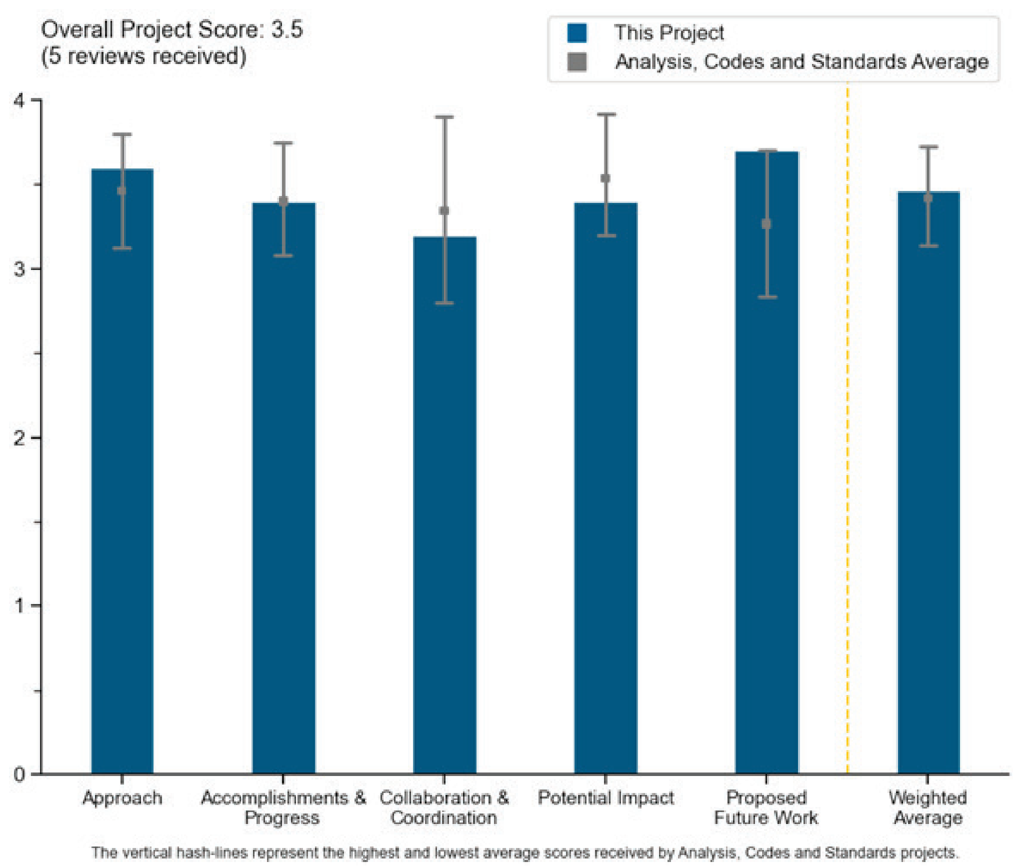
Shaun Onorato, National Renewable Energy Laboratory

DOE Contract #	WBS 6.2.0.504
Start and End Dates	2/2/2022–2/1/2024
Partners/Collaborators	Argonne National Laboratory, NextEnergy, Chevron
Barriers Addressed	• Limited availability (globally) of heavy-duty hydrogen fueling infrastructure to evaluate the performance of fueling protocol concepts and hardware • Lack of understanding of how heavy-duty fueling concepts will influence infrastructure and vehicle design, specifications, and cost • Lack of robust modeling tools for heavy-duty fueling concepts

Project Goal and Brief Summary

The goal of this project is to develop a comprehensive assessment of heavy-duty (HD) fuel cell electric vehicle (FCEV) fueling protocols and hardware to understand their impacts on station design, vehicle design, functional safety requirements, and total cost of ownership (TCO). The project involves evaluating prototypes and industry-supplied HD hydrogen fueling components and protocols at the National Renewable Energy Laboratory's research station. The project will also conduct modeling and analysis using computational fluid dynamics (CFD) and perform techno-economic assessments (TEAs) to determine TCO. This project aims to provide information and data to industry stakeholders, support the uptake of hydrogen-powered HD vehicles, and build clean energy infrastructure.

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 project has a great approach, with the hardware evaluation feeding into the modeling efforts, and then the iterative process of performing analysis, to then go back and improve the model—and all this while coordinating with the many partners/collaborators.
- Lack of an HD fueling protocol is a barrier for the industry. The multi-pronged approach of developing the fueling protocol/hardware with advanced CFD modeling capabilities and a techno-economic tool provides a full evaluation of the protocol, including the impacts to the vehicle equipment and station design.
- This project is well-thought-out, is well-connected, has a team of partners that are well focused, and provides excellent feedback to the project management.
- The project addresses an industry need for hardware, modeling, and analysis to facilitate HD FCEV fueling.
- The project has a good approach on filling a big industry need to validate HD fueling components.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- The progress demonstrated is very good to excellent—particularly good progress during the pandemic. There is concern about the CFD modeling and the interpretations of the results. The principal investigators showed two jet entrances into the tank, one straight on axis and one jetting at an angle. The discussion indicated that the angled jet was deemed better because it promoted increased turbulence within the tank, thus mixing the fluid better than the straight-on injector. While there is no problem with that observation, there is a problem with the jet impinging on the tank wall. It is not the fluid temperature that is of interest but the tank material temperature, specifically the liner. Impinging a hot jet on the tank wall will increase the temperature of the liner and could result in permeation damage. Because of the Joule–Thompson effect under these conditions, this jet will heat up when it expands—the jet will be hot. The researchers have the data to investigate this phenomenon.
- The project team has been able to accomplish 60–100 kg in less than 10 minutes without exceeding the temperature limits of the vessel, which is impressive progress. It seemed like many people in the room did not know that a model for doing this type of fill already existed (a link was provided on slide 11). Surely many people will be checking out this link/application.
- It was very exciting to see that HD fueling has occurred. The fueling needs to be conducted with the final hardware and tested significantly to ensure robustness.
- The project has good accomplishments and progress toward meeting DOE goals.
- Commendable progress has been shown in all three areas of the project focus.

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 collaborators are perfect for the project's work. It also appears that a concrete active line of communication is maintained, which should yield transparency and excellent working environments. The collaborations with the standards development organizations (SDOs) (International Organization for Standardization [ISO], SAE International, etc.) are also spot-on.
- The project has good coordination with industry and collaboration to support refueling protocol development for 70 MPa high-flow fueling.
- Although existing partners bring many key players to the table, future collaborations expanded to a broader set of industry partners, as well as to codes and standards committees and working groups beyond ISO/TC (technical committee) 197 WG (working group) 5 and 24, would be beneficial. In particular, hoses are included as a hardware component, and a relationship with ISO/TC 197 WG 22 is essential to facilitating

an international standard on hoses for HD FCEV refueling. ISO/TC 197 WG 20 addresses valves, including the dispenser breakaway. Several ISO/TC 197 component working groups have industry experts expressing a need for HD hardware requirements quickly; however, the working groups do not yet have any performance metrics with which to identify or develop suitable requirements or testing. The project should consider sharing HD component performance requirements with ISO/TC 197 (beyond WGs 24 and 5) to facilitate development of these requirements.

- This project has good coordination with industry partners. The project should coordinate with a standards organization to adopt the fueling protocol into a standard for rapid adoption of the fueling protocol.
- The project has a great number of partners. NextEnergy is an industry/partner group on its own. It is unclear in the slides how well this group is coordinated and tied into this effort.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- On completion of this work, the United States will have its first validated model of the fill physics during a fueling process. This is critically important to creating a "filling" protocol to fill hydrogen tanks on board vehicles (light-duty, medium-duty, and HD vehicles) to meet the customers' requirements. This project is on track to do just that.
- Defining the HD fueling protocol and developing the proper hardware will significantly accelerate the infrastructure build-out of HD fueling stations and the adoption of HD FCEVs.
- The project is certainly impactful and fills a substantial gap within the domestic and international hydrogen community.
- The project's work is very important in facilitating deployment of suitable hardware and protocols to support HD FCEV refueling.
- This project helps contribute to achieving four DOE goals.

Question 5: Proposed future work

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

- Future work should focus on definition of the HD fueling protocol and rapid industry adoption of the fueling protocol by partnering with a standards organization. For hydrogen fills to be a realistic tool, the actual cost and performance of equipment should be utilized from companies operating equipment.
- The proposed future work is needed for this project/effort to improve the hardware <=> modeling <=> analysis iteration, which will feed into regulations, codes, and standards; recommendations for hardware on stations; and enabling of adoption of hydrogen-powered HD vehicles.
- The proposed future work aligns well with the need and timing.
- The project's plan is spot-on with respect to achieving the project's and DOE's goals.
- Proposed future work is focused toward achieving project objectives in all three project areas.

Project strengths:

- The project is developing a model of the fill process in a hydrogen high-pressure tank during the fill process. The project compares results with other models internationally (e.g., PRHYDE [PRotocol for heavy-duty HYDrogEn refuelling]), which is excellent. The project also is on a few SDOs (ISO WG 24, WG 5, SAE 2601, etc.) to help guide that development.
- This project's work on fast fills, HD fuel cell applications, and modeling/analysis/applications for industry and the public to use will greatly help shepherd in a hydrogen economy.
- The project is well timed because industry is actively looking for a clear HD fueling protocol.
- This project is unusual, as it addresses hardware, modeling, and analysis.

Project weaknesses:

- Attention is needed to all the details provided by the modeling effort (e.g., the comment about jet impingement). This is easily dealt with simply by coding up the tank material and monitoring the temperature, pressure, and space–time history of the entire system. That will be very instructive.
- The project timeline should be accelerated to release the final protocol and equipment. The HD fuel cell market is awaiting these components before the HD fueling infrastructure can be widely designed and installed.
- The project should expand collaborations with industry partners and codes and standards bodies to meet objectives.
- Peer evaluation of the internal tank temperatures achieved during the fast-fill tests could be of benefit. The data appears to be inconsistent with other test facilities' knowledge and experience.

Recommendations for additions/deletions to project scope:

- This is a very good project in execution, planning, and collaborations. The only recommendation is to code up the tank material, along with the gas phase, and calculate the temperature, pressure, and space–time history throughout the filling process. That will prove to be very interesting. Having a complete validated computational package in the United States will be very valuable.
- Liquid hydrogen onboard solutions are ideal for semi-truck applications. A liquid hydrogen fueling protocol and the associated hardware will be a barrier for the industry. Addition of this scope is recommended to support adoption of fuel cell electric semi-trucks.
- There may be a need to support a broader set of codes and standards development committees and working groups beyond the two-year timeframe for this project to ensure the project learnings can inform developing requirements for HD FCEV refueling components.
- The project could find more ways to advertise the hydrogen fill website link/application to a bigger audience.

Project #SCS-033: Risk Assessments of Design and Refueling for Hydrogen Locomotive and Tender

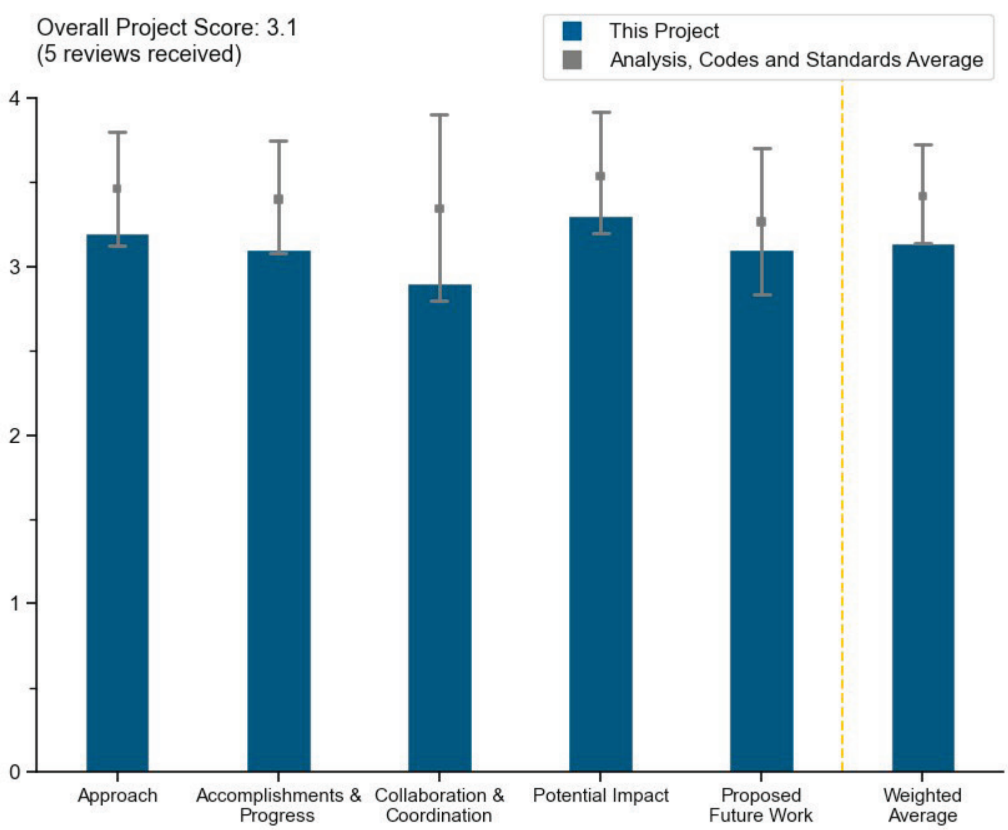
Brian Ehrhart, Sandia National Laboratories

DOE Contract #	NL0038749
Start and End Dates	2/1/2022–12/31/2023
Partners/Collaborators	Wabtec Corporation
Barriers Addressed	• Lack of requirements for new applications • Lack of scientific bases for defining requirements • Lack of widespread dissemination of safety-related information resources

Project Goal and Brief Summary

The goal of this project is to utilize qualitative and quantitative risk assessments to enable the near-term deployment of hydrogen-powered locomotives. The project aims to inform the regulatory community about the developments, needs, and identified gaps in the hydrogen-powered rail transportation sector that require attention. Existing codes and standards developed for conventional fuels (e.g., diesel) will serve as a starting point. Failure mode and effects analysis (FMEA) or a hazard and operability (HAZOP) study will be conducted to generate qualitative and quantitative risk ranking for hydrogen release scenarios, and fault tree and event tree analyses will be used to quantify risks in refueling processes and transfer scenarios. The results will help improve safety measures, inform design modifications, and contribute to the development of specific codes, regulations, and standards for hydrogen-powered rail systems.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Analysis, 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 project's goals and barriers have been clearly identified. Additionally, the project is well-designed and thus easy to follow.
- The goal of the project is to create a qualitative risk ranking for release scenarios for a hydrogen-powered locomotive by applying FMEA and HAZOP studies. This should be valuable to the railroad industry, which is an important part of national transport infrastructure. However, the reporting constitutes that of a high-level progress report, with few details describing the findings from the FMEA and HAZOP analyses. Little except the most general information about the application was provided. The explanation offered for the lack of detail was that the information was of a proprietary nature. As an approach, this may be good for the developer of hydrogen-powered rail to receive expert government-furnished help, but it does not enlighten regulations, codes, and standards (RCS) efforts.
- Proposed approaches to the technical work are appropriate. The use of Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) to develop the release and consequence behaviors is strong. More detail could be provided on which standards are being followed to conduct the FMEA or HAZOP, what the team configuration is, and what type of expert reviewers are being engaged. These are important considerations for determining the appropriate execution of the proposed work. The proposal to use fault tree analysis is sound, but it is unclear which validated tools or solution methods will be used to conduct this analysis.
- The approach was methodical and thorough with regard to individual leak sources. However, quantifying the number of failure modes and leak sources as a milestone seems odd and seems to be trying to force something that might not be there. The project mentioned an FMEA or a HAZOP being completed and then proceeded down the path of the FMEA. A HAZOP, at least to consider the potential differences that pertain to rail, could also be helpful. It is not clear whether previous refueling experience from National Fire Protection Association (NFPA) 2 was applied as a starting point for the risk analysis. It is also unclear whether rail fueling is expected to be significantly different from on-road heavy-duty vehicle fueling and, if so, how.
- Goals are clearly defined, along with relevance and potential impact. The project is clearly focused on RCS. The milestone table (slide 6) is valuable to understanding project effort and status. The risk analysis approach is centered on hydrogen gas leaks in locomotive and tender equipment. The fueling center is not in scope.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- This is a new market, and validating the safety of the overall activity can lend assurance to many that the activity is acceptable. The project laid out milestones and is working through them.
- Project slides provided clear status in the milestone table (slide 6) and in the progress slides (7–9) of effort toward project goals; however, no information was provided comparing activities against DOE goals. RCS scope contributes to DOE goals, but the project needs to clarify effort. The basic approach slide has the project conducting either an FMEA or a HAZOP. It was not clear which was performed. It is not listed in the milestone chart. Data on slide 7 can be used to infer an FMEA was performed. Reasons were not given why the HAZOP was not performed. It was unclear what specific risks are being evaluated, as noted on slide 8. A leak by itself has minimal risk to personnel unless ignited, so it is unclear whether the risk is a fire or deflagration. It is unclear whether personnel protective barriers in the locomotive are being assessed for failure, i.e., if a steel plate is being used to protect people in the locomotive cab from a deflagration and if failure of this barrier is being evaluated. This would seem to be a key protective feature mitigating risk.
- While the impression is that more in-depth results have been received, the poster did not effectively articulate the accomplishments to date. Instead of accomplishments, the poster provided a restatement of the proposed methods. The milestones state that, in the past year, failure modes were identified, outreach to the Association of American Railroads was conducted, and likelihoods of leaks were estimated. However, none of these results were described in depth in the poster or in follow-up questioning by the reviewer. It

would be instructive for the team to publish specific results. The reviewer would like to rate this section higher, but the documentation of the accomplishments is too vague.

- Although this project is relatively new, substantial progress has been made. However, since the project is due to end by December 2023, further information is needed on how the team plans to complete the four remaining 0%-completed milestones.
- The progress reported indicates a useful expenditure of effort. The results are so general that how the results apply to the locomotive setting is not clear.

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.

- This is an excellent example of industry coordination, involving a national laboratory, Wabtec, and American Public Transportation Association (APTA) working groups. Compared to other projects with similar budgets, this project has a relatively small amount of collaboration, but the quality of collaboration appears strong, with frequent meetings among the collaborators. The work would be strengthened by engaging additional expertise from the quantitative risk assessment (QRA) or process safety community or consulting firms.
- Wabtec was clearly a valuable partner and key contributor to the effort. Involvement of the regulators was also a good aspect of the project, as is the involvement of the APTA. It would have been helpful to have included other railroad manufacturers or possibly an end-user railroad operating company for their perspectives on their rail operations. HAZOP studies and FMEAs are typically required to have an "operator" for their input. Wabtec may have been able to provide a broad perspective of relevant experience, but additional parties at the beginning stage are usually helpful for brainstorming.
- The project presentation did not specifically identify collaboration with any entity other than the APTA. It is expected that the project would utilize peer review of the approach and data used in risk assessments with other national laboratories and national and international working groups working to qualify equipment and instrument failure rates. For example, the Center for Hydrogen Safety is specifically working on collecting failure data in hydrogen operations. This was not noted. Slide 9 did mention that Federal Railroad Administration (FRA) regulations apply to locomotive design, but the project did not identify how it is working with FRA to qualify data for risk analysis, nor did the project identify the gaps in FRA criteria. Slide 9 mentions that refueling facilities will "likely" be subject to NFPA 2 but fails to identify how this is relevant to the project since the project scope is only the locomotive. NFPA 2 will clearly be applicable to any hydrogen storage and fueling facility, suggesting that the project is unaware of key criteria in the code; similarly, the presentation did not mention the clear gaps in NFPA 2 for prescriptive criteria applied to locomotive operation. Slide 11 identifies collaboration with Wabtec, but this relationship is better understood as a client; therefore, the data provided may represent a potential conflict of interest in promoting Wabtec's design.
- Excellent collaboration exists with Wabtec since Wabtec provides vital information and there is consistent bi-weekly correspondence. However, the inclusion of more project partners would add breadth to the project.
- The work is coordinated with the FRA and NFPA 2 with participation of the APTA. This coordination with regulators and standards organizations is essential, but the only industry member is Wabtec.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Development and dissemination of safety information is a highly necessary enabling activity. The project is on track to make strong advances for the Hydrogen Program. The detailed project results must be made public to meet the goal of widespread dissemination of safety information and to fill the technical gaps. The FMEA is a good start and should be published to allow stakeholders beyond Wabtec to benefit from the detailed safety insights developed. Furthermore, if the work continues as planned to include a rigorous QRA, as discussed, it will represent excellent progress toward the use of a scientific basis for RCS requirements. The work is especially powerful because of its blend of qualitative and quantitative techniques with scientific underpinnings. The team should be encouraged to include full details of both the qualitative and quantitative pieces in its reports.

- This project aligns well with the Hydrogen Program. It has the potential to significantly advance progress toward DOE research, development, and demonstration goals and objectives since it is crucial to have a risk assessment of a relatively nascent application of hydrogen (e.g., hydrogen-powered locomotives).
- The project clearly aligns with DOE goals to expand the use of hydrogen as a clean fuel in a particularly difficult application.
- The project qualifies progress toward its major goals but fails to qualify this progress and future effort toward any DOE goals. Alignment with DOE goals supporting rollout of new hydrogen technologies can be inferred.
- The beneficial impact is that the FRA becomes familiar with hydrogen and rail issues. Wabtec benefits with expert assistance. It is not clear, beyond a generic rendition of how the analyses proceeded, how industry in general is helped.

Question 5: Proposed future work

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

- The future work extends analysis and examines different sets of hydrogen rail refueling. Also promised is evaluating the variability of risk and potential improvements for safety. The most important aspect is the goal of performing a gap analysis for rail-related RCS.
- The project has effectively planned its future in a logical manner by establishing reasonable future steps. For instance, performing a gap analysis of regulatory codes and standards is paramount and critical.
- The future work listing is consistent with project goals and the completed scope thus far. Future effort fails to identify any effort addressing the key barrier of limited data for hydrogen equipment failure rates. There are other hydrogen-fueling-related RCS that most probably apply to the project scope that are not listed for future evaluation, such as SAE International fueling protocols and the Compressed Gas Association (CGA).
- NFPA 2 is referenced as part of future work. It would be helpful if a section on rail fueling would include the results of the risk study, along with an annex note that this work has been done and perhaps a summary of the paper.
- Strong technical work is planned. The team should clarify how peer review of the FMEA and QRA results will be conducted.

Project strengths:

- Scientific approaches to RCS development are commendable and important. They provide meaningful progress toward reducing DOE-identified barriers. Using QRA provides a powerful, objective basis for developing safety insights and recommendations.
- This project can advance the rail market by serving as a means to assure people that the activity can be safe. It is good to see that the work will be publicly available through publication of a paper. The partners were well suited to do the work.
- Strengths include the working relationship with the key client (Wabtec) on specific component and design information, a passionate attitude in the project team, and selection of multiple components in risk scenarios.
- The project demonstrates to the FRA the future importance for rail carriers to perform FMEAs and HAZOP studies and what these analyses entail.
- The project is filling in knowledge gaps and guiding the applicable regulatory community.

Project weaknesses:

- There is minimal collaboration to qualify equipment failure rates. No peer review or analysis of data was identified. There were no source citations of equipment failure data. Risk analysis is limited to failure producing a leak without consideration of combined risk of ignition sources. For example, a leak that results in direct hydrogen flow away from any ignition sources is much lower in risk than a leak in an ignition-rich environment. Another weakness is failure to formally qualify the project against DOE goals. Also, the project fails to qualify the experience and value of Wabtec data. Finally, as a new industrial application, it is unclear how Wabtec's design is incorporating necessary safety equipment and features so that the project can have high confidence that it is evaluating failure of key equipment.

- Weaknesses include lack of articulation of specific results to date. There is also a lack of detail on configuration of the analysis team and engagement of external reviewers in the process. It is unclear which specific codes or standards will be informed. The collaborations would benefit from more perspectives.
- One barrier mentioned in the project is the lack of widespread dissemination of safety-related information resources. However, the H2Tools website provides various safety-related resources.
- The findings are pretty high-level, and it is difficult to understand what specifically the analyses addressed.
- A weakness is the lack of a HAZOP study along with the FMEA.

Recommendations for additions/deletions to project scope:

- It is unclear what is being achieved by the milestone of presenting results to minority-serving institutions or similar educational groups—whether this is a mechanism to engage experts from diverse backgrounds, to increase engagement with universities, or to mentor students from underrepresented groups. The team should articulate a clearer goal and develop a strategy to meaningfully engage educational groups from a variety of institutions to achieve these goals.
- It is recommended that the project involve peer review collaboration in its risk analysis and investigate equipment failure data from multiple sources. It is also recommended that the project investigate other RCS sources (e.g., SAE International and CGA) for failure data and code gaps.
- The team should perform a HAZOP study on the actual fueling activity, as well as co-location of a dispenser and fueling equipment in a rail yard.
- A recommendation is that future industry participants must share findings more openly.
- The project should proceed and continue with its planned future work.

Project #SCS-H2042: Hydrogen Contaminant Detector

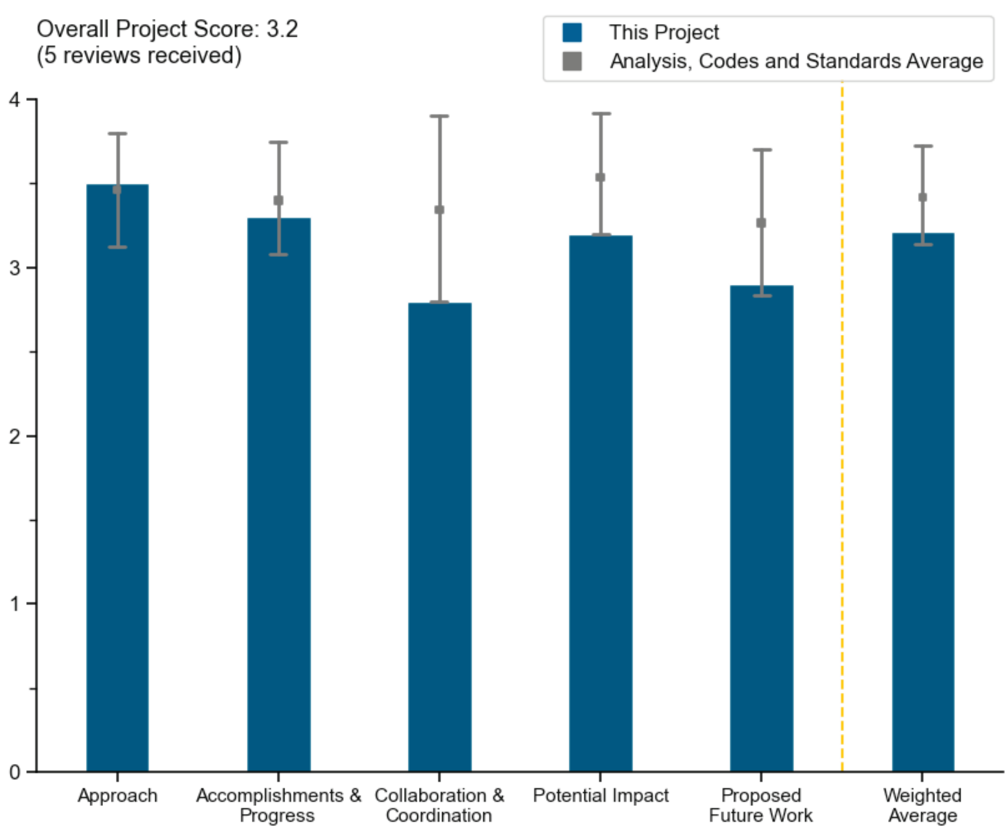
Matthew Post, National Renewable Energy Laboratory

DOE Contract #	WBS 8.6.2.1
Start and End Dates	10/1/2021–12/31/2023
Partners/Collaborators	Sandia National Laboratories, Argonne National Laboratory, California Governor's Office of Business and Economic Development, California Air Resources Board, California Energy Commission, South Coast Air Quality Management District
Barriers Addressed	Lack of information on operation and evaluation of high-flow infrastructure for heavy-duty hydrogen vehicles including: • Infrastructure examples • Tools to evaluate designs • Test devices for performance

Project Goal and Brief Summary

The goal of this project is to ensure safe and reliable hydrogen fueling by addressing the need for improved contaminant detection in hydrogen fueling infrastructure. The project will identify and evaluate viable hydrogen contaminant detector (HCD) technologies for real-time, in-line verification of hydrogen fuel quality. The project involves selecting promising HCD instruments and testing them to SAE J2719 fueling standards. Identified detectors will be integrated into high-pressure hydrogen fueling stations, including the National Renewable Energy Laboratory's (NREL's) Hydrogen Infrastructure and Testing Research Facility (HITRF) and the forecourt of a California hydrogen fueling station.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Analysis, 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 seems to focus on sampling techniques more than detection techniques, which is fine. As such, the work can definitely help meet the project goals by creating a stable sampling system for assessing different HCD technologies. Two different detectors have been looked at; whether they are most effective depends on what specific contaminants are being sought.
- The project's objectives/goals and critical barriers are clearly identified and have been addressed. The project is sufficiently designed and easy to follow. Its approach is clearly delineated into several parts.
- The approach process is logical and well-thought-out. Testing plans are valid and adequate for minimal data-gathering. The graphic wheel on slide 6, for ranking characteristics, is outstanding.
- The approach of the project is to develop a system with which to test HCDs. In that regard, the test setup appears to be well done, and a test facility has been developed. The larger question of whether an HCD is going to be practical is a related, but separate, question.
- The concept is very relevant, and work has illustrated some important practical issues for deployment. The practical advancement seems somewhat limited. The choice to focus only on CO contamination in this round of work is understandable but also limits impact. The ability to detect in near-real time is good. It is not clear how that can be parlayed into proactively preventing contaminated hydrogen from being deployed; this should be the goal, rather than indicating in near-real time that the fuel cell has already been contaminated by the fueling event in process.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- Excellent progress toward project objectives is proven by the project's clear and measurable performance indicators. The extensive and well-detailed slides in the reviewer-only slides are much appreciated. Lastly, the visual aids (e.g., pictures of the NREL dispenser HCD interface and enclosure) show the project's accomplishments.
- It appears that the test facility is set up and tested, so it is a major accomplishment to now have a location to do such testing.
- Identification of the top two HCD methods meets specific goals. Development of test apparatus and integration with the NREL system are outstanding. Appropriate safety precautions (personal protective equipment) are noted in slide pictures. However, there are several weaknesses in the presentation, validated by questions to the principal investigator, that prevented accomplishments and progress from being outstanding. First, there is no project timeline/bar chart/Gantt chart noting project status compared to a schedule or goals. Second, the investigation evaluated several detector systems, but only two are noted on the presentation. The project should list all instrument systems reviewed and provide a general ranking conclusion. The identification of only two instrument approaches is difficult to understand from just the data provided in the slides.
- The project milestones and go/no-go decision points are not clearly identified in the materials provided for reviewers. This makes it difficult to gauge the progress. Qualitatively, the description of progress shows advancement in CO contaminant detection, which has apparently been identified as the primary focus in executing the project.
- The project has set up a good sampling system and tested two different HCD technologies. However, perhaps there are other HCD technologies that should be considered.

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 specific collaboration activities with Los Alamos National Laboratory (LANL) are excellent. Presented data could be clearer by noting collaboration effort matched to project approach/goals. It is unclear whether the project plans to hold, or has held, discussions with industrial manufacturers or industry technical groups (e.g., the Microelectromechanical Systems [MEMS] and Sensors Industry Group). This interface would be valuable for validating the breadth of sensor investigation, validating the state of the art for applied technology, and identifying deployment issues for future scope.

- Collaboration with LANL is noted and seems to be well positioned for potential positive outcomes. Work with the California Air Resources Board and station operators has not been productive yet, and there is not sufficient information provided to anticipate future progress or removal of blockers.
- There is sufficient collaboration with partners such as LANL (e.g., providing electrochemical sensor and other services, e.g., evaluation). However, partnership and collaboration with industry and standards development organizations need to be included.
- The collaboration with LANL on the CO detector is good. In addition to that detector and the Fourier-transform infrared (FTIR) spectrometer, it would be good to look at two or three additional detectors to see how the sampling system works more broadly.
- It would be better if there were a fuel station provider partner to enable the installation of an HCD at a fuel station location and to provide feedback on what is realistically deployable. Even if that is part of a future project, the test apparatus, as configured at NREL, appears as if it would be very challenging to deploy at a fuel station, given the space and utilities required.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project is critical to the Hydrogen Program and has the potential to significantly advance progress concerning hydrogen fuel quality and make fuel quality verification more efficient. It is important to make improvements when detecting hydrogen contamination, especially since current fuel quality verification protocol may prove inadequate. For a burgeoning, nascent industry such as the hydrogen and fuel cell industry, it is paramount to have adequate fuel quality verification protocol to bolster station commissioning.
- Work on scoping the range and impact of contamination modes and on practical detection of CO contamination are noted. DOE might find that these more modest accomplishments satisfy its goals and objectives. Work to support practical field demonstrations, address other contamination modes, and convert the new detection capabilities to effective mitigation of contamination appears to remain more aspirational.
- This is definitely a high-impact project since there are many contaminants that can cause temporary or permanent loss of performance in a fuel cell electric vehicle, and, as the network of stations with different sources of supply and different hydrogen production technologies is used, it will become more important to be able to monitor for contaminants in real time.
- There is no question that the HCD technology would be useful to have as an additional tool to ensure product purity. Valid questions, though, become “Is it needed?” and “Is it feasible and cost-effective?” In terms of need, the likelihood of contamination when H_2 is shipped to a site is low when compared to onsite production. The prevalence of contamination-inducing onsite production has been reduced to where maybe onsite monitoring of the full slate of contaminants is less important. The more common contaminants might not be CO or S but rather O_2, inert contaminants, H_2O, and maybe lubricating oil. Similarly, a target cost per kilogram should be estimated to see if the technology would ever be cost-effective based on expectations of the technology within 5–10 years.
- The presentation did not identify how the project aligns to DOE targets and performance goals. The impact can be deduced but appears to be primarily supporting consumer cost reduction in alignment with reducing hydrogen costs. The in-line testing for contaminants has a strong value in reducing supply chain costs and should be better highlighted.

Question 5: Proposed future work

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

- The project has effectively planned its future in a logical manner. For example, a technical webinar to educate potential stakeholders is an excellent next step. Also, expanding heavy-duty applications is necessary since hydrogen trucks will be an important part of the future of heavy-duty transportation.
- The list of proposed work is thorough and valid, especially for interface with industry. The two slides (Remaining Challenges and Barriers and Proposed Future Work) could be better amplified to describe scope yet to be completed and new potential scope derived from results and issues thus far. For example, the presentation could say whether the project foresees any revision to its scope or effort to address negative impacts from sulfur and ammonia on the FTIR testing protocol. Also, it is not clear what the difference is between uncompleted project scope and "proposed" future effort. For example, it is unclear whether testing at a commercial hydrogen fueling station is in the project scope or proposed future effort. This activity is listed on goal slide 2, approach slide 6, and barrier slide 18, yet it is also listed on proposed slide 19. The addition of a slide depicting the remaining scope to be completed would help qualify the issue. This type of testing project has great value to practical system operation, and the project has a unique place in defining the state of the technology and future thrust for industrial research. Identifying improvements and the path forward for industry would be helpful.
- Expanded practical demonstrations are proposed and would be relevant in gauging the potential real-world impact of the work.
- There are good plans to validate additional HCD technologies and to implement the system into the HITRF and into one or more retail stations to validate the system effectiveness.
- It is hard to question any individual item in the proposed work since all are needed, but that also means there is a potential lack of focus or potential to be spread too thin. It would be better to select two or three specific items and provide greater detail, goals, and milestones for each for more measurable results. Alternatively, the project might lay out the objectives with a realistic timeline that is based on the current (and future) technology and amount of resources and time available.

Project strengths:

- Use of actual scale instrument systems and NREL test equipment is extremely valuable, bringing the knowledge base forward beyond literature search and laboratory-scale testing. The principal investigator is passionate and knowledgeable of technology and testing protocols. The interface with NREL testing systems is logical and well planned; actual test equipment systems appear valid for appropriate data-gathering. The presentation and poster session photographs and charts were extremely valuable. The project earns kudos for preparing an actual poster rather than simply posting slide copies. The project has a great start and should help to practically advance the fueling industry.
- The use of an HCD can take the place of periodic and relatively ineffective batch sampling. In that regard, this could be a useful approach to ensure good product purity for situations where that is necessary. The project test facility was well designed and is available for its expected role. The project was also forthright about the challenges that the HCD technology will face and that question the validity of the approach.
- The work has resulted in new capabilities for CO contamination detection. Work to assess modes and impact of contamination supports future work targets.
- The project has set up a very practical sampling system to allow sampling on a per-fill basis.
- The project is laser-focused and easy to follow.

Project weaknesses:

- The testing and apparatus will be useful only if there is a credible HCD that can be deployed. As configured, this would be very challenging to deploy commercially to a station. As a result, the project is only as good as the HCDs that are available. A fair question is whether there will ever be an HCD that meets the needs of being able to cost-effectively measure the key contaminants. The project is not giving an assessment of two key items: (1) what the cost of a deployed HCD might be, along with expected operating costs and whether those costs are feasible for a fuel station, and (2) whether there will be an HCD that can measure the full breadth of contaminants from CO to S to H_2O to inert contaminants, etc. If either of the above are not answered, then the testing may be of limited value.

- Understanding more about two potential weaknesses would be helpful. (1) Sampling is done when the hose is vented at the end of the fill, and that means that the sampling/detection is always “one fill behind.” This seems like a concern, and it is not clear how the sampling system might be configured to take the sample at the beginning of the fill instead of the end. (2) It is acknowledged in the poster that contaminants such as sulfur and oil can be very “sticky” and, as such, can contaminate the inside of the sampling system, be difficult to clean, and possibly cause false positive detections. It was unclear whether consideration has been given to how to purge the sampling system or how to filter results to avoid “echoes” from previous contaminants.
- This is the first time this project has been reviewed at an Annual Merit Review. The basic data is provided, but more information would be helpful to understand the investigative process, alignment with DOE goals, and project status. Additional collaboration with industry would be very valuable since the project involves actual sensor systems at scale. Identification of a complete listing of considered instrumentation is lacking, along with the results of the strategic evaluation. Safety planning should be described.
- Significant challenges remain to be addressed, and the plans to mitigate risk are not entirely clear. Practical field demonstrations will be important and have not occurred beyond the single installation. Some collaboration with LANL is noted, but the contributions of other project partners to the work that has been accomplished are not clear.
- More in-depth information on the numerical ranking of the prioritized specifications and the estimated amount of time used for real-time fuel quality verification would be appreciated.

Recommendations for additions/deletions to project scope:

- Addition of an amplified interface with industry and/or industry sensor groups is recommended. Deletion of the full-scale testing forecourt demonstration at a commercial hydrogen fueling station is recommended unless agreements are in place already and funding is available. Obtaining this agreement seems unlikely, with the risk a commercial fueling supplier would need to take on, and the demonstration would require a large amount of resources. Slide 3 notes that there is no planned Fiscal Year 2023 funding from DOE; remaining project dollars would be best used in completing testing at NREL and project improvements noted in the review. The NREL test facilities appear adequate to provide a full-scale demonstration and data collection instead of testing at a commercial facility.
- An estimate of a best-case installed cost of an HCD long-term should be added, as should a technical assessment of whether the concept of an HCD is feasible for this application, even given expected advancements in technology in the foreseeable future.
- If the narrowed scope is acceptable to DOE, driving to more practical validation of the CO detection might yield the most impact from this project as it currently stands.
- The project should consider purging the sampling system and sampling at the beginning of the fill.
- The project should proceed and continue with its planned future work.

Appendix A: 2023 Hydrogen Program Review Summary

This appendix shows the results of the Hydrogen-Program-level peer review for the 2023 Annual Merit Review and Peer Evaluation Meeting (AMR), including feedback from a subset of the reviewers attending the AMR. A total of 23 Program-level reviewers provided feedback. As shown in the table below, 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.

Peer Review Panel: Represented Organizations

3M Company	Patturns
Electric Hydrogen	Plug Power Inc.
Energy and Environmental Research Center, University of North Dakota	Toyota Motor North America
Fuel Cell and Hydrogen Energy Association	U.S. Nuclear Regulatory Commission
Hydrogen Fuel Cell Partnership	University of California, San Diego
Hyrax Intercontinental LLC	University of Illinois Urbana-Champaign
Ionomr Innovations Inc.	Victoria University of Wellington
Los Alamos National Laboratory	West Virginia University
Nel Hydrogen	World Bank Group

1. The Hydrogen Program plan and strategy were clearly articulated and well-aligned with mission and goals of the National Clean Hydrogen Strategy and Roadmap and the Hydrogen Shot.

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.

	Hydrogen Program Overall Strategy
Average Score	**9.2**
Number of Responses	21

General Comments:

- Well described. The H2Hubs program will provide funds and de-risking of much larger deployments of clean energy in the form of hydrogen. This, in essence, is the aim of the national plan—to bring a full-scale hydrogen economy into existence—so the alignment really could not be better. The several smaller research funding opportunity announcements (FOAs), the fairly large clean hydrogen electrolysis and manufacturing FOA, and the tax credits for hydrogen will support work on enabling the research and near-commercial development needed to significantly reduce the cost of hydrogen and its delivery, which of course is what is needed to stabilize those hydrogen ecosystems economically and make them financially and ecologically sustainable. The constant underlying theme of doing this in a way that brings the benefits to the underserved aligns the Program's work with the administration's environmental justice and diversity, equity, and inclusion (DEI) objectives as well.
- The Hydrogen Program is one of the very best organized, closely managed, and carefully executed programs in DOE. Drs. Satyapal and Miller, as well as the other managers, provide excellent leadership—the highest-quality leadership—for the Program. They masterfully integrate the entire government-wide hydrogen effort to ensure attaining 2026, 2031, and 2050 goals.

- The visionary leadership of Dr. Satyapal and her team, along with the persistent and continued efforts over the years, has established a strong foundation that warrants and maintains the Program's health, thus ensuring the meeting of goals and objectives. Another important strength of the Program is mentoring the next generation of managers—an important accomplishment that warrants the continued success of the program.
- In my opinion, this Hydrogen Program is one of the very best programs among all different federal agencies. I was able to attend, in person, all key presentations, from Monday's plenary talks to the very last excellent talk delivered by the National Renewable Energy Laboratory on Thursday late afternoon. I am very impressed with the technical quality of the projects and the different programs presented throughout the 2023 AMR.
- The Office of Energy Efficiency and Renewable Energy (EERE) has done excellent work to articulate the mission and goals of the Hydrogen Program.
- Opening speakers did a good job tying the Hydrogen Program to U.S. goals for decarbonization, climate change action, good paying jobs, and community benefits. It was also great to see the opening speakers and panels discuss safety.
- Very strong integration is clear, both across DOE and across the government. This is a major advancement for the Hydrogen Program across the last few years.
- The Hydrogen and Fuel Cell Technologies Office (HFTO) has done an excellent job managing the multi-dimensional program.
- The plan and strategy were clear and well aligned.
- The hydrogen strategy came out too close to the meeting to be able to tell whether the Program plan is aligned. The Program plan was clearly articulated.
- I think there needs to be some realism about consumption and the smart use of energy rather than looking for a business-as-usual solution that looks for a technology switch rather than a serious reinvention of how society uses energy.

Specific Comments on how well the Hydrogen Program has identified important challenges to meeting goals and articulated plans to address the challenges.

- There is so much here, it could never be captured in 4,000 characters. Let's try to summarize instead. The key barriers for production, delivery, storage, and fuel cell use in light-duty transportation have been in place for over a decade; and while the levels are new, the heavy-duty barriers are the same, just more so. The Program has subsequently expanded its target to be essentially all energy uses and has elucidated the barriers in these many new uses. They are perhaps surprisingly similar qualitatively but in some cases are easier quantitatively (though, for example, cost for rail use is even harder), so the barriers are and have been well understood by the Program for some time. What is new is the plan for meeting the challenges. There is a significantly more product-focused or engineering-guided nature to the research and development (R&D) plans this year and last, with more focus on what could be done with that material that would benefit the taxpayer. Specifically, the transportation focus, while still a part of the Program, no longer dominates it, and there is real work to seek other and, fortunately, easier ways to launch hydrogen applications. There is also a greater emphasis on hard-to-decarbonize applications where electricity is simply not going to help. At the same time, the Program retains its efforts on codes and standards, which are indispensable, critical even, to a functioning economy, because this is what allows predictable and swift permitting and affordable insurance. I think, overall, this is a healthier and more helpful approach for the nation.
- The Hydrogen Program, as in the past, has done a very good job of developing and communicating technology roadmaps for the R&D activities with which I am most familiar: fuel cells and hydrogen infrastructure. The goals are generally stretch goals to challenge the R&D community, and the progress toward these goals is communicated regularly.
- In the electrolysis area, DOE has set the viable 2026 goals and specifically identified very clear target performance parameters—including cost, cell area-specific resistance (ASR), and current density (hydrogen production rate)—to be able to achieve those goals.

- The focus of the Hydrogen Program's goals on the industrial utilization of hydrogen (e.g., blending hydrogen for combustion, green steel, ammonia production and combustion, energy storage) is the strongest facet of the Program beyond its goals in the transportation space.
- Goals are very clear and aggressive. The presentations demonstrated how different pieces of the system (production, delivery, end use, etc.) contribute to success and what the Program is doing to drive down costs and address challenges.
- HFTO has identified technical issues, supply chains, and manufacturing to improve electrolyzers' service life, production rate, processing, and materials cost to meet the cost target.
- It was great to see the opening speakers and panel discuss the challenges for safety and describe the level of coordination involved.
- One of the major issues is that $1/kg in 1 decade may not be a realistic goal, given that, for electrolysis, it requires (at 60% of cost from electricity) that the cost of electricity is far below the long-run marginal cost of renewable energy. The perception that variable renewable energy prices will continue to decrease ad infinitum is not realistic, given realities of commodity costs, supply chains, and labor/soft costs. I worry a bit about setting such a target and then making funding decisions on potentially unrealistic numbers.
- There seem to be significant gaps in correcting and addressing funded projects that are not performing. There are good plans in place for different technology readiness level (TRL) development, but the reliance on established national lab scientists and the "usual" crowd of players seems to belie the concept of enacting change.
- The largest challenge is the need for more staff at HFTO. The office was constrained from hiring in the previous administration, and it shows. The understaffing makes it difficult to get FOAs and funding out on time.

2. The Hydrogen Program is aligned well with industry and stakeholder needs and appropriately complements private-sector, state, and other non-DOE investments and RDD&D.

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.

	Hydrogen Program Stakeholder Alignment
Average Score	**8.4**
Number of Responses	19

General Comments:

Please describe any areas that you feel are not well aligned with industry needs or that require more (or less) federal funding support.

- The Hydrogen Program is well aligned with industry and stakeholder needs. Through intense communication and integration, DOE is ensuring that information, including DOE objectives and Program goals, is conveyed to all stakeholders in a clear and timely manner. DOE realizes the approach of funding a few entities and walking away will not work. To achieve the DOE goals, DOE must make sure that funding goes to diverse corporations and entities. The DOE Hydrogen Program realizes that fact and is executing intense integration to ensure goals are achieved.
- I have given about as high a grade as is possible under the new, wider scope of work. Because they have taken on so many more beneficiaries to the work they fund and manage, it becomes increasingly difficult to "align" with all of them. They seek industry input, either via tech teams or project by project, with industrial collaborators offering direction but no funds or goods. There are examples of state and private investment complementing DOE funding, and there is little if any complaint about DOE doing work that

should be done by industry. Of course, there are industrial groups as principal investigators or as subs on larger FOA projects, and of course, the cooperation between industry and DOE is perfect there.

- While there is probably some interagency alignment, the Program feels slightly inward-facing and focused on the national labs. There is tremendous capability there, of course, but in the photoelectrochemical (PEC) area, I would suggest that there is no industry interest because there is no obvious path to market. There is also perhaps too much focus on the United States and little appetite for international collaboration at the top level, though of course individual researchers will have their networks. It was encouraging, however, to read that DOE had provided funding to work with Synhelion; this is the sort of potential win–win that helps better use public money. Natural gas cracking research should be discontinued—you will never get to an emissions-free supply chain, even if the hydrogen production itself does not emit CO_2.
- Industry appreciates the R&D efforts yet has been requesting additional market implementation activities and support. There have been times when industry feedback on this has left the impression that market development and implementation are not as valued or supported as base R&D. The hope is that establishment of the Office of Clean Energy Demonstrations (OCED) is recognition of this change toward driving needed R&D into full market realization (as a partnership between government and industry).
- The integration is good, and cost-sharing efforts are clear. It seems like there is still some struggle to find end uses and adoption for what could be an abundant supply. The "clean energy" market is full of various alternatives for consumers and businesses, so additional effort to spark adoption may be needed.
- The national lab consortium approach limits access to industry participation through FOA-funded projects, very expensive "work for others," and intellectual property (IP)-conflicted cooperative research and development agreements (CRADAs). In addition, there is insufficient responsiveness to stakeholder feedback when weighted by national labs. Examples of this include (1) the ElectroCat (electrocatalysis) program, which has been criticized for relying on iron, a known poison for proton exchange membrane fuel cell (PEMFC) membranes, and (2) the goals for heavy-duty fuel cells, which include inflated system costs and therefore place an unrealistically high burden on materials development. These approaches hinder the national lab projects' relevance.
- The funding for the Inflation Reduction Act (IRA) needs to get out faster. Hydrogen from Next-generation Electrolyzers of Water (H2NEW) had no related FOAs since its inception until the electrolyzer one came out a few months ago. Project selection and contracting needs to happen quickly.
- In the future, the Program may wish to focus more on end users that are the engine of the hydrogen economy. In fact, it is the end users that will lift off the hydrogen economy. Efforts on hydrogen production are already well under way.
- It would be great if the Program could also include the real consumers as one important stakeholder and consider how the Program resources could be invested wisely to let the consumers see/feel the benefits.
- It is not clear from all the presentations how DOE has aligned the Hydrogen Program with industry and stakeholder needs.

Office-Specific Comments:

Please comment on particular strengths and/or improvement opportunities relative to specific DOE Hydrogen Program offices in the table below:

DOE Office	Strengths	Improvement Opportunities
EERE	• Strengths include the organizational structure, active involvement of the technical managers with the technical projects, clear outline of goals and objectives, coordination between national laboratories and industry, a rigorous review program, and the organization and impact of the AMR. • SuperTruck projects are a good example of partnering with industry on helping develop hydrogen versions of medium- and heavy-duty trucks that will sell by having industry leaders develop them with DOE de-risking the effort. • Dr. Satyapal's long tenure translates to a powerful "corporate memory" and a steady hand at operating a very complex set of R&D activities, ranging from rather foundational to demonstration and deployment. • The Hydrogen Program HFTO is providing outstanding leadership under its director, Dr. Satyapal. • The Program is collaborative, with both industry and other DOE program offices, and is building unprecedented collaboration with other government agencies. • EERE activities are centered on the DOE mission. • Strengths include clear leadership and coordination. • A strength is the Program's ability to link the excellent work at national labs and universities with industrial teams able to begin commercialization.	• DOE has put out excellent efforts to drive three or four different fuel cell technologies to demonstration. The historical fact is that the cost of developing a particular fuel cell technology to the demonstration stage has taken at least a $1 billion per technology and decade(s) per technology. To aggressively achieve and possibly exceed the Hydrogen Shot 1-1-1 goal, for now, DOE must be very selective in choosing the most promising and highest-TRL technologies in which to invest. Those must be able to impact 2026 and 2031 goals. Among those fuel cell technologies, the proton-conducting solid oxide electrolysis cell (p-SOEC) is at a very low TRL level and lacks commercial interest worldwide because of the lack of validated, consistent, repeatable results. The low-TRL technologies (p-SOEC, tubular SOEC, direct methanol PEMFC) will each take $1 billion and decade(s) to validate and demonstrate. There are only eight years left to 2031 and only limited funding to reach the Hydrogen Program goals. DOE cannot indulge every distraction, however promising the seedlings claim to be. • There should be more active interactions with the DOE Basic Energy Sciences program and the National Science Foundation toward removing science and engineering roadblocks such as catalyst degradation and materials issues. The Program should focus on end-user small businesses that will advance commercialization. • The Program could provide one-stop shopping for the public to integrate the work of the offices.
FECM		• In the area of high-temperature electrolysis, DOE should leverage the progress and advancement of solid oxide fuel cell (SOFC) technology funded for more than 30 years by the Office of Fossil Energy and Carbon Management (FECM). DOE should continue SOFC work (or at least SOFCs via reversible SOFCs).
NE	• Behind-the-meter hydrogen production at plants is another good example of proper positioning vis-à-vis industry. Years of DOE research made the technology worth trying, and de-risking funds made it worth trying economically. However, a power company actually did the implementation. • Nuclear electricity for electrolytic hydrogen production is a great approach to clean hydrogen production.	• The country's nuclear fleet is old. Can the emerging hydrogen economy be planned on using nuclear electrons for hydrogen production? This question needs to be addressed. Is small modular reactor technology more relevant to hydrogen's future than existing nuclear plants? • Fusion projects could be folded into the fission ones being described.

	• The nuclear energy work is much more integrated than in the past.	
SC	• The AMR did a good job highlighting how basic science efforts are contributing to advancing the hydrogen sector. • There are generally good efforts to promote "scientific" discovery.	• National lab scientists should not review business or marketing FOAs. • It would be helpful to clarify which projects/ advancements are far enough out that they need this basic effort, *vice* later-stage adoption efforts other offices are doing.
ARPA-E	• The focus is on commercial impact and outcomes, as well as disruptive technology. Commercialization is wrapped into the technology. There is active program management, as well as excellent exposure and training to fundraising.	• The SCALE-UP (Seeding Critical Advances for Leading Energy technologies with Untapped Potential) program is a great idea to enable deployment demonstrations; a more guided/couched approach from SEED (Supporting Entrepreneurial Energy Discoveries) to general ARPA-E to SCALE-UP would be helpful.
OCED	• Hubs are the strength. They are not in place yet, of course, but these are a mix of DOE technical developments bringing technical advancement in all aspects of the hydrogen economy, with major groups of companies, state agencies, community groups, and so on designing the implementation to work economically. • The work is market-development-focused, extending EERE's R&D focus into real-world success. • It was great to have OCED involved in the panels in the opening session.	• Opportunities include (1) keeping focused on what the market needs to develop at the upper end of TRLs and (2) helping to de-risk "last-step" industry needs into real market opportunities. • There should be a way to ensure applicants are aware of programs run through this office and other offices. Perhaps there could be a clearinghouse in coordination with EERE.
Other (specify)	• Collaboration with development finance institutions is a strength.	• There is a good deal of scope to leverage DOE efforts in the context of coordinating with the World Bank to further work on this topic.

EERE: Office of Energy Efficiency and Renewable Energy

FECM: Office of Fossil Energy and Carbon Management

NE: Office of Nuclear Energy

SC: Office of Science

ARPA-E: Advanced Research Projects Agency–Energy

OCED: Office of Clean Energy Demonstrations

3. The Hydrogen Program's portfolio of projects is appropriately balanced across research areas to help achieve its mission and goals, and it has an appropriate balance between near-, mid-, and long-term RDD&D (including lab projects and consortia, FOA projects, CRADA projects, etc.).

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.

	Hydrogen Program Project Portfolio
Average Score	**8.5**
Number of Responses	17

General Comments:

Please describe any over- or under-represented areas, including any gaps in the overall Hydrogen Program project portfolio or any comments you may have on whether funding levels in each area are appropriate.

- The Program encompasses the Basic Energy Sciences program doing TRL 1 and 2 all the way through OCED doing TRL 9, de-risking and supplier–user matchmaking to generate a stable hydrogen economy. Plus, there are Small Business Innovation Research (SBIR) projects and Loan Programs Office work, too. The funding tends to scale with TRL, as is appropriate. The distribution of projects is uniform across TRL, though one might argue there is a little less in the TRL 5 and 6 area, as that seems handled mostly via SBIR projects, which are a small component. This is not a significant flaw, and many would argue this is an area industry should be shouldering anyway. A wide variety of topics is covered—almost every method of production and delivery and many use cases—essentially everything where R&D might move the needle. There are no obvious blank spots.
- I like the broad spread of research areas and the inclusion of some high-risk areas such as solar thermochemical, which has the potential for serendipitous discovery, as it is such a challenging area scientifically and practically. I am less convinced about PEC, as the main progress has been in perovskite photovoltaics (PVs), and successfully connecting this with a wet surface seems unlikely. I also simply cannot see how a large electrolyzer surface could be practically applied. PV and electrolysis with the process intensification of high current density seems so superior that there might not be much point to continuing this area of research.
- There are no gaps. DOE has driven three or four fuel cell technologies to market. The cost of developing a technology to the demonstration stage has taken at least $1 billion per technology and decade(s) per technology. There are only eight years left to 2031. DOE must trim and focus to drive toward its goals with the limited funding and time available.
- A really strong balance has developed.
- Research, development, and demonstration (RD&D) are needed and important, yet even this question leads only to research needs vs. other opportunities and needs the Hydrogen Program *must* include to move R&D into full market reality. Additional activities around connecting and expanding R&D to policy, workforce, community, implementation, and other "market-based" development activities are critical; otherwise, the R&D does not result in full market potential (or not in a timely fashion). Establishment of OCED appears to be the first real recognition of this and is critical to the success of current and previous investments.
- The national lab consortium approach limits access to industry participating through FOA-funded projects, very expensive "work for others," and IP-conflicted CRADAs. In addition, there is insufficient responsiveness to stakeholder feedback when weighted by national labs. Examples of this include (1) the ElectroCat program, which has been criticized for relying on iron, a known poison for PEMFC membranes; and (2) the goals for heavy-duty fuel cells, which include inflated system costs and therefore place an unrealistically high burden on materials development. These approaches hinder the national lab projects' relevance.
- I would put more effort into systemic approaches to get projects to the final investment decision. Socioeconomics of hydrogen remains a difficult and complex issue globally. I recommend putting a bit more effort into global cooperation—the World Bank Hydrogen for Development Partnership (H4D), the Clean Energy Ministerial and Mission Innovation, the International Renewable Energy Agency (IRENA), etc.—given the need to develop a global industry.
- An under-represented area is near-term hydrogen production and infrastructure development, which is critically needed to address the current high hydrogen retail price issue. Lab and consortia projects may be a little over-weighted. Projects from academic groups are underrepresented.
- Besides demonstrations and large-volume manufacturing development, it is recommended that DOE have a significant R&D focus on *transformative* modifications of current *stack* technologies, not development of a brand new technology (e.g., new electrolytes), to meet the DOE goals within the established timeframe (e.g., $2/kg hydrogen in 2026).
- Stronger collaboration between the national labs and academia is essential for roadblock removal, e.g., to meet the "111" goal of the Hydrogen Shot.

Office-Specific Comments:

Please comment on particular project portfolio strengths and/or gaps relative to specific DOE Hydrogen Program offices in the table below:

DOE Office	Project Portfolio Strengths	Project Portfolio Gaps
EERE	• EERE has a wide range of funding portfolios to support different hydrogen programs from RD&D to technology demonstration and manufacturing. The recent $750 million investment in electrolyzer technology, supply chains, manufacturing, and materials recycling will advance green hydrogen production technologies and accelerate commercialization of these technologies. • The hydrogen production, delivery, and infrastructure subprograms are very strong. The safety, codes and standards technical assistance programs are expected to be impactful. Work and contributions from national laboratories are important. The national lab collaborations with industry are very strong. • Breadth and depth of Program R&D activities is accompanied by a strong analysis function of most of the aspects of the Program sectors that allows for tracking progress over the years. • There is a broad portfolio of production, delivery, and use—and at many TRLs from 2–3 to 6 or even 7, with SBIRs counted. • HFTO, with its excellent leadership, is driving, through integration, a diverse set of stakeholders to achieve 2031 goals. • The Program has a well-structured, comprehensive portfolio covering all aspects of hydrogen and fuel cell technology developments. • The Hydrogen Program regularly seeks stakeholder input and addresses RD&D needs.	• I hope to see increased investment in biofuel and its production. For manufacturing and industrial decarbonization, the key driver is the TRL for hydrogen production. For example, the ammonia and steel industry may not need high-purity hydrogen. The hydrogen production from coal/biomass/ waste gasification may have advantages since there is existing infrastructure and lower capital cost investment. • It would be great if more and quicker investments could be guided toward hydrogen infrastructure development to address near-term hydrogen supply and cost issues. • A gap is education of local managers for commerce and economic development at the county level within states. In the end, it is these managers who will work to attract and interact with prospective end users. • There are no gaps.
FECM	• A variety of funding was provided to support gasification of coal, plastic, biomass, agricultural waste to produce syngas, and hydrogen, which can be used as fuel to operate SOFCs to generate clean electricity with higher efficiency or as starting materials to produce chemicals. Based on the characteristics of renewable energy,	• The hydrogen economy relies on multi-level and multi-dimensional technologies, including hydrogen production and applications. Some applications, such as PEMFCs, require high-purity hydrogen. Some, such as high-temperature SOFCs and the ammonia and steel industries, have no strict requirements for hydrogen purity. I hope to see increased investment for hydrogen production from gasification combined with carbon capture to

	FECM also funded the RD&D for reversible solid oxide cells, which can produce both hydrogen and electricity. This funding ensures hydrogen technologies continue advancement in the United States.	provide hydrogen to these industries to achieve Hydrogen Program targets earlier and with lower cost. The combination of gasification and carbon capture is expected to reduce CO_2 by emission by 80%–90%.
NE	• Good work is happening now to demonstrate the advanced electrolyzer technologies by taking advantage of low-cost electricity from nuclear energy. It will generate a good amount of operational data and provide valuable experience to accelerate the commercialization of hydrogen production via electrolyzer. • More on the upper TRL and pretty much on hydrogen production.	• There could be stronger support of local government and nuclear power plants to support more technology demonstrations.
SC	• I did notice the FOA-3003 from SC early this year to provide a variety of funding opportunities for fundamental research, including Energy Earthshots™, which provided good opportunities for researchers/scientists to perform scientific research to help the Hydrogen Program.	• The office may want to provide a more detailed description about the areas of interest for funding to differentiate from EERE funding, such as how to differentiate the electrolysis for the funding opportunities between SC and EERE.
ARPA-E	• ARPA-E provides funding opportunities for transformative research at the $1 million level up to $100 million for disruptive technology demonstrations to promote the technology innovation and commercialization pathway. • Early TRLs and a broad spectrum of possible uses are strengths. • I am happy to see increased funding to support the carbon capture program for natural gas fuel.	• Trucks and cars are moving to hydrogen, aircraft are undergoing experimentation, and there is a driver not to negatively impact the stratosphere. I think it may be a matter of time before railroads are viable. Shipping, according to the panel discussion at the AMR, is still not in a viable mode. This is a significant source of greenhouse gas and criteria pollutants, burning large amounts of less refined fuel across the world. There are some demonstration ferries, but what would it take in hydrogen storage to make the shipping industry confident of global transport? What sort of fuel cell would be best for marine applications, and how do we get there? Can that fuel cell bank that drives a gigagram-mass-loaded freighter through water and massive ocean storms really turn down to hotel power levels in port, or must a second compatible fuel cell be provided for port operations? These are a few open and broad-level questions that ARPA-E might think about taking on.
OCED	• H2Hubs is an excellent program to support clean energy demonstration to accelerate the commercialization pathway. • OCED is not yet active but will be the home of TRL 7–9 work, at least on a money-spent basis.	• OCED seems to have a very nice program to generate nuclei of a full hydrogen economy in a few places and let them grow with the hubs. A few gaps might remain. The main one is that if hydrogen is to become a major power/energy commodity, as electrical power is now, it will need a system to *ensure* continuity of that power or energy, as the current interconnect system does for electricity. This will be complex and will absolutely require input from business, state, and national levels. Also, the current electric

		interconnect with three grids (West, East, and Texas), while conceptually similar, will almost certainly not be the right model because hydrogen does not flow at the speed of light in aluminum; because of travel time, hydrogen produced in Florida cannot help with a supply disruption in Minnesota. Yet there will be a need for at least adjacent geographic areas to support each other in times of supply/demand stress. On the plus side, hydrogen is energy, not power, so a certain amount of lag time can be built into the system with storage at a local, state, and geographic level. The best model may well take aspects of the electric grid and natural gas and oil pipeline systems. Modeling will almost certainly be needed, as will life cycle analysis, all done under a variety of non-standard operating conditions. At a minimum, we need to understand how much pipeline and delivery redundancy is cost-optimal, how much storage capacity is needed at various distance scales from point of use, and whether the eventual national hydrogen energy system will benefit from or be hindered by a private overseer, as with the electric interconnects, and some or no regulation. All this needs to be understood well before the hubs start to grow toward each other and connect up. • As a new technology and product, clean energy may a have higher cost than traditional energy for a longer time after its introduction to the market. The federal government may design a variety of tax credit programs at different times to encourage companies and consumers to accept clean energy sooner rather than later. The mass production may help to further reduce the cost.
Other (specify)	• I am happy to see increased funding to support the R&D in new materials and concepts. The innovation in new materials and concepts eventually will benefit the broader application and cost reduction of clean energy in the long run.	• Just as DOE took on the challenge of heavy-duty transport several years ago to be ready when needed, there is a similar gap or opportunity out there. Railroads demand even faster and larger amounts of hydrogen fill and storage for long-haul applications (a very hard-to-decarbonize area). Thousands of kilograms of cryo or liquid hydrogen in under 30 minutes will require new equipment and standards. Trains have the pleasant property of staying on tracks, so the required fueling network can be pretty much deduced, but it *must* go into Canada and Mexico, so there is a need to estimate the size of the lift to do the science/engineering to make the fueling and storage possible, as well as to get the price of hydrogen down to where railroads will accept it, estimate the network of fueling needed (which may not logically be putting hydrogen where diesel is now), estimate whether the safety checks done at refueling are an opportunity or challenge for

		hydrogen, and estimate the cost of the North American fueling network implied by the foregoing and figure out what loans or de-risking (think hubs) projects are needed to make it happen. It would need to be done with the U.S. Department of Transportation. Argonne National Laboratory's methods of looking at delivery might well be a start.

4. The Hydrogen Program is effectively collaborating in RDD&D across the DOE offices and with other agencies.

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.

	Hydrogen Program Effective Collaborations
Average Score	**8.5**
Number of Responses	18

General Comments:

Please comment generally on offices or agencies that should be more engaged or leveraged and in what manner.

- Speakers from the U.S. Departments of State, Transportation, and Labor all showed clear desire to work with DOE, plus indications of support and work on the clean hydrogen economy support and development. The panels and keynotes demonstrated a cooperative intersection between DOE research on making, moving, and using hydrogen and the U.S. Department of Transportation (DOT) in regulating and supporting broad-scale transport of hydrogen safely and effectively. There also seem to be plans to increase interaction in the future. Plus, there are projects with NASA, the U.S. Department of Defense, etc. There is an interagency work group to ensure the many agencies are working in a way that they are informed by one another's work and to help maintain a state of working in complementary work streams. More fundamentally, there is a joint office between DOE and DOT. Also, less obvious areas, such as the Maritime Administration, are working to bring hydrogen to the very hard-to-change ship industry.
- The Hydrogen Program is likely the best-organized, -managed, and -executed program in DOE. Drs. Satyapal and Miller, as well as the other managers, provide excellent and the highest-quality leadership for the program throughout DOE. They masterfully integrate the entire government-wide effort to ensure attaining 2026, 2031, and 2050 goals.
- There is large-scale funding, and this seems to be getting buy in from different departments. There is focus on competitiveness of industry, good jobs, and equitable pathways (with a laser focus on human capital). The goal is 100,000 jobs by 2030.
- This was clear from the participation and program presentations from other DOE and government agencies, e.g., the U.S. Navy, NASA, U.S. Geological Survey, and National Oceanic and Atmospheric Administration.
- Collaboration across DOE offices has improved significantly in recent years—great job!
- General question: Is the Hydrogen Program collaborating with the National Institute of Standards and Technology, for example, in the area of reference standards for hydrogen station refueling? Perhaps this is not needed if the majority of the projects take place in SAE International.
- While there seems to be a growing emphasis on collaboration, the execution to date seems questionable. From personal experience, the SC, ARPA-E, EERE continuum for hydrogen was built on separation of technology rather than TRL.

- There are some areas, particularly for hydrogen, where EERE may need to work more closely with other agencies. For example, hydrogen for aviation or space applications may need a collaborative effort with the Federal Aviation Administration, DOT, NASA, etc.
- Other agencies could have been highlighted more. In addition to the U.S. Departments of Commerce, Labor, and Transportation (including the Pipeline and Hazardous Materials Safety Administration), there are various regulatory agencies that can partner. Initial conversations began on research coordination with the U.S. Nuclear Regulatory Commission, for example, but I am not sure how that played out.
- International work cooperation with DOE could be strengthened further.
- This theme was clearly front-of-mind for most DOE presenters.

Office-Specific Comments:

Please comment on particular strengths and/or improvement opportunities relative to specific DOE Hydrogen Program offices in the table below:

DOE Office	Collaboration Strengths	Improvement Opportunities
EERE	• International collaborations, e.g., the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), help to maintain contact with current happenings around the world. Staying abreast of these international developments—which vary country by country, with their varying requirements and priorities—helps to keep U.S. R&D activities and perspectives up to date. • HFTO has organized and is executing an outstanding Hydrogen Program across all agencies.	• Strengthening the interactions between national labs and academia will further advance the goals and objectives of the offices. Strengthening metrics such as numbers of joint publications, lab internships, job placements, etc. need to be developed.
FECM		
NE		• The Nuclear Energy University Program can be used to further advance the intersection between nuclear energy and hydrogen production.
SC		
ARPA-E		
OCED		
Other (specify)	• International cooperation on safety and codes is a great collaboration, and this just has to be done cooperatively, or we end up with a mess of conflicting regulations worldwide.	

5. The Hydrogen Program is sufficiently incorporating a diversity of approaches for addressing energy and environmental justice (EEJ), as well as diversity, equity, inclusion, and accessibility (DEIA), in the execution and impacts of its RDD&D activities.

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.

	Hydrogen Program EEJ and DEIA
Average Score	**8.4**
Number of Responses	18

General Comments:

Please comment on which stakeholders, external groups, or resources (e.g., academia, companies, small businesses, types of industries, states, other agencies) should be more engaged with or leveraged and in what manner.

- Most speakers emphasized that every project supported will have extensive community consultation and desire to build in EEJ. The U.S. Department of Labor is gearing up to provide training for underrepresented groups to be sure they share in the well-paying jobs expected via the various recent funding initiatives, using proven methods such as apprenticeships aimed at DEI communities. Community benefits agreements in contracts and up-front labor (e.g., construction) discussions to prepare potential workers to prepare a workforce in DEI communities can help with construction and advance disadvantaged communities. There are programs to include minority students and listening sessions with communities and tribes. HFTO has greatly increased its DEI staffing in a show of the Office's commitment. HFTO is working with the Office of Energy Justice and Equity to better educate and take in the inputs of communities impacted by new hydrogen-based companies and transport.
- It is great to see EEJ become an essential aspect of the Hydrogen Program. Please continue and expand the effort.
- This has been one of the greatest areas of growth, and I support and encourage these. In my personal experience, I have and will continue to interact with and support these programs.
- The Hydrogen Program is a model for DEIA in DOE.
- HFTO did have a policy and guidance to increase the clean energy funding in disadvantaged communities.
- There is a strong focus on EEJ and community engagement, especially through requiring community impact plans. In future years, will need to see the outcomes of this effort to demonstrate that it was not just a goal. The Office of Energy Justice and Equity presentation could have been better connected to specific projects on which that office is partnering.
- Time will tell. There are a number of exemplary activities, such as Mr. Rockward's at Los Alamos National Laboratory, that engage students from historically black colleges and universities in the area of fuel cell R&D. With time, we will see if these students transition into the technology companies, national labs, and academia and take on leadership responsibilities.
- It is really cool to see so much focus on equity. However, I am very uncomfortable with any research that encourages the ongoing use of fossil fuels. We need to find technologies that minimize consumption rather than new pathways to exploit fossil energy—this is a very dangerous thing to promote when the world is teetering on the brink of a climate catastrophe. Fundamentally, we need to reduce our footprints, and I am a little worried that the Hydrogen Program is based on the belief that we can just switch fuels without a more holistic assessment of environmental and social impacts.
- These EEJ goals make projects harder to deliver. They often are outside the core skillsets of participants. We all understand the goal of trying to fix EEJ issues while also rebuilding a fossil-free energy infrastructure, but it is humanity's hardest problems, squared. This suggests that far more support

specifically in EEJ skills needs to be provided to Hydrogen Program participants. Simply put, the best hydrogen technologist is not likely also the best community outreach organizer.

- DOE needs to educate business leaders (hydrogen producers, infrastructure developers, and hydrogen end users) on how to approach, engage, and interact with tribal communities. DOE should develop awareness and education programs for leaders in environmentally distressed communities on the importance of hydrogen in decarbonizing local communities.
- I did not hear a lot on this topic during the review meeting. I know it is in the design, with the 40% in structurally weak areas, but the conceptual part could be strengthened.
- General comment: Have the definitions for DEIA (each term) been codified as national standards? Do they have "staying power" and stability as national standards?

Targeted Comments:

Please comment on particular strengths and/or improvement opportunities in EEJ and DEIA relative to the overall DOE Hydrogen Program and/or to specific offices:

- The Hydrogen Program director tirelessly advocates for all, especially for women and minorities, as it should be.
- It seems like the pieces are there to make this change. The key will be whether they are used. To be fair, it is too early to see much change, other than the inclusion of DEIA in FOA requirements and staffing up to handle this new management aspect. So the Program gets high marks for doing that, saying the right things at the AMR, and even making some DEI efforts in pre-existing programs (e.g., HyMARC) and giving an award of excellence to a person who has been walking this road already. But going forward, the proof will be in what is actually achieved. Will meaningful DEI efforts start showing up regularly in proposals, or will it be a cut-and-paste of the university or company public relations on DEI issues? The score I gave (7) reflects this uncertainty of what the current efforts will yield. DOE gets a 9 for effort in setting up a new paradigm, but I prorate it down for the uncertainty of success at this moment.
- Clean energy is another revolution in human history. HFTO may want to collaborate with other DOE offices to take immediate actions to come up with feasible plans for increasing the funding and investment in disadvantaged communities and rural areas to ensure these communities/areas can benefit from clean energy, as other large cities do, and not be left behind.
- These are hard to judge and implement. Perhaps focusing on pilot projects designed to determine and scout the best way to implement these is a good approach.
- Here is one idea: initiate a DOE EERE technical fellowship or post-doc program for researchers to be available to be embedded into awarded projects.

6. Please comment on whether the Hydrogen Program is doing enough to advance goals for workforce development and science, technology, engineering, and mathematics (STEM) education.

General Comments:

Please comment on how the Program could build on and/or adjust its current portfolio to accomplish goals in workforce development and STEM.

- There are great initial efforts thus far, yet this is a growing need—as the market appears to be growing faster than the qualified workforce—and thus this needs to continue and be expanded.
- It is good to see some centrally coordinated focus on education. This work clearly needs to continue and engage with the fledgling industry to identify what specific skills are needed.
- Yes, in general the STEM area is addressed very well. Is there a way that the community college program can be "elevated" in terms of available courses? I read the community college catalogs and find no references to the DOE funding. Would it be possible to add references to DOE funding?
- It is hard to know; the efforts are really just starting. It sounds like this might be part of the huge hubs funding, but until those are contracted, we cannot know. Perhaps DOE should pair with the other DOE (the

U.S. Department of Education) to develop and drive a clean energy curriculum at the high school and junior college/technical college levels.

- DOE can institute scholarships and fellowships for graduate education in all areas of hydrogen. In particular, the area of life cycle analysis for hydrogen technologies and decarbonization is urgently needed, as this space is not covered in universities. This will also enrich and expand the graduate programs in academia, or even bring them up to speed on the rapidly developing hydrogen economy.
- H_2EDGE is a great start in developing a sustainable pathway to meet the needs for workforce development. I hope the lessons learned from H_2EDGE are used to expand efforts in this area.
- It seems to me a larger impact could be to start earlier—K-12—and prime the pump long before these kids enter into a science and engineering, etc., education.
- This did not appear to be highlighted in the plenaries, other than noting that there were GEM fellow recipients to support underrepresented groups. Greater workforce development and STEM education for these groups, especially Native Americans, would be welcome.
- More is needed. As a technology manager who has hired 30+ folks in hydrogen in the last 10 years and has 6 open positions now, I can say that we need better education and training at all levels.
- I have not seen the practical and solid plans to advance achieve goals for workforce development, especially in the disadvantaged communities and rural areas.

Targeted Comments:

Please comment on particular highlights and/or improvement opportunities in workforce development and STEM relative to the overall DOE Hydrogen Program and/or to specific offices.

- I am happy to see more funding to support internship and R&D programs for college students and graduates in STEM to promote their interests. Technology innovation is the foundation to keep U.S. leadership in the world.
- Basic outreach and education at lower levels of the educational system—education that is reaching elementary and high school children to inspire them early—could be expanded, along with more traditional higher education workforce development.
- Helping professional associations convert the fossil-fuel-heavy curriculum would be of great benefit—at high schools, technical high schools, colleges, and trade schools and in the re-education of our existing workforce. Perhaps example curricula could be developed for dissemination.
- DOE might consider partnering with the American Indian Science and Engineering Society to develop scholarships, fellowships, and internships.
- DOE could reach out and make the states aware of opportunities for workforce development programs in hydrogen technologies.

7. The Hydrogen Program also collaborates with other countries through several international partnerships, such as the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), Clean Energy and Hydrogen Ministerials, Mission Innovation, the International Energy Agency, and others. Please comment on actions DOE can undertake in conjunction with these or other international activities that can effectively accelerate U.S. progress in hydrogen and fuel cell technologies.

Comments:

- It would be very hard, but if the approach to the hydrogen economy was done on an international basis (rather than through countries competing against each other), we would do so much better with a world plan, rather than a national plan. Once you do that, world peace will be easy. To the extent the U.S. plan can collaborate with, rather than compete with, the European Union’s and China’s and Australia’s plans, that will be more efficient. International cooperation on safety and on codes is a good model in an easier area in which to accomplish global cooperation.

- This is an area for focus and growth, as the United States is too inwardly focused. Targeted collaboration is essential. My own experiences with the International Energy Agency's Hydrogen Technology Collaboration Programme suggest this is a particularly useful avenue of fostering collaboration at the research level.
- Integrated energy systems with nuclear may warrant partnership with the International Atomic Energy Agency (on both the promotional and safety sides) and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development.
- This is a very important opportunity to observe how other international entities are approaching their specific regional requirements. This can inform many aspects of U.S. hydrogen R&D policy.
- DOE may already do this, but this person is not aware of it: It is suggested that we have a small group of experts to monitor progress and advancements in international activities and report information/data regularly to stakeholders.
- Our world is integrated, from supply chain, to workforce, to products, to national defense. Clean energy is a national defense matter, and we should support it as we do our allies. Perhaps organizations such as the North Atlantic Treaty Organization (NATO) could be a template for energy.
- I recommend that the Hydrogen Program administer a working group to develop a technical report on DEIA used in the EERE FOAs so the concept can be promulgated worldwide.
- Data production and sharing is an important subject. Perhaps this is an area where we can collaborate, for example, with Japan.
- It is important to follow and leverage any international hydrogen efforts to inform the DOE strategy.
- More frequent and more open (shared) activities are recommended.

8. Please provide any additional suggestions you may have for improvement of the overall DOE Hydrogen Program (e.g., in areas such as technology development, demonstration, and scale-up; technoeconomic and environmental impact assessments; safety, codes, and standards; soft costs; commercial liftoff; outreach and education; etc.).

Comments:

- In my opinion, this Hydrogen Program is one of the very best programs among all the different federal agencies. I was able to attend, in person, all key presentations from Monday's plenary talks to the very last excellent talk delivered by the National Renewable Energy Laboratory on Thursday in the late afternoon. I am very impressed with the technical quality of the projects and the different programs presented throughout AMR 2023. Apparently, higher-TRL technologies would help DOE to achieve the DOE 1-1-1 goals. If the Hydrogen Program stays focused on investment and continuously promotes the high-TRL directions (such as oxide-conducting SOECs), it will help the hydrogen technology and help DOE to achieve its goals.
- DOE and, in particular, the current "moon shot" approaches are inspiring. I urge DOE to enact real change and persist. Perhaps creating "pilot" programs designed for quick understanding of the issues involved in in new thrusts would be helpful. For example, what is needed to convert a lab-level novel ammonia synthesis catalyst to a field trial? How does one map other such technologies onto a lab-to-field trajectory?
- The increased focus on safety, codes, and standards is encouraging.
- The $1 target is encouraging distorted and unrealistic techno-economic analyses. I would like to see at least some framing of the narrative in a way that hydrogen is truly a critical part of transitioning society to more sustainable and equitable practices. It is no silver bullet, though, but is the only foreseeable option for some applications. It is great that significant funding is now available, but we need to be careful to avoid a boom–bust cycle and be very mindful of what the longer-term strategy for the overall energy system is.
- I have a comment about my rating in the question about reaching 1-1-1 goals. My rating is not purely technical. It includes other factors such as loss of funding due to a change in who holds the White House, geopolitical turmoil rearranging priorities, and inflation (seeing as there is no year for the dollar listed).

- Recommendations include more market-based (implementation) efforts; more workforce development to meet the rapidly expanding market; and more education and outreach, including early education years and the general public.
- Suggestions include (1) a national program to educate local (county) governments on the benefits of the hydrogen economy and (2) an initiative that will incentivize universities and community colleges to introduce courses and certificates in the areas of hydrogen energy, codes and standards and safety, etc.
- Standards, safety, and codes require additional efforts and funding, as well as collaboration with other countries.

9. Based on DOE's hydrogen activities, and given the Bipartisan Infrastructure Law (BIL) funding across the RDD&D spectrum, how likely do you think:

a) The BIL target of $2/kg clean H_2 be achieved by 2026?*

	10 – very likely 1 – not likely
Average Score	**7.1**
Number of Responses	20

b) Hydrogen Shot will be achieved ($1/kg clean H_2 by 2031)?*

	10 – very likely 1 – not likely
Average Score	**6.5**
Number of Responses	20

** Note: these are modeled levelized costs of production only, at high volumes (e.g., GW scale)*

Appendix B: 2023 Hydrogen Program Annual Merit Review and Peer Evaluation Meeting Attendee List

Note: This list excludes those who expressed a preference not to have their names published.

Last Name	First Name	Organization
Abdel-Baset	Tarek	Forvia Faurecia Hydrogen Solutions
Abdelrahman	Mohamed	Moleaer Inc.
Abhayawardhana	Anusha	Zinc8 Energy Solutions
Abilova	Zarina	InEnergy Group
Abramowitz	Howard	Washington Gas Light Company
Acevedo	Yaset	Strategic Analysis, Inc.
Aceves	Salvador	Lawrence Livermore National Laboratory
Acharya	Chethan	Southern Company
Ackiewicz	Mark	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
Adachi	Shuhei	Kansai Electric Power Co., Inc.
Adair	Sarah	Duke Energy
Adams	Amy	Cummins Inc.
Adams	Jesse	U.S. Department of Energy
Adeoye	Olumide	University of Southern California
Adnan	Salma	Air Liquide
Afzal	Kareem	PDC Machines, LLC
Afzal	Shaik	GTI Energy
Agapov	Alexander	W.L. Gore & Associates, Inc.
Agarwal	Tanya	Los Alamos National Laboratory
Agarwal	Vishal	Washington State University, Consortium for Hydrogen and Renewable E-fuels (CH2ARGE)
Ager	Joel	Lawrence Berkeley National Laboratory
Agnani	Milan	Sandia National Laboratories
Agnihotri	Vincent	Corporate E(energy) Solutions, Inc.
Ahlstrand	Carolina	Hycamite TCD Technologies Oy
Ahluwalia	Rajesh	Argonne National Laboratory
Ahmadi	Maryam	University of Connecticut
Akabori	Sho	American Honda Motor Company, Inc.
Albert	Gil Esmendia	University of California, Irvine

Last Name	First Name	Organization
Alborghetti	Silvia	zhero
Aldas	Rizaldo	California Energy Commission
Alden	Andy	Virginia Polytechnic Institute and State University
Al-Douri	Ahmad	University of Maryland
Alekhina	Ekaterina	InEnergy Group
Ali	Muntasir	Barksdale Inc.
Alia	Shaun	National Renewable Energy Laboratory
Alink	Robert	Aerostack GmbH
Allendorf	Mark	Sandia National Laboratories
Aloulou	Faouzi	U.S. Energy Information Administration
Alvarado	Diana	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
Alvarado	Natalie	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
Amirmoeini	Kamyar	HEC Montréal
Amirthalingam	Raja	Plug Power Inc.
Amos	Stephen	3M Company
Ananthanarayanan	Vijaykumar	Cummins Inc.
Anderson	Brian	AQST USA
Angel	Ana	Hinicio S.A.
Annon	Michael	I&C Engineering Associates
Anson	Colin	Virent, Inc.
Antoni	Laurent	International Partnership for Hydrogen and Fuel Cells in the Economy
Antonio	Alexandra	General Electric Company
Antonov	Stoichko	National Energy Technology Laboratory
Anyenya	Gladys	Wabtec Corporation
Archipley	Corey	Pacific Northwest National Laboratory
Arges	Christopher	The Pennsylvania State University
Arjona	Vanessa	U.S. Department of Energy
Arlia	Nicola	Westinghouse Electric Company, LLC
Arman	Tanvir	Los Alamos National Laboratory
Armstrong	Phillip	Mott Corporation
Arroyo	Christopher	California Public Utilities Commission

Last Name	First Name	Organization
Aryal	Utsav	Toyota Research Institute, Inc.
Asaoka	Takahiko	FC-Cubic TRA
Ashcraft	Robert	Samsung Electronics Co., Ltd.
Assanis	Dimitris	Stony Brook University
Asterita	Anthony	Waterotor Energy Technologies Inc.
Aszklar	Henry	Yardarm Energy
Atherton	Dwight	University of Connecticut
Augustine	Alex	Air Liquide
Autrey	Tom	Pacific Northwest National Laboratory
Auvil	Tatum	Electric Power Research Institute
Ayers	Katherine	Nel Hydrogen
Aziz	Fatima	Toronto Metropolitan University
Ba	Chaoyi	Argonne National Laboratory
Badgett	Alex	National Renewable Energy Laboratory
Bafana	Adarsh	Argonne National Laboratory
Bağ	H. Mustafa	Tubitak Marmara Research Center
Bahar	Bamdad	Fortescue Future Industries Ionix
Bailey	Carol	U.S. Army Corps of Engineers
Bailey	Sam	Clean Air Task Force
Baker	Andrew	Nikola Corporation
Baker	Joe	Nexight Group LLC
Baker	Ryan	National Research Council Canada
Bala Chandran	Rohini	University of Michigan
Balazadeh Meresht	Navid	Simon Fraser University
Balema	Viktor	ProChem, Inc.
Banda	Pedro	Hidrógeno de Burgos
Banerjee	Abhishek	Shell Global
Banner	John	Empyreal Power LLC
Barclay	John	Pacific Northwest National Laboratory
Barilo	Nick	Pacific Northwest National Laboratory
Barmota	Deepak	National Institute of Technology, India
Barnes	Ted	GTI Energy
Baronas	Jean	Patturns

Last Name	First Name	Organization
Bathrick	Mark	U.S. Department of Transportation, Federal Transit Administration
Batool	Mariah	University of Connecticut
Batten	William	Energetics
Batts	Zachary	Apex Clean Energy
Bauer	Matt	U.S. Department of Energy, Solar Energy Technologies Office
Bauer	Tim	Sabine Storage & Operations, Inc.
Bawa	Ajay	Thiozen, Inc.
Bay	Christopher	National Renewable Energy Laboratory
Beagle	Emily	The University of Texas at Austin
Bealer	Christine	Oak Ridge Associated Universities, Oak Ridge Institute for Science and Education
Beaumont	Robert	Constellation Energy
Beckwith	Jackie	Electrify America
Bekemohammadi	Roxana	U.S. Hydrogen Alliance
Belarbi	Zineb	National Energy Technology Laboratory
Belchuk	Mark	Freudenberg Group
Beliaev	Alexander	Pacific Northwest National Laboratory
Bellamy	Denise	Gaia Energy Research Institute, LLC
Bender	Guido	National Renewable Energy Laboratory
Bennett	Janice	Match Point Strategies LLC
Benson	Bryan	Solvay
Berry	Isabelle	National Renewable Energy Laboratory
Berteletti	Dan	National Renewable Energy Laboratory
Bestrom	Stuart	Johnson Matthey Hydrogen Technologies Ltd.
Beyer	Johan	PowerCell Sweden AB
Bezdek	Roger	Cavendish Energy
Bierschenk	David	Phillips 66 Company
Billa	Triveni	HyAxiom, Inc.
Bioret	Lucie	Resources for the Future
Biradar	Mahesh	General Motors Company
Birckett	Aaron	General Motors Company
Birky	Alicia	National Renewable Energy Laboratory

Last Name	First Name	Organization
Bishop	Sean	Sandia National Laboratories
Blackburn	Scott	The Chemours Company
Blank	Hermann	
Blekhman	David	California State University, Los Angeles
Block	Gus	Nuvera Fuel Cells, LLC
Boardman	Richard	Idaho National Laboratory
Bobba	Pallavi	Electric Power Research Institute
Bobo	Diana	U.S. Department of Energy
Bodén	Andreas	PowerCell Sweden AB
Boettcher	Shannon	University of Oregon
Bomtempo	Jose Vitor	Universidade Federal do Rio de Janeiro
Booras	George	Electric Power Research Institute
Borger	John	Teledyne Energy Systems, Inc.
Borole	Abhijeet	Electro-Active Technologies, Inc.
Borup	Rod	Los Alamos National Laboratory
Bouwkamp	Nico	GTI Energy
Bouwman	Peter	Schaeffler Group USA Inc.
Bowden	Mark	Pacific Northwest National Laboratory
Bower	Stan	Ford Motor Company
Boyce	Ken	UL Solutions
Boyd	Michael	Ford Motor Company
Boyd	Robert	Boyd Hydrogen, LLC
Bozorgi	Payam	HPlus Inc.
Braaten	Jonathan	Robert Bosch LLC
Bracci	Justin	National Renewable Energy Laboratory
Brandao	Filipe	Oak Ridge National Laboratory
Brauch	Joe	National Renewable Energy Laboratory
Braunecker	Wade	National Renewable Energy Laboratory
Brett	Perlman	Center for Houston's Future
Breunig	Hanna	Lawrence Berkeley National Laboratory
Britton	Nicholas	EFI Foundation
Brizes	Michael	Teledyne Energy Systems, Inc.
Brooker	Paul	Orlando Utilities Commission

Last Name	First Name	Organization
Brophy	Brenor	Plug Power Inc.
Brouwer	Jack	University of California, Irvine
Brown	George	The Chemours Company
Brown	Jeffrey	Arizona Public Service
Brown	Kenneth	University of Virginia
Brown	Truc	The Chemours Company
Bryan	Lee Ann	International Technology and Trade Associates
Buchholz	Matt	Hexagon Purus
Buckley	Bill	R&D Dynamics Corporation
Buek	Connor	Plug Power Inc.
Bulic	Matej	Heraeus Deutschland GmbH & Co. KG
Bump	Maggie	NanoSonic, Inc.
Bunce	Michael	MAHLE Powertrain Limited
Burgunder	Albert	Linde plc
Burns	James	University of Virginia
Busa	Anthony	Johnson Matthey
Buscheck	Thomas	Lawrence Livermore National Laboratory
Butcher	Tom	Brookhaven National Laboratory
Buttner	William	National Renewable Energy Laboratory
Butts	Mark	CB&I McDermott
Buyadgie	Olexiy	Wilson Engineering Technologies Inc
Byman	Michelle	Concurrent Technologies Corporation
Cabrera	Gonzalo	C Energy Consulting
Cai	Hao	Argonne National Laboratory
Cano	Marco	Canonetics
Cantrell	Ben	Caterpillar Inc.
Cao	Hongbo	GE Research
Cappello	Vincenzo	Argonne National Laboratory
Capuano	Christopher	Nel Hydrogen
Caradine	Reginold	U.S. Department of Energy
Carey	Kevin	U.S. Department of the Interior, Division of Energy and Mineral Development
Carfagna	Cosimo	Solvay

Last Name	First Name	Organization
Carl	Amy	EDP Renewables
Carlisle	Des	Kimbro Oil Company
Carlstrom	Charles	Plug Power Inc.
Carter	Michael	U.S. Department of Transportation, Maritime Administration
Casteel	Micah	Idaho National Laboratory
Caviasca	Jesse	University of North Dakota
Celada Murillo	Ana Teresa	National Institute of Electricity and Clean Energies (INEEL, Mexico)
Celestine	Asha-Dee	Oak Ridge Associated Universities, Oak Ridge Institute for Science and Education
Celt	Stephanie	Washington State Department of Commerce
Centeck	Kevin	U.S. Army Ground Vehicle Systems Center
Chadderdon	David	NeoGraf Solutions, LLC
Chakulski	Brian	Doosan Fuel Cell Co., Ltd.
Chanda	Sayonsom	National Renewable Energy Laboratory
Chandekar	Amol	Nanoptek Corporation
Chandra	Rishi	Cummins Inc.
Chandra	Suchetana	NTPC School of Business
Chang	Kaycee	California Energy Commission
Chang	Pingchia	Choshu Industry Corporation of America, Inc.
Chapman	Bryan	Exxon Mobil Corporation
Charles	Ricardo	U.S. Federal Energy Regulatory Commission
Chatrathi	Raghu	CSX Transportation
Chavez	Manuel	Kellogg's Company
Chemelli	Doug	Ford Motor Company
Chen	Dejun	Georgetown University
Chen	Hsiang-Sheng	University of Central Florida, Florida Solar Energy Center
Chen	Jixin	Hyzon Motors
Chen	Qingzhe	Niterra Co., Ltd.
Chen	Yingying	W.L. Gore & Associates, Inc.
Chen	Yun	West Virginia University
Cheng	Derek	UFI Filters
Cheng	Lei	Bosch Research and Technology Center
Cheng	Mark	University of Alabama

Last Name	First Name	Organization
Cheng	Yingwen	Northern Illinois University
Chenglin	Zhao	University of Science and Technology of China
Chernow	Victoria	Playground Global Ventures
Chevrier	Vincent	
Chiteme	Cosmas	Department of Science and Innovation, Republic of South Africa
Choi	Saemin	NX Fuels Inc.
Choi	Seung-Young	HD Hyundai Oilbank Co., Ltd.
Chou	Katherine	National Renewable Energy Laboratory
Christopher	Joshua	Argonne National Laboratory
Chu	Kevin	U.S. Army, Program Executive Office Soldier
Chung	Mark	National Renewable Energy Laboratory
Chuy	Carmen	Unilia (Canada) Fuel Cells Inc.
Cierpik-Gold	Kim	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Clark	Caitlin	AJW, Inc.
Clark	Theresa	U.S. Nuclear Regulatory Commission
Cole	Kevin	Verdagy Inc.
Collier	Craig	Del Llano Resources
Collins	Elizabeth	National Renewable Energy Laboratory
Combs	Todd	Idaho National Laboratory
Comperchio	Dan	Amazon Web Services
Conley	Donald	Sandia National Laboratories
Conn	Edith	U.S. Department of Energy, Office of Clean Energy Demonstrations
Conrad	Michael	Ford Motor Company
Contini	Vince	Battelle Memorial Institute
Conway	Graham	Southwest Research Institute
Cook	Desmond	Solvay
Cooper	Phyllis	U.S. Department of Energy
Cordier	Ryan	University of Virginia
Cordova	Joseluis	Mohawk Innovative Technology, Inc.
Corgnale	Claudio	CC Energy Consulting
Coronato	Cecile	New Jersey Economic Development Authority

Last Name	First Name	Organization
Cortes	Tim	Plug Power Inc.
Cortright	Randy	National Renewable Energy Laboratory
Costall	Aaron	Costall Engineering Limited
Coste	Wayne	ISO New England Inc.
Cott	Joelson	Nissan Chemical America Corporation
Courtney	Jake	Unilia (Canada) Fuel Cells Inc.
Cox	Chris	Teledyne Energy Systems, Inc.
Craig	Kutter	Oak Ridge Associated Universities, Oak Ridge Institute for Science and Education
Crane	Simon	The Lubrizol Corporation
Crawford	Clark	GKN Hydrogen
Croft	Trevor	National Renewable Energy Laboratory
Curtin	Dennis	
Cusnir	Felipe	Swell Capital Inc.
Dagan	Douglas	Suburban Renewable Energy, LLC
Dai	Sheng	Oak Ridge National Laboratory
Daimon	Hideo	Doshisha University
Damjanovic	Ana Marija	EKPO Fuel Cell Technologies GmbH
Damle	Ashok	Techverse, Inc.
Dance	Smruti	Exxon Mobil Corporation
Daniel	Claus	Argonne National Laboratory
Daniels	Christina	BP North America
Daniels	Jessica	U.S. Environmental Protection Agency
Das	Rajib	ACS Industries, Inc.
Dattelbaum	Andrew	Los Alamos National Laboratory
Daugherty	Mark	Avium, LLC
Davenport	Rachel	Energetics
Davies	Rich	Oak Ridge National Laboratory
Davis	Brendan	Sandia National Laboratories
Davis	James	Angi Energy
De Castro	Emory	Advent Technologies, Inc.
De La Fuente	Rodolfo	Industrial Gas Consultants LLC
De Souza Cardoso	Samuel Rodrigo	Fraunhofer IWKS

Last Name	First Name	Organization
De Valladares	Mary-Rose	Avium, LLC
Delshad	Mojdeh	The University of Texas at Austin
Delsol	Kevin	General Electric Company
Demars	Loren	Advanced Ionics
Derouiche	Imed	H2GHUB
Deshpande	Girish	Cytec Engineered Materials, Inc.
Desrosiers	Michael	Luna Labs USA, LLC
Devanathan	Ram	Pacific Northwest National Laboratory
Devi	Sakthi	Baker Hughes
Devlin	Pete	U.S. Department of Energy
Dey	Moutushi	
Dial	Tyrell	Idaho National Laboratory
Diderich	Michael	Hydrogen Europe
Diener	Matthew	California Air Resources Board
Dietl	Elisabeth	Thyssenkrupp Nucera
Dillingham	Gavin	Schlumberg Limited (SLB)
Dilwali	Sandeep	Sandia National Laboratories
Dimeglio	John	PPG Industries, Inc.
Ding	Dong	Idaho National Laboratory
Ding	Hanping	University of Oklahoma
Ding	Lei	University of Tennessee, Knoxville
Dinh	Huyen	National Renewable Energy Laboratory
Dirlea	Violetka	EY Parthenon
Dirschka	Eric	NASA Kennedy Space Center
Dismukes	Charles	Rutgers University
Do	Van	California Energy Commission
Doctor	David	Industry Innovation and Intelligence, Inc.
Dogdibegovic	Emir	Origis Energy
Dong	Cunhai (Josh)	Dongyue Canada Performance Materials Ltd.
Dong	Pei	George Mason University
Dong	Qi	University of Maryland
Dornheim	Martin	University of Nottingham
Dorsel	Roger	ABB Ltd.

Last Name	First Name	Organization
Dosunmu	Olusola	DEMS, LLC
Dowling	Alexander	University of Notre Dame
Drake	George	Hartford Steam Boiler Inspection and Insurance Company
Dreyer	Andrew	Mitsubishi Corporation
Driscoll	John	Patronus Green Hydrogen
Duan	Chuancheng	Kansas State University
Dubel	Zachary	Federation of Electric Power Companies of Japan
Duggal	Anil	GE Research
Duggan	Conor	First Mode
Duh	Steve	
Duin	Andrew	ERM International Group Limited
Dukes	Hadassah	3M Company
Dunn	Christina	U.S. Department of Energy
Dupont	Andre	Dupont Renewable Energy
Durst	Julien	Symbio SAS
Dyer	Brian	ConocoPhillips Company
Dziekan	Nicole	Denso International America, Inc.
Dzurak	Michael	Arizona Public Service
Easton	Jacqueline	U.S. Department of Energy
Ebbesen	Sune Dalgaard	Topsoe
Ebrahimpour Tolouei	Nadia	University of California, Irvine
Edamana	Biju	General Motors Company
Eddy	Eric	Davinci Hydrogen
Edwards	David	Air Liquide
Edwards	Troid	
Ehrhart	Brian	Sandia National Laboratories
Ehteshami	Mohsen	Symbio SAS
Eisman	Glenn	Eisman Technology Consultants, LLC
Elangovan	S. (Elango)	OxEon Energy, LLC
Elder	Scott	City of Sitka
Elgowainy	Amgad	Argonne National Laboratory
Ellis	Geof	U.S. Geological Survey
Elrick	William	Hydrogen Fuel Cell Partnership

Last Name	First Name	Organization
Engbrocks	Stefanie	3M Company
Englander	Jacob	California Air Resources Board
Enomoto	Hiroshi	New Energy and Industrial Technology Development Organization (NEDO)
Erb	Bryan	De Nora Tech, LLC
Erlebacher	Jonah	Johns Hopkins University
Erne	Frank	Proton Motor Fuel Cell GmbH
Erwin	Rebecca	U.S. Department of Energy
Eshel	Paz	General Motors Company
Eskinazi	Nessim	Westinghouse Electric Company, LLC
Esposito	Anne Marie	U.S. Department of Energy
Esposito	Daniel	Columbia University
Fackler	Sean	Indrio Technologies
Fairclough	Dale	Messer North America, Inc.
Fairhurst	Alasdair	University of California, Irvine
Fairlie	Matthew	Next Hydrogen Corporation
Fakhry	Rachel	Natural Resources Defense Council
Falta	Steven	General Motors Company
Farahati	Rashid	Schaeffler Group USA Inc.
Farese	David	Air Products and Chemicals, Inc.
Farmer	Crystal	U.S. Department of Energy, Office of Clean Energy Demonstrations
Farmer	Molly	GE Research
Fau	Christian	General Motors Company
Feaver	Aaron	Washington State University, Consortium for Hydrogen and Renewable E-fuels (CH2ARGE)
Fecko	Chris	U.S. Department of Energy, Basic Energy Sciences
Feenstra	Mark	Canadian Solar
Felder	Spencer	Creadis Innovative Engineering
Feng	Zhili	Oak Ridge National Laboratory
Fennessy	Craig	Atlas Copco
Fentas	Zubayr	New Energy and Industrial Technology Development Organization (NEDO)
Ferguson	Calum	AP Ventures
Ferner	Kara	Carnegie Mellon University

Last Name	First Name	Organization
Festa	Capella	Genvia SAS
Figueroa	Joaquin	VCA
Findley	Kip	Colorado School of Mines
Fisher	Paul	Fuel Cell Enabling Technologies, Inc.
Fontanetta	Ryan	Argonne National Laboratory
Foster	Simon	Intelligent Energy
Foti	Suzanne	Syzygy Plasmonics
Fowler	Andrew	Oak Ridge Associated Universities
Fox	Mahtab	Power to Hydrogen, LLC
Fox	Michelle	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Fox	Rachel	American Petroleum Institute
Fraser	Kwasi	Green Powered Technology
Frazier	Tim	Cummins Inc.
Freedman	Yuri	Southern California Gas Company
Freer	Alex	Exxon Mobil Corporation
Frischknecht	Amalie	Sandia National Laboratories
Fritz	Katrina	California Hydrogen Business Council
Froman	Sarah	U.S. Environmental Protection Agency
Frost	Dillon	Frost Innovations
Frost	Ryan	West Monroe Partners
Frye	Evan	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
Fryzowski	Kam	Public Service Enterprise Group
Fu	Jian	U.S. Department of Energy, Wind Energy Technologies Office
Fu	Richard	Southwest Research Institute
Fujimoto	Cy	Sandia National Laboratories
Fujiwara	Hirotada	Chemicals Evaluation and Research Institute, Japan
Fuller	Glenn	Kern Energy
Funk	John	RTO Insider, LLC
Furukawa	Hiroyasu	University of California, Berkeley
Furusawa	Takashi	De Nora Tech, LLC
Gadkari	Navinchandra	R&D Dynamics Corporation

Last Name	First Name	Organization
Gaillard	Nicolas	University of Hawaii
Galarneau	Caitlin	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
Galera	Eduardo	UL Solutions
Galperin	Diana	U.S. Department of Energy
Galviz	Nathalia	Air Liquide
Gambone	Livio	Nikola Corporation
Ganesan	Prabhu	Savannah River National Laboratory
Gangavarapu	Pranathi	University of Tennessee, Knoxville
Gangloff	John	Raytheon Technologies Research Center
Gans	Maurice	Exelon Corporation
Gao	Wenyang	Ohio University
Garavel	Alexis	AP Ventures
Garcia	Al	Accenture
Gardiner	Monterey	Cryo H2 LLC
Garfunkel	Alan	Marine Dolphin Enterprises LLC
Garlock	Sarah	Bennett Pump Company
Garman	Sarah	Avangrid
Garner	Sarah	Dongyue Canada Performance Materials Ltd.
Garrard	Tyler	BorgWarner, Inc.
Garzon	Fernando	University of New Mexico, Center for Micro-Engineered Materials
Gaspar	Daniel	Pacific Northwest National Laboratory
Gath	Kerrie	AES Corporation
Gaussa	Louis	Westinghouse Electric Company, LLC
Geary	Joan	Linde plc
Genatowski	Siegfried	Bradford Ventures, LLC
Gennett	Tom	National Renewable Energy Laboratory
Gervasio	Dominic	University of Arizona
Getz	Matt	NeoGraf Solutions, LLC
Ghaboulian Zare	Sara	University of Montreal
Ghezel-Ayagh	Hossein	FuelCell Energy, Inc.
Gibbons	Bradley	NanoSonic, Inc.

Last Name	First Name	Organization
Gibbons	William	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Gielen	Dolf	World Bank Group
Gilbert	Andrew	U.S. Department of Energy, Office of Clean Energy Demonstrations
Gilleon	Spencer	National Renewable Energy Laboratory
Ginsberg	Michael	Avina Clean Hydrogen Inc.
Ginter	David	Caterpillar Inc.
Girdis	Dean	Green H2
Gittleman	Craig	General Motors Company
Glaser	Paul	GE Research
Glass	Timothy	University of Missouri
Golub	Kristina	Phillips 66 Company
Goodhand	Robin	California Energy Commission
Gopalan	Srikanth	Boston University
Gore	Colin	U.S. Department of Energy, Advanced Research Projects Agency–Energy (ARPA E) (contractor with Booz Allen Hamilton)
Goswami	Subhadip	GE Research
Gotkin	Alison	Raytheon Technologies Research Center
Goto	Risei	AP Ventures
Gould	Benjamin	U.S. Department of Energy
Gould	Rachel	U.S. Department of Energy, Office of Clean Energy Demonstrations
Goyal	Amit	DNV
Green	Daniel	U.S. Federal Energy Regulatory Commission
Green	Ed	Ed Green Engineering
Green	Malcolm	Taconic
Green	Tomas	U.S. Department of Energy
Green	Zachary	Plug Power Inc.
Greene	Jon	ITA International, LLC
Greene	Lori	University of California, Irvine
Greenlee	Lauren	sHYp BV
Greenwood	Gig	
Greseth	Steven	Kiewit Engineering Group, Inc.

Last Name	First Name	Organization
Griffin	Emily	Cataler North America
Grimes	Andy	The University of Texas at Austin, Cockrell School of Engineering
Grot	Stephen	Ion Power
Groth	Katrina	University of Maryland
Gruber	Allen	JouleOne
Grumet	Stephanie	U.S. Environmental Protection Agency
Grundy	Dean	Manchester Metropolitan University
Gu	Tong	BP North America
Guan	Panpan	Shanghai Jiaotong University
Guerra	Eduardo	Hyro Power
Guerra	John	Nanoptek Corporation
Guo	Juchen	University of California, Riverside
Gupta	Manav	UBS Group AG
Gupta	Tanmay	DRE Motors LLC
Gurau	Marc	The Chemours Company
Gurciullo	Chris	Exxon Mobil Corporation
Habibzadeh	Bahman	U.S. Department of Transportation
Hadzalic	Nejira	BMW of North America, LLC
Hafidi	Kawtar	Argonne National Laboratory
Hahn	Alison	U.S. Department of Energy, Office of Nuclear Energy
Hahn	Michael	U.S. Department of Energy
Hai	Bingxin	Enerflex Ltd.
Haines	Kevin	Old Line Professional Services LLC
Halliday	Devin	GTI Energy
Hamilton	Hugh	Johnson Matthey
Hamilton	Jennifer	California Hydrogen Business Council
Hamm	Susan	U.S. Department of Energy
Han	Feng	Southeast University
Han	Taehoon	University of Michigan
Hanlin	Jason	Center for Transportation and the Environment
Hanson	Eve	Energy Impact Partners
Hanson	Tobias	Fuel Cell and Hydrogen Energy Association

Last Name	First Name	Organization
Happ	Patricia	U.S. Department of Transportation, Federal Transit Administration
Hara	Daishu	New Energy and Industrial Technology Development Organization (NEDO)
Hara	Tomoki	The High Pressure Gas Safety Institute of Japan
Harenbrock	Michael	Mann+Hummel GmbH
Harker-Klimes	Genevra	U.S. Department of Energy
Harrington	Forrest	Honeywell International, Inc.
Harris	Alexander	Brookhaven National Laboratory
Harris	Zachary	University of Pittsburgh
Harrison	Jeffrey	PCC Hydrogen Inc.
Harrison	Kevin	National Renewable Energy Laboratory
Hartman	Kevin	National Renewable Energy Laboratory
Hartman	Richard	U.S. Department of the Air Force
Hasa	Bjorn	Toyota Research Institute, Inc.
Hashimoto	Michio	University of Tokyo
Haubenstock	Arthur	Bloom Energy
Havig	Sara	National Renewable Energy Laboratory
Haynes	Comas	Georgia Tech Research Institute
Haynes	Daniel	National Energy Technology Laboratory
He	Rong	New Mexico State University
He	Xin	Aramco Americas
Hecht	Ethan	Sandia National Laboratories
Heckle	Christine	Argonne National Laboratory
Hegadekatte	Vishwanath	Freudenberg Group
Heidlage	Michael	Los Alamos National Laboratory
Helbling	James	3M Company
Helft	Matthieu	Solvay
Hengstebeck	Andrew	Shaw Development
Henk	Ramon	NOW GmbH
Hennis	Jennifer	GenH2
Henrichsen	Lars	Cummins Inc.
Henry	Theodore	TJH Properties, LLC
Henteleff	Sammy	Long Ridge Energy & Power

Last Name	First Name	Organization
Heo	Tae Wook	Lawrence Livermore National Laboratory
Heo	Yeongae	Sandia National Laboratories
Hershey	Robert	Robert L. Hershey, P.E.
Hertz	Kristin	Sandia National Laboratories
Hewitt	Christopher	BASF SE
Heyward	Hack	EH Group Engineering AG
Hickman	Thomas	Booz Allen Hamilton
Hiel	Clement	CSSI, Inc.
Higashi	Shougo	Toyota Research Institute, Inc.
Hill	Caroline	University of Florida
Hill	Laura	U.S. Department of Energy
Hill	Michael	U.S. Federal Energy Regulatory Commission
Hilton	Shelley	University of Missouri
Hinkley	Jim	Victoria University of Wellington
Hiraiwa	Hiro	The Kansai Electric Power Co., Inc.
Hirano	Shinichi	Hyzon Motors
Hirschon	Al	SRI International
Hlavacek	Kyle	Boston Government Services, LLC
Ho	Donna	U.S. Department of Energy
Holby	Edward	Los Alamos National Laboratory
Holgate	Ed	Shell Global
Holladay	Jamie	Pacific Northwest National Laboratory
Hollett	Douglas	MH Technology Partners LLC
Hom	Andrew	California Energy Commission
Homison	Chris	Wabtec Corporation
Hong	John	GE Research
Hong	Junsung	Phillips 66 Company
Hopkins	Owen	Hexagon Purus
Horita	Teruhisa	National Institute of Advanced Industrial Science and Technology
Hotta	Yoshihiro	Toyota Motor Corporation
Houchins	Cassidy	Strategic Analysis, Inc.
Houlihan	Christina	bspkl

Last Name	First Name	Organization
Hsiao	Stephen	Walsin Lihwa Corporation
Hu	Leiming	National Renewable Energy Laboratory
Hu	Shan	Iowa State University
Hu	Shu	Yale University
Huang	Byron	West Monroe Partners
Huang	Duo	China National Petroleum Corporation
Huang	Henry	U.S. Department of Energy
Huang	Kevin	University of South Carolina
Huang	Kuan-Tsae	AzTrong
Hubert	McKenzie	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Hughes	Doug	Eaton Corporation
Hullman	Dustin	SFC Energy AG
Hulvey	Zeric	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Hunter	Brian	U.S. Department of Energy
Hunter	Rob	3M Company
Hupp	Gregory	Rotoflow
Hurst	Katherine	National Renewable Energy Laboratory
Hussey	Daniel	National Institute of Standards and Technology
Huya-Kouadio	Jennie	Strategic Analysis, Inc.
Ibanez	Sergio	Nexceris, LLC
Ichikawa	Ryosuke	Hokkaido University
Iiyama	Akihiro	University of Yamanashi
Ikawa	Yasutaka	Materion Japan Ltd.
Ikeda	Tetsufumi	Hydrogen Supply and Utilization Technology Association
Imai	Takashi	Toyota Motor North America
Ioroi	Tsutomu	National Institute of Advanced Industrial Science and Technology
Ireland	Daniel	Ionomr Innovations Inc.
Irwin	Levi	Electric Power Research Institute
Iwasaki	Kouta	Toyota Boshoku Corporation
Jacob	Abigail	California Energy Commission
Jade	Shyam	Robert Bosch LLC

Last Name	First Name	Organization
Jain	Kartik	De Nora Tech, LLC
Jain	Ravi	InnoSepra, LLC
Jain	Rishabh	National Renewable Energy Laboratory
Jakupca	Ian	NASA
James	Brian	Strategic Analysis, Inc.
James	Will	Battelle Memorial Institute
Jaramillo	Thomas	Stanford University
Jaworski	Casey	Tanaka Kikinzoku International
Jensen	Craig	University of Hawaii
Jerome	Gbenga	West African Science Service Centre on Climate Change and Adapted Land Use
Jeske	Gerald	Umicore
Jessop	Justin	Daimler Truck North America
Ji	Chunxin	BASF Environmental Catalyst and Metal Solutions
Jia	Chenglin	Umicore
Jia	Hongfei	Toyota Motor North America
Jin	Xinfang	University of Massachusetts Lowell
Jo	Young Suk	Amogy Inc.
John	Ivor	Hydrogen Power Partners, LLC
Johnson	Kristin	U.S. Department of Energy
Johnson	Paul	Corning Incorporated
Johnson	Travis	BCS, LLC
Johnson	William	Johnson & Associates Solutions
Jollie	Jeffrey	U.S. Environmental Protection Agency
Joneja	Galen	Schlumberg Limited (SLB)
Jones	David	
Jones	Sean	Airbus SE
Jorgensen	Scott	Hyrax Intercontinental LLC
Joseck	Fred	Idaho National Laboratory
Josefik	Nicholas	U.S. Army Corps of Engineers, Engineer Research and Development Center, Construction Engineering Research Laboratory
Joshi	Prasanna	Jacobs
Jourdain	Anne	Azur Advisory

Last Name	First Name	Organization
Juergensen	Mark	RAI Energy
Jun	Jiheon	Oak Ridge National Laboratory
Jurcoi	Alex	pH Matter LLC
Kakinuma	Katsuyoshi	University of Yamanashi
Kanach	Brianne	Exxon Mobil Corporation
Kanesaka	Hiroyuki	FC-Cubic TRA
Kang	Donghyeon	Argonne National Laboratory
Kang	Meng	Guangzhou Hybot Co, Ltd.
Kapur	Dheeraj	FEV Consulting
Karimian Bahnamiri	Fazele	Toronto Metropolitan University
Karkamkar	Abhi	Pacific Northwest National Laboratory
Karlsen	Kristine	Washington Gas Light Company
Karlsson	Tim	Susalea Global Consulting
Kasab	John	AVL Fuel Cell Canada
Kass	Mike	Oak Ridge National Laboratory
Kast	Jeffrey	National Academies of Science
Katikaneni	Sai	Aramco Americas
Kazemi	Elias	Proton Motor Fuel Cell GmbH
Kazmouz	Samuel	Argonne National Laboratory
Kedzie	Elyse	California Energy Commission
Kee	Benjamin	National Renewable Energy Laboratory
Kelety	Stephen	University of California, San Diego, Scripps Institution of Oceanography
Keller	Jay	Zero Carbon Energy Solutions, Inc.
Kennedy	John	Institute of Geological and Nuclear Sciences Limited (GNS Science)
Kent	Andrew	Washington Gas Light Company
Kent	Emily	Clean Air Task Force
Kenyon	Deanna	Johnson Matthey
Keonhag Lee	Jason	Lawrence Berkeley National Laboratory
Kern	Neil	Electric Power Research Institute
Khaled	Amal	Delegation of German Industry and Commerce in Washington, DC
Khanal	Arti	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office

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Kilgore	Trenton	Daimler Truck North America
Killingsworth	Nick	Lawrence Livermore National Laboratory
Kim	Han-Jin	Hyundai Motor Company
Kim	Hwitae	Hyundai Motor Company
Kim	Jae Jin	Argonne National Laboratory
Kim	Jai-Woh	U.S. Department of Energy
Kim	Jiwan	Hyundai Motor Company
Kim	Jung Ho	Kolon Industries
Kim	Nayoung	HD Hyundai Oilbank Co., Ltd.
Kim	Yuseung	Los Alamos National Laboratory
King	Jennifer	Alliance for Sustainable Energy, LLC
Kinoshita	Shinji	AGC Inc.
Kirshenboim	Lee	Center for Transportation and the Environment
Kiser	Lee-Ann	Oak Ridge Associated Universities, Oak Ridge Institute for Science and Education
Klages	Merle	cellcentric GmbH & Co. KG
Klahr	Benjamin	U.S. Department of the Navy
Klaus	Herman	Hyster-Yale Materials Handling, Inc.
Klebanoff	Lennie	Sandia National Laboratories
Kleen	Gregory	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Knapek	Carter	Plug Power Inc.
Knight	Eli	University of Virginia
Knights	Shanna	Ballard Power Systems
Ko	Youngdon	Los Alamos National Laboratory
Kobayashi	Kosuke	AP Ventures
Kobayashi	Yohei	Honda Motor Co., Ltd.
Kocha	Shyam	Shyam Kocha Consulting
Kohl	Paul	Georgia Institute of Technology
Koka	Jona	Environmental Defense Fund
Koleva	Mariya	National Renewable Energy Laboratory
Komalla	Nikhil	The Pennsylvania State University
Komini Babu	Siddharth	Los Alamos National Laboratory
Kondo	Touma	Southern California Gas Company

Last Name	First Name	Organization
Kong	Shuang	SANY Group
Kongkanand	Anusorn	General Motors Company
Kopasz	John	Argonne National Laboratory
Kort-Kamp	Wilton	Los Alamos National Laboratory
Koshima	Kimihiko	Sumitomo Corporation
Kota	V. M. K. Kireeti	DRE Motors LLC
Kowalski	Peter	Argonne National Laboratory
Kraft	Jürgen	EKPO Fuel Cell Technologies GmbH
Krause	Theodore	Argonne National Laboratory
Krogstad	Jessica	University of Illinois Urbana-Champaign
Krumdick	Gregory	Argonne National Laboratory
Krupnick	Alan	Resources for the Future
Kubran	Krystyna	352 Innovation, LLC
Kulkarni	Aniruddha	Cavendish Renewable Technology
Kunko	Damian	Strategic Marketing Innovations, Inc.
Kunna	Jenny	City of San Diego
Kuppa	Shashi	U.S. Department of Transportation
Kuriyama	Nobuhiro	National Institute of Advanced Industrial Science and Technology
Kuroki	Taichi	National Renewable Energy Laboratory
Kushner	Sandy	Air Products and Chemicals, Inc.
Kusoglu	Ahmet	Lawrence Berkeley National Laboratory
Kuykendall	Olivia	Exeter Associates
Kwan	May	GTI Energy
Kweon	Kyoung Eun	Lawrence Livermore National Laboratory
Kyle	Page	Pacific Northwest National Laboratory
La Valle	Tim	HydrogenEconomy.org
Lackey	Gregory	National Energy Technology Laboratory
Laffen	Melissa	Energetics
Lafleur	Chris	Sandia National Laboratories
Lago Sair	Rafael	Aramco Americas
Lakshmanan	Balasubramanian	Versogen
Lalli	Jennifer	NanoSonic, Inc.

Last Name	First Name	Organization
Lamba	Harinder	Solar Hydrogen, Inc.
Lambert	Devinn	U.S. Department of Energy, Office of the Under Secretary of Science and Innovation
Lancaster	Camilla	GPC
Landgraf	Michael	U.S. Environmental Protection Agency
Lane	Jonathan	Linde plc
Lange	Simon	Cummins Inc.
Lasam	Baldomero	California Energy Commission
Laske	Matthias	Forschungszentrum Juelich GmbH
Laskin	Jay	Hyenergy Consulting, LLC
Lathwal	Priyank	World Bank Group
Lattimer	Judith	Giner, Inc.
Lauritzen	Mike	Ballard Power Systems
Lawy	T.J.	Ballard Power Systems
Lazorski	Megan	Metropolitan State University of Denver/National Renewable Energy Laboratory
Le	Dang	Solar Turbines Incorporated
Leachman	Jacob	Washington State University
Leblanc	Luc	Cummins Inc.
Lecoustre	Vivien	U.S. Department of Energy, Advanced Research Projects Agency–Energy (ARPA-E)
Lee	Chunghyuk	Toronto Metropolitan University
Lee	Heonjoong	General Motors Company
Lee	Hoonhee	Techcross
Lee	Jane	Ricardo
Lee	Myoungseok	De Nora Tech, LLC
Lee	Rob TwoEagles	TwoEagles, Inc.
Lee	Sangkun	Toyota Motor Corporation
Lei	Yinkai	National Energy Technology Laboratory
Leick	Noemi	National Renewable Energy Laboratory
Leighton	Delisa	Gas Transport Leasing
Leighty	Bill	The Leighty Foundation
Leon	Fernando	Sandia National Laboratories
Lesher	Everett	Universal Solutions International, Inc.

Last Name	First Name	Organization
Letterio	Michael	HyAxiom, Inc.
Levesque	Claire	California Energy Commission
Lewandowski	Michal	HynErgy GmbH
Lewis	Michael	Komatsu
Lewis	Michael	The University of Texas at Austin, Center for Electromechanics
Li	Gong Liang	Niterra Co., Ltd.
Li	Guangwei	Tongji University
Li	Jian	Volvo Group
Li	Kui	Los Alamos National Laboratory
Li	Meng	Idaho National Laboratory
Li	Rui	Phillips 66 Company
Li	Sirui	Los Alamos National Laboratory
Li	Wen	AAIT
Li	Xianglin	Washington University in St. Louis
Li	Yunan	Stanford University
Ligh	David	Capstone Public Policy Solutions, LLC
Light	Joshua	Air Liquide
Lim	Yong Chae	Oak Ridge National Laboratory
Lin	Hongfei	Washington State University
Lin	Honghong	Toyota Motor Corporation
Lin	Ye	Emerson Electric Co.
Lindfield	Nick	Johnson Matthey
Ling	Yansong	University of California, Los Angeles
Linton	Bill	Linton Consulting LLC
Lipman	Tim	University of California, Berkeley/Lawrence Berkeley National Laboratory
Lipp	Ludwig	T2M Global
Litster	Shawn	Carnegie Mellon University
Liu	Chang	National Renewable Energy Laboratory
Liu	Di-Jia	Argonne National Laboratory
Liu	Eric	McMaster University, Higgins Lab
Liu	Hong	Oregon State University
Liu	Meilin	Georgia Institute of Technology

Last Name	First Name	Organization
Liu	Ru-Fen	CDTi Advanced Materials, Inc.
Liu	Wen	W.L. Gore & Associates, Inc.
Liu	Xingbo	West Virginia University
Liu	Yi	BASF SE
Liu	Yuanchao	3M Company
Liu	Zengcai	Dioxide Materials
Liu	Zeyan	
Liu	Zheng	Weichai America Corporation
Liu	Zhien	University of North Dakota, Energy and Environmental Research Center
Liyanage	Wipula	Los Alamos National Laboratory
Lloyd	Alan	The University of Texas at Austin
Locklear	Moriah	Arizona State University
Lohmann	Chris	Boeing Research & Technology
London	Mitch	GP100 Energy Advisors
Long	Brian	Fuel Cell Enabling Technologies, Inc.
Long	Rachel	Pacific Northwest National Laboratory
Longman	Douglas	Argonne National Laboratory
Loprete	Ashley	Kivvit
Loughrin	Casey	Sargent & Lundy, L.L.C.
Louie	Melissa	Sandia National Laboratories
Love	Michelle	Oak Ridge Associated Universities
Lown	Anne	Ford Motor Company
Lozier	Jacob	General Motors Company
Lu	Bo	Air Liquide
Luangdilok	Wison	H2Technology LLC
Lubawy	Andrea	Toyota Motor North America
Lucht	Erich	Thermo King
Lucht	Robert	Purdue University
Luo	Hongmei	New Mexico State University
Luo	Jian	University of California, San Diego
Luo	Jinyong	Hyzon Motors
Lupion	Monica	Linde plc

Last Name	First Name	Organization
Lusardi	Christopher	Caterpillar Inc.
Luster III	Claude	LR3Technologies, LLC
Lutz	Hannah	Automotive News
Lyons	K. David	National Energy Technology Laboratory
Lyu	Xiang	Oak Ridge National Laboratory
Lyubovsky	Maxim	Booz Allen Hamilton
Mace	Alan	Ballard Power Systems
Macherla	Sai Praneeth	Verdagy Inc.
Macholz	Jessic	Argonne National Laboratory
Macintire	Ian	U.S. Department of Transportation
Maes	Miguel	NASA White Sands Test Facility
Mahajan	Devinder	Stony Brook University
Mahesh	Siddharth	Daimler Truck North America
Makar	Ellen	Energy Concepts Company
Malhotra	Deepika	Pacific Northwest National Laboratory
Malkamäki	Matti	Hycamite TCD Technologies Ltd.
Malone	Keith	RE+ Events
Manders	Jacqueline	Southwest Research Institute
Mangeney	Estelle	West Monroe Partners
Manjarekar	Vishakha	
Manogaran	Indu Priya	National Renewable Energy Laboratory
Mansoor Basha	Abdul Bashith	University of Calgary
Mansour	Marianne	Southern California Gas Company
Mao	Wade	GTI Energy
Maranville	Alex	Energy Futures Initiative
Marathe	Radhika	Analog Devices, Inc.
Marcinkoski	Jason	U.S. Department of Energy
Marina	Olga	Pacific Northwest National Laboratory
Mark	Danielle	Pacific Gas and Electric
Markham	Lauren	General Motors Company
Markkassery	Abhilash	Nikola Corporation
Markovich	Steven	U.S. Department of Energy
Martinez	Alex	Johnson Matthey

Last Name	First Name	Organization
Martinez	Andrew	California Air Resources Board
Maruta	Akiteru	Technova Inc.
Marxen	Sara	CSA Group
Maserumule	Rebecca	Department of Science and Innovation, Republic of South Africa
Mason	David Cameron	Air Liquide
Masten	David	General Motors Company
Masubuchi	Kohei	New Energy and Industrial Technology Development Organization (NEDO)
Mathuraiveeran	Thangaraj	Cummins Inc.
Matsuki	Takanori	Hioki E.E. Corporation
Matter	Paul	pH Matter LLC
Matz	Stephanie	W.L. Gore & Associates, Inc.
Mauger	Scott	National Renewable Energy Laboratory
Maurer	William	HyAxiom, Inc.
Maurya	Sandip	Los Alamos National Laboratory
Mayer	Steven	W.L. Gore & Associates, Inc.
McAndrew	James	Air Liquide
McArdle	Brian	New Jersey Economic Development Authority
McAvoy	Shannon	Flexitallic
McCord	Dylan	University of Florida
McCracken	Ian	Denso International America, Inc.
McDaniel	Anthony	Sandia National Laboratories
McDonald	Nikkia	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
McGovern	Leah	U.S. Department of Energy (contractor)
McGowan	Darcy	Ballard Power Systems
McGuire	Meaghan	BASF SE
McGuirk	Michael	Colorado School of Mines
McKittrick	Michael	Honeywell Aerospace
McKlveen	Ted	Verne Inc.
McKone	James	University of Pittsburgh
McNamara	Kevin	Strategic Analysis, Inc.
McNaul	Shannon	National Energy Technology Laboratory

Last Name	First Name	Organization
McQueen	Shawna	U.S. Department of Energy
McShane	William	U.S. Department of Energy, Water Power Technologies Office
McSweeney	Elspeth	Brookhaven National Laboratory
Medina	Samantha	National Renewable Energy Laboratory
Meeks	Noah	Southern Company
Mehrazi	Shirin	Robert Bosch LLC
Mehta	Darius	Garrett Motion, Inc.
Mehta	Dinesh	U.S. Department of Energy, Loan Programs Office
Melaina	Marc	Boston Government Services, LLC
Melnikov	Alexey	European Synchrotron Radiation Facility
Merrill	Jerilyn	UL Solutions
Mesa	Juan	Carnegie Mellon University
Michaud	Samuel	De Nora Tech, LLC
Middleton	Erin	Carbon Solutions LLC
Miller	Eric	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Miller	James	Argonne National Laboratory
Miller	Jim	Arizona State University
Miller	Missy	Oak Ridge Associated Universities
Mills	Michael	Lawrence Berkeley National Laboratory
Min	Byunghyun	Phillips 66 Company
Minh	Nguyen	University of California, San Diego
Mistry	Dipak	Ceres Power
Mita	Masaaki	Japan Science and Technology Agency
Mitchell	Reginald	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
Miyata	Nobuhiro	Panasonic Holdings Corporation
Mizutani	Yasunobu	National Institute of Advanced Industrial Science and Technology
Mochizuki	Takashi	Honda Motor Co., Ltd.
Moen	Chris	Sandia National Laboratories
Moen	Ryan	Honeywell International, Inc.
Mohite	Aditya	Rice University
Mohr	Jeffrey	National Renewable Energy Laboratory

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Molinaro	David	State of Hawaii, Department of Business, Economic Development & Tourism/Hawaii Technology Development Corporation
Molloy	Patrick	Rocky Mountain Institute
Monroe	Nicholas	Hornblower Energy LLC
Montano	Raul	KraftPowercon
Moore	Amy	Oak Ridge National Laboratory
Moore	Daniel	Bloomberg Industry Group, Inc.
Moore	Sarah	U.S. Department of Energy, Office of Clean Energy Demonstrations
Moorehead	John	Idaho National Laboratory
Mora	Edgar	Cummins Inc.
Moreland	Greg	General Dynamics Information Technology
Moreno Jimenez	Daniel	State University of New York at Albany
Morimoto	Yu	University of California, Irvine
Morita	Takanari	KI Professional Engineer Office
Moriya	Takashi	Honda Motor Co., Ltd.
Morris	Ashley	University of Kentucky, Center for Applied Energy Research
Morris	Julia	Plug Power Inc.
Morse	Paige	Aspen Technology, Inc.
Mortazavi	Mehdi	Worcester Polytechnic Institute
Mortensen	Matt	3M Company
Motupally	Sathya	Boston Government Services, LLC
Motyka	Mark	U.S. Army Combat Capabilities Development Command, Armaments Center, Pyrotechnics Technology Division
Motyka	Theodore	CC Energy Consulting
Mourmouras	Tom	Shell Global
Mow	Rachel	Oak Ridge Associated Universities, Oak Ridge Institute for Science and Education
Mphahlele	Brian	Technology Innovation Agency
Mu	Zongjin	Howden Group
Mukerjee	Sanjeev	Northeastern University
Mukherjee	Subhajyoti	Oak Ridge National Laboratory
Mukundan	Rangachary	Lawrence Berkeley National Laboratory

Last Name	First Name	Organization
Mulder	Martijn	HyET Hydrogen B.V.
Mulhall	Michael	Kohler Co.
Mullins	Richard	Infinity Fuel Cell and Hydrogen, Inc.
Munster	Jason	U.S. Department of Energy, Office of Clean Energy Demonstrations
Murawa	Jeff	Daimler Truck North America
Murdoch	Hannah	U.S. Department of Energy, Office of Technology Transitions
Murthi	Vivek	Nikola Corporation
Musgrave	Charles	University of Colorado Boulder
Myers	Charles	General Dynamics Information Technology
Myers	Debbie	Argonne National Laboratory
Myhre	Richard	Frontier Energy, Inc.
Nadeau	John	Solution Mining Research Institute, Inc.
Naeini	Mina	Jacobs
Nagai	Tomoyuki	Toyota Central Research and Development Laboratories, Inc.
Nagarad Dasavandi Krishnamurthy	Vinay	Bosch Research and Technology Center
Nahale'a	Elsie	Oak Ridge Associated Universities
Nakamura	Yoko	N.E. Chemcat Corporation
Nakano	Akihiro	The High Pressure Gas Safety Institute of Japan
Nakatsuji	Hayate	Honda Motor Co., Ltd.
Nandwa	Eugene	Sands Capital
Nanjundan	Ashok	Wabtec Corporation
Nanninga	Nicholas	Secat, Inc.
Napp	Gary	ERM International Group Limited
Nara	Yuri	Tokyo Metropolitan University
Nasu	Ryo	Japan Organization for Metals and Energy Security/Ministry of Economy, Trade and Industry
Natividad	Lauren	Southern California Gas Company
Nayan Veettil	Shafeen	Schneider Electric USA
Nazemi	Reza	Colorado State University
Nelson	Amy	AVL Fuel Cell Canada
Nemec	Tomas	Czech Academy of Sciences, Institute of Thermomechanics

Last Name	First Name	Organization
Newhouse	Norman	Hexagon Group
Neyerlin	Kenneth	National Renewable Energy Laboratory
Ng	Junhong	Argonne National Laboratory
Ng Li	Harris	Toronto Metropolitan University
Nguyen	Hien	Ionysis GmbH
Nguyen	Phuc	Advanced Ionics
Nguyen	Tho	University of Georgia
Nguyen	Thuan	CITGO Petroleum Corporation
Nibur	Kevin	Hy-Performance Materials Testing, LLC
Nicholas	Kyle	Teledyne Energy Systems, Inc.
Niezrecki	Christopher	University of Massachusetts Lowell
Nikiforova	Kristina	National Grid plc
Nishimura	Shin	Kyushu University
Norko	Natalia	Washington Gas Light Company
Norley	Julian	Norley Carbon & Graphite Consultants, LLC
Norris	Bob	Oak Ridge National Laboratory
Obregon	Cesar	UBS Group AG
Ocampo	Minette	pH Matter LLC
Odgaard	Madeleine	IRD Fuel Cells
Odom	Sara	Electricore, Inc.
Odufuwa	Esther	California Energy Commission
O’Flarity	Steven	
Ogawa	Takanobu	Isuzu Motors Ltd.
Ogitsu	Tadashi	Lawrence Livermore National Laboratory
Ohira	Eiji	New Energy and Industrial Technology Development Organization (NEDO)
Ohnuma	Akira	Toyota Boshoku Corporation
Oistad	Brian	Saint-Gobain Research North America
Okaya	Kazuki	Tanaka Kikinzoku International
Okazaki	Nobutaka	Ishifuku Metal Industry Co., Ltd
Olivier-Stevens	Vicky	U.S. Department of Energy
Oloriz	Margaret	West Monroe Partners
Olson	Gregory	U.S. Department of Energy (contractor)

Last Name	First Name	Organization
Olson	Rudolph	CONSOL Innovations LLC
O'Malley	Rachel	GKN Aerospace
Ong	Gary	Celadyne Technologies, Inc.
Onorato	Shaun	National Renewable Energy Laboratory
Orr	Calder	Port Authority of New York and New Jersey
O'Shea	Katie	U.S. Department of Energy, Office of Clean Energy Demonstrations
Osmond	Haboon	Fuel Cell and Hydrogen Energy Association
Ostraat	Michele	Pajarito Powder, LLC
Osusky	Lana	GE Research
Osvatics	Cassandra	The Building People
Ott	Kevin	Los Alamos National Laboratory
Outen	Barry	Daimler Truck North America
Owejan	Jon	Plug Power Inc.
Owens	Jeff	Oak Ridge Associated Universities, Oak Ridge Institute for Science and Education
Oyamada	Kenji	The High Pressure Gas Safety Institute of Japan
Padgett	Elliot	National Renewable Energy Laboratory
Padmaperuma	Asanga	Pacific Northwest National Laboratory
Paffhausen	Chad	Bennett Pump Company
Pakhare	Devendra	PCC Hydrogen Inc.
Pal	Narendra	Hornblower Energy, LLC
Pan	Yuwei	Imperial College London
Papadias	Dionissios	Argonne National Laboratory
Papageorgopoulos	Dimitrios	U.S. Department of Energy
Papandrew	Alexander	Mott Corporation
Parfomak	Paul	Congressional Research Service
Parilla	Philip	National Renewable Energy Laboratory
Park	Andrew	The Chemours Company
Park	Gu-Gon	Korea Institute of Energy Research
Park	Heemin	Rensselaer Polytechnic Institute
Park	Hyounmyung	Hyundai Motor Company
Park	Jae Hyung	Argonne National Laboratory
Park	Jihyeon	McMaster University

Last Name	First Name	Organization
Park	Jinsoo	Sangmyung University
Park	Sarah (Eun Joo)	Los Alamos National Laboratory
Park	Seokhee	Korea Institute of Energy Research
Parkan	John	Providence Entertainment
Parkhurst	James	Mitsubishi Power Americas, Inc.
Parks	James	Oak Ridge National Laboratory
Pasmay	Fausto	Carnegie Mellon University
Patel	Mukesh	Nikola Corporation
Patel	Pinakin	T2M Global
Paterson	Andrew	Allied Nuclear Partners
Paterson	Jack	JA Paterson LLC
Paul	Devproshad	Ballard Power Systems
Paul	Mou	National Renewable Energy Laboratory
Paulot	Fabien	Geophysical Fluid Dynamics Laboratory
Pavageau	Bertrand	Solvay
Pavlicek	Ryan	Advent Technologies, Inc.
Paxson	Adam	Plug Power Inc.
Peacock	Tanya	EcoEngineers
Pease	Leonard	Pacific Northwest National Laboratory
Pederzoli	Andrea	zhero
Pedram	Sara	University of Connecticut
Pekarskaya	Evgenia	Supercool Metals
Penev	Michael	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Peng	Bosi	University of California, Los Angeles
Peng	Peng	Lawrence Berkeley National Laboratory
Peng	Xiong	Lawrence Berkeley National Laboratory
Perea	Samantha	Sandia National Laboratories
Periasamy	Chendhil	Air Liquide
Perlman	Brett	Center For Houston's Future
Perry	Grayson	Woodside Energy
Perry	Mike	Largo Clean Energy
Perry	Robert	Synergistic Solutions

Last Name	First Name	Organization
Pesek	Frank	Hartford Steam Boiler Inspection and Insurance Company
Petek	Tyler	The Lubrizol Corporation
Peters	Nathan	MAHLE Powertrain Limited
Peterson	David	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Petitpas	Guillaume	Air Liquide
Petrinec	Bryan	AECOM
Petrovic	John	Petrovic and Associates
Pham	Tuan Anh	Lawrence Livermore National Laboratory
Pierce	Ben	ENTRUST Solutions Group
Pierce	Rita	Green Energy Partners of Virginia
Pierre	Fritz	
Pierson	Rachel	U.S. Department of Energy
Pietras	John	Saint-Gobain Research North America
Pietrasz	Patrick	Ionomr Innovations Inc.
Pillay	Gautam	University of Cincinnati
Pinatton	Melanie	CSA Group
Pinney	Reese	Gulf South Holding, Inc.
Pinti	Quirino	Hy Stor Energy LP
Pinton	Eric	Alternative Energies and Atomic Energy Commission (CEA, France)
Piper	Alex	Rocky Mountain Institute
Pitchford	Taylor	Oak Ridge Associated Universities, Oak Ridge Institute for Science and Education
Pivovar	Bryan	National Renewable Energy Laboratory
Plazas	Alejandro	Eaton Corporation
Plymill	Austin	The Chemours Company
Poindexter	Joseph	Teledyne Energy Systems, Inc.
Polevaya	Olga	Nuvera Fuel Cells, LLC
Pomerantz	Mike	ANGI Energy Systems, Inc.
Pomeroy	Elias	National Research Council, Naval Research Laboratory
Poplawski	Nicholas	U.S. Global Energy LLC
Porter	Sam	NeuVentus
Post	Matt	National Renewable Energy Laboratory

Last Name	First Name	Organization
Postlethwaite	Oliver	Ceres Power
Pottow	Victor	GCP Capital Partners LLC
Poudel	Sajag	Argonne National Laboratory
Pouliot	Cole	AECOM
Powell	Cindy	Pacific Northwest National Laboratory
Powell	Joseph	University of Houston, Energy Transition Institute
Pradhan	Ajit	Chevron Corporation
Prasanna	Bulusu	Greenko Group
Prasse	Marc	Sargent & Lundy, L.L.C.
Preece	Jeffery	Electric Power Research Institute
Preston	Jessica	Westinghouse Electric Company, LLC
Price	Devon	Cataler North America
Prison	Patricia	Pacific Northwest National Laboratory
Pritchard	Zach	U.S. Department of Energy
Procter	Michael	cellcentric GmbH & Co. KG
Prosser	Jacob	Strategic Analysis, Inc.
Pryor	Martin	Ford Motor Company
Pu	Heting	University of California, Los Angeles
Pu	Xiaofei	National Renewable Energy Laboratory
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Puglia	Peter	California Energy Commission
Pulver	Daniel	U.S. Department of Energy
Purcell	Patrick	Enercon Services, Inc.
Purswani	Sanjay	Boston Consulting Group
Pylypenko	Svitlana	Colorado School of Mines
Pyrzynski	Travis	GTI Energy
Qi	Manman	State University of New York at Buffalo
Qian	Xin	Saint-Gobain Research North America
Qiao	Li	Purdue University
Qin	Fan	Air Liquide
Qin	Feng	PBI Performance Products
Qiu	Xianlei	Daimler Truck China
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Last Name	First Name	Organization
Quackenbush	Karen	Fuel Cell and Hydrogen Energy Association
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Quong	Spencer	Quality Assurance International
Rahman	Aijazur	John Crane
Rakhou	Erik	Boston Consulting Group
Ramaiyan	Kannan	University of New Mexico
Ramaswamy	Nagappan	General Motors Company
Ramotowski	Michael	Solar Turbines Incorporated
Ramsey-Idem	Karen	Cummins Inc.
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Raney	David	Texas Hydrogen Alliance
Rao	Prady	PACCAR Inc
Rashilla	Richard	Hexagon Group
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Rasik	Christopher	The Lubrizol Corporation
Rastogi	Shitij	BMW of North America, LLC
Raun	Jeff	EXP Energy Services
Rawat	Vandana	DRE Motors LLC
Rawlings	Michael	Transportation Management Services
Reddi	Krishna	Argonne National Laboratory
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Reiley	Toby	FastForward Energy
Reis	Signo	Missouri University of Science and Technology
Rempe	Ty	Hexagon Agility
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Reshetenko	Tatyana	University of Hawaiʻi at Mānoa, Hawaiʻi Natural Energy Institute
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Reynolds	Robert	NeoGraf Solutions, LLC
Reznicek	Evan	National Renewable Energy Laboratory
Rice	Brian	University of Dayton Research Institute

Last Name	First Name	Organization
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Richards	Mark	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Richards	Nadia	California Energy Commission
Richardson	Stephanie	U.S. Department of Energy
Richmond	Anja	Wyoming Energy Authority
Rinaldi	Katherine	H2U Technologies, Inc.
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Roberts	Ashley	Technology Development
Roberts	George	TechScale Solutions, LLC
Roberts	Holly	Akoya
Robertson	Jessica	The Chemours Company
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Rodby	Kara	Volta Energy Technologies
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Rohatgi	Aashish	Pacific Northwest National Laboratory
Roig	Francisco	InRoig
Romeri	Mario Valentino	
Romero	Tatiana	National Institute of Electricity and Clean Energies (INEEL, Mexico)
Romo De La Cruz	Cesar Octavio	West Virginia University
Rosner	Fabian	Lawrence Berkeley National Laboratory
Rossi	Ruggero	Johns Hopkins University
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Rother	Gernot	Oak Ridge National Laboratory
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Ruiz	Antonio	
Ruple	Matthew	National Renewable Energy Laboratory
Rupnowski	Peter	National Renewable Energy Laboratory

Last Name	First Name	Organization
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Ruszkowski	Shelley	Exxon Mobil Corporation
Ryan	Amy	Toyota Motor Corporation
Ryan	Liam	Toyota Motor Corporation
Ryan	Lukas	Toyota Motor Corporation
S N	Sheshachala	Hindustan Petroleum Corporation Limited
Sachdeva	Madan	SkipperSeil Limited
Saddler	Kylie	National Renewable Energy Laboratory
Sahoo	Madhumita	Volvo Group
Saini	Raj	RKS Technology and Services
Saitoh	Hiroyuki	National Institutes for Quantum Science and Technology
Saitoh	Kenichiro	Japan Hydrogen Association
Sakaue	Tomohiro	Toray Industries, Inc.
Salahshoor	Shadi	GTI Energy
Salinas	Adrian	Australian Renewable Energy Agency (ARENA)
San Marchi	Chris	Sandia National Laboratories
Sano	Takeru	The High Pressure Gas Safety Institute of Japan
Sapon	William	Tri-Sector Advisors LLC
Saraidaridis	James	Raytheon Technologies Research Center
Sasabe	Takashi	Tokyo Institute of Technology
Sasaki	Kotaro	Brookhaven National Laboratory
Sasseen	Tim	Ballard Power Systems
Sato	Toyoto	Shibaura Institute of Technology
Satomi	Tomohide	Fuel Cell Commercialization Conference of Japan
Satyapal	Sunita	U.S. Department of Energy
Saur	Genevieve	National Renewable Energy Laboratory
Savage	Troy	Mazzetti
Saveski	Tomi	Denso International America, Inc.
Schaal	Michael	OnLocation Inc.
Schaedig	Eric	National Renewable Energy Laboratory
Scheffe	Jonathan	University of Florida

Last Name	First Name	Organization
Schipani	Jeffrey	Wabtec Corporation
Schlueter	Debbie	IRD Fuel Cells
Schneeberger	Chad	ONEOK, Inc.
Schnell	William	Kohler Co.
Schoentgen	Raphael	Hydrogen Advisors
Schoenung	Susan	Longitude 122 West, Inc.
Schulte	Jurgen	RockeTruck, Inc.
Schulz	Robert	Hydro-Québec
Schumacher	Stefanie	U.S. Federal Energy Regulatory Commission
Schwenzer	Birgit	U.S. National Science Foundation
Seligman	Arthur	Fuel Cell Enabling Technologies, Inc.
Selman	Nancy	SKYRE Inc.
Sena	Gregori	U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy
Senior	Constance	
Serov	Alexey	Oak Ridge National Laboratory
Serre-Combe	Pierre	Alternative Energies and Atomic Energy Commission (CEA, France)
Severa	Godwin	University of Hawai‘i, Hawai‘i Natural Energy Institute
Shah	Minish	Linde plc
Shah	Shailesh	U.S. Army Combat Capabilities Development Command C5ISR Center
Shahbazi	Mahboobeh	Queensland University of Technology
Sharma	Abhilash	Hudorr Inc.
Sharma	Preetam	University of Tennessee, Knoxville
Sharma	Saurabh	Isuzu Technical Center of America, Inc.
Sharma-Gibbs	Sunkalp	Hydro Havrand
Shaw	Tom	Element Resources LLC
Shefelbine	Terri	3M Company
Sherif	S. A.	University of Florida
Shethji	Jayraj	Solvay
Shi	Ken	National Research Council Canada
Shibano	Yuta	The High Pressure Gas Safety Institute of Japan
Shih	Jhih-Shyang	Resources for the Future

Last Name	First Name	Organization
Shimotori	Soichiro	Toshiba Energy Systems & Solutions Corporation
Shimozawa	Norihisa	DBJ Americas Inc.
Shin	Jae Eun	Korea Institute of Geoscience and Mineral Resources
Shodhan	Pinky	Grant Thornton LLP
Shrestha	Gyami	Lynker
Shukla	Deepak	Ionomr Innovations Inc.
Shulda	Sarah	National Renewable Energy Laboratory
Shum	David	Utility Global, Inc.
Shumaker	David	GE Research
Shurland	Melissa	U.S. Department of Transportation, Federal Railroad Administration
Shviro	Meital	National Renewable Energy Laboratory
Si	Dechun	Tsinghua University
Sievers	Robert	Institute of Electrical and Electronics Engineers Aerospace Conference
Sigler	Matt	International Code Council
Silva	Paulo	BorgWarner, Inc.
Simmons	Kevin	Pacific Northwest National Laboratory
Simon	Michael	RockeTruck, Inc.
Simoneau	Martin	Hydro-Québec
Simonoff	Ethan	Southern California Gas Company
Singh	Jas (Jaswinder)	Caterpillar Inc.
Singletary	Scott	Thyssenkrupp Nucera
Sinha	Manish	General Motors Company
Sirolli	Eustaquio	Netz
Skriba	Louis	Gigajoule Jug Consultants
Skrzypczak	Luke	University of Virginia
Slack	John	Nikola Corporation
Slezycki	Stephanie	FIRST Global (IFCA)
Slusser	Kevin	Daimler Truck North America
Smith	Christopher	Pacific Northwest National Laboratory
Smith	Owen	National Renewable Energy Laboratory
Smith	Phillip	NASA Glenn Research Center
Snyder	Joshua	Drexel University

Last Name	First Name	Organization
Sofronis	Petros	University of Illinois Urbana-Champaign
Soherr-Hadwiger	David	New Mexico Department of Transportation
Sokaras	Dimosthenis	SLAC National Accelerator Laboratory
Soleymani	Amir Peyman	University of Connecticut
Solomon	Todd	ZeroAvia
Soloveichik	Grigorii	SolEXS Consulting LLC
Somerday	Brian	
Somsel	James	Ford Motor Company
Song	Xueyan	West Virginia University
Song	Zhaoning	University of Toledo
Sosa	Siari	Southern California Gas Company
Souvaliotis	Akis	Exxon Mobil Corporation
Spatz	John	
Spence	Kieran	De Nora Tech, LLC
Spendelow	Jacob	Los Alamos National Laboratory
Spira	Ethan	AJW, Inc.
Spitzer	Ben	Daimler Truck North America
Sprik	Sam	National Renewable Energy Laboratory
Sreekumar	Shravan	Nexight Group LLC
Staller	Corey	Celadyne Technologies, Inc.
Stamenkovic	Vojislav	University of California, Irvine
Stavila	Vitalie	Sandia National Laboratories
StClair	Tracy	Energy Harbor
Steele	Lindsay	Pacific Northwest National Laboratory
Stege	Alex	CF Industries Holdings, Inc.
Steinbach	Andrew	3M Company
Steinkusz	Martina	Renewable Hydrogen Alliance
Stephenson	Thomas	Pajarito Powder, LLC
Stern	Lesley	California Air Resources Board
Stetson	Ned	U.S. Department of Energy
Stevens	Robert	National Energy Technology Laboratory
Stewart	Frederick	Idaho National Laboratory
Stewart	Sarah	Robert Bosch LLC

Last Name	First Name	Organization
Stiles	Dennis	Pacific Northwest National Laboratory
Stoeckli	Albert	Niala Systems
Stottler	Gary	Stottler Development LLC
St-Pierre	Jean	Cummins Inc.
Strange	Nicholas	SLAC National Accelerator Laboratory
Streltsov	Nikita	Nuclear Research Institute, Czech Republic
Stroman	Richard	U.S. Naval Research Laboratory
Stuckey	Philip	FC Renew
Stuehmeier	Bjoern	Robert Bosch LLC
Suh	Dongmyung	Cummins Inc.
Sujan	Vivek	Oak Ridge National Laboratory
Sulic	Martin	Allegheny Science & Technology
Sullivan	Joseph	Universal Solutions International, Inc.
Sumba	Kelvin	Gilbarco Veeder-Root
Sun	Fuxia	3M Company
Sun	Pingping	Argonne National Laboratory
Sun	Qiang	Plug Power Inc.
Sushchenko	Andriy	University of Virginia
Suzuki	Yoshitaka	Chubu Electric Power Co., Inc.
Swamy	Priya	Allegheny Science & Technology
Swartz	Scott	Nexceris, LLC
Swider-Lyons	Karen	Plug Power Inc.
Sylvester	Dylan	Xcel Energy
Tabuchi (Sakon)	Kana	Mitsubishi Heavy Industries, Ltd.
Tadd	Andrew	University of Michigan
Takagi	Mika	New Energy and Industrial Technology Development Organization (NEDO)
Takagi	Shigeyuki	Tohoku University
Takanabe	Kazuhiro	The University of Tokyo
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Last Name	First Name	Organization
Tanveer	Sheik Mohammed Saeed	Argonne National Laboratory
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Taylor	Ben	Independence Hydrogen
Taylor	Bryan	Blackcurrant
Taylor	Faith	Yale University
Tedeschi	Rick	Tedeschi Consulting Solutions, LLC/Hydrogen Safety Panel
Tejima	Go	Toyota Research Institute, Inc.
Terada	Ichiro	AGC Inc.
Tesar	Joseph	Quantalux LLC
Tesfaye	Meron	Bipartisan Policy Center
Tessier	Pascal	FuelCell Energy, Inc.
Thomas	Taniya	APCO Worldwide LLC
Thompson	Gregory	University of Alabama
Thorez	Grégoire	European Institute for Energy Research
Thotapalli	Santhosh	cellcentric GmbH & Co. KG
Tiangco	Valentino	Sacramento Municipal Utility District
Toelle	Sascha	Umicore
Tolfree	Ian	Emerald Development Managers
Tong	Jianhua	Clemson University
Toops	Todd	Oak Ridge National Laboratory
Topolski	Kevin	National Renewable Energy Laboratory
Torkamani	Sarah	Air Products and Chemicals, Inc.
Torres	Eduardo	
Torres	George	Rapid Global Aerospace
Townsend	Justin	Oak Ridge Associated Universities
Tran	Kevin	Toyota Research Institute, Inc.
Trask	Beth	Environmental Defense Fund
Travis	Charles	26th Street Group
Tripathi	Rupali	Congressional Research Service
Trojanowski	Rebecca	Brookhaven National Laboratory
Troy	Makennah	ClearPath

Last Name	First Name	Organization
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Tsai	Yinwen	Industrial Technology Research Institute
Tucker	Amy	Solvay
Tucker	Emily	Clean Air Task Force
Tucker	Michael	Lawrence Berkeley National Laboratory
Tumas	William	National Renewable Energy Laboratory
Turk	David	U.S. Department of Energy
Turner	Liam	Washington State University
Tusing	Richard	National Renewable Energy Laboratory
Tylenda	Craig	Washington Gas Light Company
Uchida	Hiroyuki	University of Yamanashi
Ulsh	Michael	National Renewable Energy Laboratory
Urban	Marek	Clemson University
Uribe	Camilo	ENGIE Colombia
Usami	Takatada	Isuzu Motors Ltd.
Valdez	Thomas	Plug Power Inc.
Van-Brunt	Alexander	Robert Bosch LLC
Vasquez	Camila	Chile Ministry of Energy
Vasquez Franco	Mariana	cellcentric GmbH & Co. KG
Vedros	Kurt	Idaho National Laboratory
Veeramany	Arun	Pacific Northwest National Laboratory
Velluva	Abhijai	Council of Scientific and Industrial Research, National Chemical Laboratory
Veneketaraman	Anand	UL Solutions Canada
Venkatesh	Akshay	HyAxiom, Inc.
Venkatesh	T. A.	Stony Brook University
Venkateshwaran	Vasu	W.L. Gore & Associates, Inc.
Veoni	Daniel	3M Company
Verbofsky	Christen	Westinghouse Electric Company, LLC
Verma	Gaurav	University of North Texas
Vetrano	John	U.S. Department of Energy, Basic Energy Sciences
Vickers	James	U.S. Department of Energy
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Last Name	First Name	Organization
Vijan	Meera	Innovation Partnerships, University of Michigan
Vijayagopal	Ram	Argonne National Laboratory
Vijayakumar	Vishnu	Hyundai Motor Company
Villani	Manfredi	The Ohio State University
Villeneuve	Darek	Daimler Truck North America
Vivio	Brian	BMTS Technology
Vyawahare	Pradeep	Argonne National Laboratory
Wachsman	Eric	University of Maryland
Wagner	Emanuel	Washington Gas Light Company
Wagner	Hugo	Airbus SE
Wall	Todd	Pacific Northwest National Laboratory
Walls	Christina	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Wang	Alex	U.S. Environmental Protection Agency
Wang	Bin	University of Oklahoma
Wang	Conghua (CH)	TreadStone Technologies, Inc.
Wang	Daria	Oak Ridge Associated Universities, Oak Ridge Institute for Science and Education
Wang	Heli	Phillips 66 Company
Wang	Huamin	Pacific Northwest National Laboratory
Wang	Lareina	HASI Capital, Inc.
Wang	Michael	Argonne National Laboratory
Wang	Paul	Caterpillar Inc.
Wang	Ran	University of California, Los Angeles
Wang	Weitian	University of Tennessee, Knoxville
Wang	Xiaohua	Argonne National Laboratory
Wang	Xiaojing	Los Alamos National Laboratory
Wang	Yexing	cellcentric GmbH & Co. KG
Ward	Jeremy	Westinghouse Electric Company, LLC
Ward	Michael	BorgWarner, Inc.
Warford	Bruce	Oak Ridge Associated Universities, Oak Ridge Institute for Science and Education
Warren	Mitch	W.L. Gore & Associates, Inc.
Wasiloff	Eric	U.S. Army Ground Vehicle Systems Center

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Watabe	Hiroyuki	AGC Inc.
Watson	Christine	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Weaver	Matt	GKN Hydrogen
Weaver	Robert	
Weber	Adam	Lawrence Berkeley National Laboratory
Weber	Michael	Schaeffler Group USA Inc.
Weeks	Brian	GTI Energy
Wegge	Erik	R&D Dynamics Corporation
Weiland	Nathan	National Energy Technology Laboratory
Weimer	Alan	University of Colorado Boulder
Weisenberger	Matthew	University of Kentucky
Wendt	Daniel	Idaho National Laboratory
Wenger	Fabian	Smoltek Hydrogen AB
Wentlent	Luke	Plug Power Inc.
Westhoff	Casey	Umicore
Westlake	Brittany	Electric Power Research Institute
Westover	Tyler	Idaho National Laboratory
Wheeler	Robert	Sandia National Laboratories
White	Eric	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
White	Sean	Amentum Services, Inc.
White	Zakar	Carnegie Mellon University
Whitney	Erin	U.S. Department of Energy, Arctic Energy Office
Whittaker	Joshua	Element Resources LLC
Whitty	Kevin	University of Utah
Wichlinski	Joseph	BMTS Technology
Wieliczko	Marika	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Wil	Mel	Oak Ridge Associated Universities
Wilburn	Steve	VerdeWatts, LLC
Wilcox	Ben	U.S. Department of the Navy
Wilcox	Mina	Art Mina Inc.
Williams	Mark	West Virginia University

Last Name	First Name	Organization
Williams	Martha	GenH2
Williams	Stefan	U.S. Army Combat Capabilities Development Command C5ISR Center
Williams	Travis	University of Southern California
Wilson	Adria	Breakthrough Energy
Wilson	Alan	Sargent & Lundy, L.L.C.
Wilson	Chris	Hexagon Agility
Winter	Amanda	Oak Ridge Associated Universities, Oak Ridge Institute for Science and Education
Winter	Dylan	Evonik Corporation
Wipke	Keith	National Renewable Energy Laboratory
Wiryadinata	Steven	Sandia National Laboratories
Wismer	Samantha	University of Maryland
Wofford	Bryan	Sandia National Laboratories
Wolak	Frank	Fuel Cell and Hydrogen Energy Association
Wolf	Stan	U.S. Federal Energy Regulatory Commission
Wolffe	Vaughn	
Wolff-Klammer	Edgar	UL Solutions
Wollenberg	Steve	H2U Technologies, LLC
Woo	Christine	TwoEagles Labs
Wood	Brandon	Lawrence Livermore National Laboratory
Woods	Stephen	NASA White Sands Test Facility
Wormald	Amanda	Australian Government, Department of Foreign Affairs and Trade
Worsham	Elizabeth	Idaho National Laboratory
Wright	Charles	
Wright	Ruishu	National Energy Technology Laboratory
Wrigley	Krystal	ExxonMobil Corporation
Wu	Gang	State University of New York at Buffalo
Wu	Mengjia	Solvay
Wu	Wei	Idaho National Laboratory
Wycisk	Ryszard	eSpin Technologies
Wymer	Jess	Clean Air Task Force
Xie	Jian	Indiana University–Purdue University Indianapolis

Last Name	First Name	Organization
Xie	Zhiqiang	University of Tennessee, Knoxville
Xing	Yangchuan	University of Missouri
Xu	Fan	South Coast Air Quality Management District
Xu	Hui	Envision Energy USA
Xu	Leo	EKPO Fuel Cell Technologies GmbH
Xu	Siguang	General Motors Company
Xu	Zhan	University of Birmingham
Yabe	Akira	New Energy and Industrial Technology Development Organization (NEDO)
Yadav	Abhishek	BASF SE
Yamaguchi	Jin	Ministry of Economy, Trade and Industry (Japan)
Yamamoto	Atsushi	Toyota Motor Corporation
Yamamoto	Steve	Matrix Sensors, Inc.
Yamano	Naoki	American Honda Motor Co., Inc.
Yamaya	Tim	3M Company
Yanagibashi	Naoki	Nippon Kayaku Co., Ltd.
Yandrasits	Michael	Johnson Matthey
Yang	Fan	Plug Power Inc.
Yang	Hong	Stanford University
Yang	Jae Choon	Doosan Fuel Cell Co., Ltd.
Yang	Ji	University of Maryland
Yang	Ruochen	University of Maryland
Yazici	Suha	ITU Energy Institute
Yen	Jerry	UL Solutions
Yesilyurt	Serhat	Sabanci University
Yi	Yaofan	Chevron Corporation
Yik	Edwin	M2X Energy
Ying	Sun	Guangzhou Hybot Co, Ltd.
Yokomoto	Katsumi	Kyushu University
Yoon	Songhak	Fraunhofer IWKS
Yoon	Wonseok	Caterpillar Inc.
York	Krystal	Electric Power Research Institute
Yoshida	Toshihiko	Nagoya University

Last Name	First Name	Organization
Young	Alan	Ballard Power Systems
Young	James	National Renewable Energy Laboratory
Youssefi	Ali	Symbio SAS
Yu	Ji Haeng	Korea Institute of Energy Research
Yu	Shule	Versogen
Yuan	Xiaozi	National Research Council Canada
Yuh	Chao-Yi	FuelCell Energy, Inc.
Yurko	Joseph	Jay of Northeast Ohio, LLC
Zacharia	Renju	Nikola Corporation
Zachman	Michael	Oak Ridge National Laboratory
Zahoor	Noman	
Zawodzinski	Tom	Oak Ridge National Laboratory/University of Tennessee, Knoxville
Zelenay	Piotr	Los Alamos National Laboratory
Zeng	Xiangqun	Oakland University
Zeng	Zhenhua	Purdue University
Zenyuk	Iryna	University of California, Irvine
Zhai	Shang	The Ohio State University
Zhai	Yunfeng	University of Hawai‘i at Mānoa, Hawai‘i Natural Energy Institute
Zhan	Wei	Southeast University
Zhanda	Brandon	AP Ventures
Zhang	Ao	University of California, Los Angeles
Zhang	Bingzhang	State University of New York at Buffalo
Zhang	Feng-Yuan	University of Tennessee, Knoxville
Zhang	Kun	Shell Global
Zhang	Qian	Idaho National Laboratory
Zhang	Sen	University of Virginia
Zhang	Yan	General Motors Company
Zhang	Yanwen	Idaho National Laboratory
Zhang	Yuepeng	Argonne National Laboratory
Zhao	Jian	Mississippi State University
Zhao	Nana	National Research Council Canada
Zhao	Xueru	Brookhaven National Laboratory

Last Name	First Name	Organization
Zheng	Sue	Analog Devices, Inc.
Zheng	Xiaolin	Stanford University
Zhu	Jingbing	Zhejiang Haizhou Renewable Energy Technology Co. Ltd.
Zhu	Tianli	Raytheon Technologies Research Center
Zhuang	Cg	Corning Incorporated
Zokoe	James	Cummins Inc.
Zorniger	Alex	Power to Hydrogen, LLC
Zulevi	Barr	Electric Hydrogen

Appendix C: Evaluation Forms

General Project Evaluation Form

This evaluation form is for use with the following Hydrogen and Fuel Cell Technologies Office review panels/projects: Hydrogen Production Technologies;[1] Hydrogen Infrastructure Technologies (Delivery/Infrastructure/Storage); Fuel Cell Technologies; Systems Development and Integration; and Analysis, Codes and Standards.[2]

Evaluation Criteria: U.S. Department of Energy (DOE) 2023 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 higher weights 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 led directly 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. Potential Impact

The degree to which the project supports and advances progress toward the project's specific performance targets and the Hydrogen Program goals and objectives, as delineated in the Program and subprogram overview presentations given during the Annual Merit Review. **(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 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:

SUMMARY OF REVIEWER COMMENTS

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)
2023 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 and feasible. 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. Outstanding progress toward ambitious go/no-go criteria; accomplishments are supported by strong and convincing data; difficult to improve significantly.

3.5 – Excellent. Excellent progress toward impactful go/no-go criteria; accomplishments are supported by strong data.

3.0 – Good. Significant progress toward meaningful go/no-go criteria; accomplishments are supported by adequate data.

2.5 – Satisfactory. Satisfactory progress toward adequate go/no-go criteria; accomplishments are supported by some data.

2.0 – Fair. Limited data and accomplishments to support the go/no-go criteria; go/no-go criteria may be weak.

1.5 – Poor. Unlikely to meet the go/no-go criteria; go/no-go criteria may be weak.

1.0 – Unsatisfactory. Unlikely to meet the go/no-go criteria; go/no-go criteria are inadequate 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 Energy Materials Network 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 crosscutting 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 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 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; there is little or no apparent coordination with partners or the HydroGEN Consortium.

1.0 – Unsatisfactory. No apparent coordination with partners and 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 Collaboration Effectiveness with HydroGEN and, if applicable, other research entities:

4. Potential Impact

The degree to which the project supports and advances progress toward the DOE Hydrogen Program goals and objectives, and also supports and advances 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 $1/kg H2 or interim hydrogen production goal of $2/kg H2. 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, 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, 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 only 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 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, meets 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, meets 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:

SUMMARY OF REVIEWER COMMENTS

Project Strengths:

Project Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

2023 AMR – DOE Hydrogen Program Review Questions

Dear DOE Hydrogen Program Reviewer: We appreciate your input on the overall DOE Hydrogen Program and its participating DOE offices. Please provide your scores and comments on the questions below *based on the Annual Merit Review (AMR) sessions you attended and your particular areas of expertise and focus.* You may answer as many questions as you like; blank or N/A scores will not affect the merit review results. Your comments will be useful in helping to guide future DOE program strategies and priorities.

The DOE Hydrogen Program is being coordinated through the Hydrogen and Fuel Cell Technologies Office (HFTO) in the DOE Office of Energy Efficiency and Renewable Energy (EERE), with research, development, demonstration, and deployment (RDD&D) activities across multiple DOE offices including Fossil Energy and Carbon Management (FECM), Nuclear Energy (NE), Science (SC), Advanced Research Projects Agency–Energy (ARPA-E), Office of Clean Energy Demonstrations (OCED), Office of Technology Transitions (OTT), Loan Programs Office (LPO), Office of Electricity (OE), Office of Indian Energy Policy and Programs (IEPP), and others. For each question you answer, please provide comments (as applicable) on the overall Hydrogen Program and, as appropriate, on specific Hydrogen Program offices.

Please refer to the AMR's plenary program for overview presentations on the overall DOE Hydrogen Program. Information on specific RDD&D activities being carried out by the different DOE offices can be found in the plenary, oral, and poster AMR presentations.

1. The Hydrogen Program plan and strategy were clearly articulated and well-aligned with the mission and goals of the National Clean Hydrogen Strategy and Roadmap and of the Hydrogen Shot.

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.

1	Hydrogen Program Overall Strategy
Score	

General Comments:

Specific Comments: on how well the Hydrogen Program has identified important challenges to meeting goals and articulated plans to address the challenges.

2. The Hydrogen Program is aligned well with industry and stakeholder needs and appropriately complements private-sector, state, and other non-DOE investments and RDD&D.

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.

2	Hydrogen Program Stakeholder Alignment
Score	

General Comments: Please describe any areas that you feel are not well aligned with industry needs or that require more (or less) federal funding support.

Office-Specific Comments: Please comment on particular strengths and/or improvement opportunities relative to specific DOE Hydrogen Program offices in the table below:

DOE OFFICE	STRENGTHS	IMPROVEMENT OPPORTUNITIES
EERE		
FECM		
NE		
SC		
ARPA-E		
OCED		
OTHER (specify)		

3. The Hydrogen Program's portfolio of projects is appropriately balanced across research areas to help achieve its mission and goals, and it has an appropriate balance between near-, mid- and long-term RDD&D (including lab projects and consortia, FOA [funding opportunity announcement] projects, CRADA [cooperative research and development agreement] projects, etc.).

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.

3	Hydrogen Program Project Portfolio
Score	

General Comments: Please describe any over- or under-represented areas, including any gaps in the overall Hydrogen Program project portfolio or any comments you may have on whether funding levels in each area are appropriate.

Office-Specific Comments: Please comment on particular project portfolio strengths and/or gaps relative to specific DOE Hydrogen Program offices in the table below:

DOE OFFICE	PROJECT PORTFOLIO STRENGTHS	PROJECT PORTFOLIO GAPS
EERE		
FECM		
NE		
SC		
ARPA-E		
OCED		
OTHER (specify)		

4. The Hydrogen Program is effectively collaborating in RDD&D across the DOE offices and with other agencies.

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.

4	Hydrogen Program Effective Collaborations
Score	

General Comments: Please comment generally on offices or agencies that should be more engaged or leveraged and in what manner.

Office-Specific Comments: Please comment on particular strengths and/or improvement opportunities relative to specific DOE Hydrogen Program offices in the table below:

DOE OFFICE	COLLABORATION STRENGTHS	IMPROVEMENT OPPORTUNITIES
EERE		
FECM		
NE		
SC		
ARPA-E		
OCED		
OTHER (specify)		

5. The Hydrogen Program is sufficiently incorporating a diversity of approaches for addressing energy and environmental justice (EEJ), as well as diversity, equity, inclusion, and accessibility (DEIA), in the execution and impacts of its RDD&D activities.

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.

5	Hydrogen Program EEJ and DEIA
Score	

General Comments: Please comment on which stakeholders, external groups, or resources (e.g., academia, companies, small businesses, types of industries, states, other agencies) should be more engaged with or leveraged and in what manner.

Targeted Comments: Please comment on particular strengths and/or improvement opportunities in EEJ and DEIA relative to the overall DOE Hydrogen Program and/or to specific offices:

6. Please comment on whether the Hydrogen Program is doing enough to advance goals for workforce development and science, technology, engineering, and mathematics (STEM) education.

General Comments: Please comment on how the Hydrogen Program could build on and/or adjust its current portfolio to accomplish goals in workforce development and STEM.

Targeted Comments: Please comment on particular highlights and/or improvement opportunities in workforce development and STEM relative to the overall DOE Hydrogen Program and/or to specific offices.

7. The Hydrogen Program also collaborates with other countries through several international partnerships, such as the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), Clean Energy and Hydrogen Ministerials, Mission Innovation, the International Energy Agency, and others. Please comment on actions DOE can undertake in conjunction with these or other international activities that can effectively accelerate U.S. progress in hydrogen and fuel cell technologies.

Comments:

8. Please provide any additional suggestions you may have for improvement of the overall DOE Hydrogen Program (e.g., in areas such as technology development, demonstration, and scale-up; technoeconomic and environmental impact assessments; safety, codes, and standards; soft costs; commercial liftoff; and outreach and education).

Comments:

9. Based on DOE's hydrogen activities, and given the Bipartisan Infrastructure Law (BIL) funding across the RDD&D spectrum, how likely do you think it is that:

a) The BIL target of $2/kg clean H2 will be achieved by 2026?*

	10 – very likely 1 – not likely
Score	

b) The Hydrogen Shot ($1/kg clean H2 by 2031) will be achieved?*

	10 – very likely 1 – not likely
Score	

** Note: These are modeled levelized costs of production only, at high volumes (e.g., GW scale).*

Appendix D. List of Projects Presented but Not Reviewed

Project ID	Project Title	Principal Investigator Name	Organization
ARPAE-001	Carbon-Dioxide-Free Hydrogen and Solid Carbon from Natural Gas via Metal Salt Intermediates	Jonah Erlebacher	Johns Hopkins University
ARPAE-002	Efficient Production of H_2/NH_3 Fuel Blends for Zero-Carbon Combustion	Colin Wolden	Colorado School of Mines
ARPAE-003	A Hybrid Electrochemical and Catalytic Compression System for Direct Generation of High-Pressure Hydrogen at 700 Bar	Wei Wang	Pacific Northwest National Laboratory
ARPAE-004	Co-Synthesis of Hydrogen and High-Value Carbon Products from Methane Pyrolysis	Matteo Cargnello	Stanford University
ARPAE-005	Understanding the Potential for Geologic Hydrogen Resources	Geoffrey Ellis	U.S. Geological Survey
ARPAE-006	Overview of ARPA-E Methane Pyrolysis Program and Possible Future Directions	Jack Lewnard	U.S. Department of Energy, Advanced Research Projects Agency–Energy
BES-001	Underpinning Science for Hydrogen Technologies	Chris Fecko	U.S. Department of Energy, Office of Basic Energy Sciences
BES-002	A Programmable Non-Equilibrium Electrified Ammonia Synthesis for Efficient Hydrogen Storage	Qi Dong and Ji Yang	University of Maryland
BES-003	Enabling Reversible Hydrogen Storage and Transfer with Graphene-Based Carbon–Boron–Nitrogen Materials	Tom Autrey	Pacific Northwest National Laboratory
FC-000	Fuel Cell Technologies Subprogram Overview	Dimitrios Papageorgopoulos	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
FC-167	Fiscal Year 2022 Small Business Innovation Research (SBIR) IIC: Multi-Functional Catalyst Support	Minette Ocampo	pH Matter, LLC
FC-335	Additive Functionalized Polymers for Extended Heavy-Duty Polymer Electrolyte Membrane Lifetimes	Tom Corrigan	The Lubrizol Corporation
FC-341	Advanced Anion Exchange Membrane Fuel Cells through Material Innovation	Yu Seung Kim	Los Alamos National Laboratory
FC-342	Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells	Bryan Pivovar	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
FC-343	Fiscal Year 2020 Small Business Innovation Research (SBIR) II: Improved Ionomers and Membranes for Fuel Cells	Chris Topping	Tetramer Technologies, LLC
FC-354	L'Innovator Program	Emory De Castro	Advent Technologies
FC-355	Los Alamos National Laboratory Minority-Serving Institution Program	Tommy Rockward	Los Alamos National Laboratory
FC-356	Fiscal Year 2022 Small Business Innovation Research (SBIR) II: Durable High-Efficiency Membrane and Electrode Assemblies for Heavy-Duty Fuel Cell Vehicles	Natalia Macauley	Giner, Inc.
FC-361	Fiscal Year 2022 Small Business Innovation Research (SBIR) I: Durable Bulk Metallic Glass Catalysts for Medium- and Heavy-Duty Proton Exchange Membrane Fuel Cells	Evgenia Pekarskaya	Supercool Metals LLC
FC-362	Fiscal Year 2022 Small Business Technology Transfer (STTR) I: Mobile Fuel Cell Generator	Paul Scott	RockeTruck, Inc.
FE-000	Office of Fossil Energy and Carbon Management Hydrogen Activities Overview	Eva Rodezno and Evan Frye	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
FE-001	Performance Testing of a Moving-Bed Gasifier using Coal, Biomass, and Waste Plastic Blends to Generate White Hydrogen	George Booras	Electric Power Research Institute
FE-002	Enabling Entrained-Flow Gasification of Blends of Coal, Biomass, and Plastics	Kevin Whitty	The University of Utah
FE-003	Experimental Research of Feedstock Gasification with Neutron Techniques	Jim Parks	Oak Ridge National Laboratory
FE-004	Coal Syngas Cleanup for Commercially Viable Solid Oxide Fuel Cell Performance	Zhien Liu	University of North Dakota, Energy and Environmental Center
FE-005	Performance Improvements for Reversible Solid Oxide Fuel Cell Systems	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.
FE-006	Additively Manufactured High-Temperature Centrifugal Impellers for Low-Cost Solid Oxide Fuel Cell Anode Recycle Blowers	Jose Cordova	Mohawk Innovative
FE-007	Cummins Reversible Solid Oxide Fuel Cell System Development	Lars Henrichsen	Cummins Inc.
FE-008	Reversible Solid Oxide Cell Degradation: Characterization, Simulation, and Mitigation	Yinkai Lei	National Energy Technology Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
FE-009	Designing Internal Surfaces of Porous Electrodes in Solid Oxide Electrolysis Cells for Highly Efficient and Durable Hydrogen Production	Xueyan Song	West Virginia University
FE-010	Investigation of Flame Structure for Hydrogen Gas Turbine Combustion	Robert Lucht	Purdue University
FE-011	Characterizing U.S. Subsurface Hydrogen Storage Potential in Existing Natural Gas Storage Reservoirs	Gregory Lackey	National Energy Technology Laboratory
FE-017	Technoeconomic Evaluation of Solid-Oxide-Fuel-Cell/Solid-Oxide-Electrolyzer-Cell-Based Integrated Energy Systems for the Co-Production of Electricity and Hydrogen	Anthony Burgard	National Energy Technology Laboratory
FE-018	Raman Gas Analyzer for Real-Time Gas Composition Monitoring	Benjamin Chorpening	National Energy Technology Laboratory
FE-019	Hydrogen Safety Review for Office of Fossil Energy and Carbon Management Applications	Sam Bayham	National Energy Technology Laboratory
FE-020	Market-Based Technoeconomic Optimization of Integrated Energy Systems that Co-Produce Hydrogen and Electricity	Alexander Dowling	University of Notre Dame
H2-057	Electrolyzer/Bioreactor Integration (EBI)	Kevin Harrison	National Renewable Energy Laboratory
HFTO-001	Community Benefits Plans and You!	Julie Fornaciari and Michelle Fox	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
HFTO-002	Energy and Environmental Justice Policies and Programs	Anne Marie Esposito and Cassandra Osvatics	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
HFTO-003	Chesapeake First Robotics Team: The Titans		
IA-001	U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office Overview	Sunita Satyapal	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
IA-002	DOE National Clean Hydrogen Strategy and Roadmap	Neha Rustagi	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
IA-004a	U.S. Department of Transportation Panel	Michael Carter	U.S. Department of Transportation

Project ID	Project Title	Principal Investigator Name	Organization
IA-004b	Federal Railroad Administration Hydrogen and Fuel Cell Research Program	Melissa Shurland	U.S. Department of Transportation
IA-004c	Federal Transit Administration Update	Mark Bathrick	U.S. Department of Transportation
IA-004d	Pipeline and Hazardous Materials Safety Administration Hydrogen Pipeline Safety Regulations	Mary McDaniel	U.S. Department of Transportation
IA-004e	Bipartisan Infrastructure Law Electric Vehicle and Alternative Fuel Provisions	Diane Turchetta	U.S. Department of Transportation
IA-005	Pathways to Commercial Liftoff and Future Analysis	Jason Munster	U.S. Department of Energy, Office of Clean Energy Demonstrations
IA-006	U.S. Environmental Protection Agency's Ports Initiative and the New Clean Ports Program in the Inflation Reduction Act	Sarah Froman	U.S. Environmental Protection Agency
IA-007	Perspective and Case Examples on Development of Hydrogen at Shore	David Cook	U.S. Navy
IA-008	U.S. Army Combat Capabilities Development Command Ground Vehicle Systems Center: Hydrogen Fuel Cell Update	Kevin Centeck	U.S. Army
IA-009	H2@Rescue DOE-DOD-FEMA Initiative	Nicholas Josefik	U.S. Army
IA-010	Fuel Cell Systems for the Dismounted Soldier	Shailesh Shah	U.S. Department of Defense
IA-011	Fuel Cell Rural Energy for America Program (REAP) Awards	Chris Cassidy	U.S. Department of Agriculture
IA-012	NASA Fuel Cell and Hydrogen Research Activities	Ian Jakupca	NASA
IA-013	Hydrogen Biogeochemical Cycle: Implications for Hydrogen Climate Impact	Fabien Paulot	National Oceanic and Atmospheric Administration
IA-014	International Partnership for Hydrogen and Fuel Cells in the Economy: Early Career Network	Tomas Green and Christine Watson	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
IEDO-001	Flexible Natural Gas/Hydrogen Combined Heat and Power System Development and Demonstration	Jaswinder Singh	Caterpillar, Inc.

Project ID	Project Title	Principal Investigator Name	Organization
IN-000	Hydrogen Infrastructure Technologies Subprogram Overview	Ned Stetson	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
IN-004	Magnetocaloric Hydrogen Liquefaction	John Barclay	Pacific Northwest National Laboratory
IN-014	Nondestructive Evaluation Techniques for Pressure Vessels (Small Business Innovation Research): Detection of Micron-Scale Flaws through Nonlinear Wave Mixing	Michael Desrosiers	Luna Innovations Inc.
IN-038	High-Pressure, Low-Temperature Composite Nozzles for Long-Term Hydrogen Dispensing	Jennifer Lalli	Nanosonic, Inc.
LPO-001	Building the World's First Clean Hydrogen Hub – Advanced Clean Energy Storage (ACES) Delta	Michael Ducker	Mitsubishi Power
NE-002	Light Water Reactor Integrated Energy Systems Interface Technology Development and Demonstration	Dylan Sylvester	Northern States Power Company/Xcel Energy
NE-003	Integrated Energy Systems: Supporting Transportation and Industry with Nuclear Power	Richard Boardman	Idaho National Laboratory
NE-004	Preconceptual Design of Thermal and Electrical Power Interfaces for Hydrogen Production	Alan Wilson	Sargent and Lundy
NE-005	Safety and Hazards Analysis of Hydrogen Production at Nuclear Power Plants	Kurt Vedros	Idaho National Laboratory
P-000	Hydrogen Production Technologies Subprogram Overview	David Peterson	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
P-148A	HydroGEN: Low-Temperature Electrolysis	Shaun Alia	National Renewable Energy Laboratory
P-148B	HydroGEN: High-Temperature Electrolysis	Dong Ding	Idaho National Laboratory
P-148C	HydroGEN: Photoelectrochemical Water Splitting	Joel Ager	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

Project ID	Project Title	Principal Investigator Name	Organization
P-154	Thin-Film, Metal-Supported High-Performance and Durable Proton Solid Oxide Electrolyzer Cell	Tianli Zhu	Raytheon Technologies Research Center
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-183	Extremely Durable Concrete Using Methane Decarbonization Nanofiber Co-Products with Hydrogen	Alan Weimer	University of Colorado, Boulder
P-185	High-Performance Anion Exchange Membrane Low-Temperature Electrolysis with Advanced Membranes, Ionomers, and Platinum-Group-Metal-Free Electrodes	Paul Kohl	Georgia Institute of Technology
P-186	Performance and Durability Investigation of Thin, Low-Crossover Proton Exchange Membranes for Water Electrolyzers	Andrew Park	The Chemours Company FC, LLC
P-187	Pure Hydrogen Production through Precious-Metal-Free Membrane Electrolysis of Dirty Water	Shannon Boettcher	University of Oregon
P-188	Advanced Coatings to Enhance the Durability of Solid Oxide Electrolyzer Cell Stacks	Sergio Ibanez	Nexceris, LLC
P-194	New High-Entropy Perovskite Oxides with Increased Reducibility and Stability for Thermochemical Hydrogen Generation	Jian Luo	University of California, San Diego
P-195	A New Paradigm for Materials Discovery and Development for Lower-Temperature and Isothermal Thermochemical Hydrogen Production	Jonathan Scheffe	University of Florida
P-196a	Hydrogen from Next-generation Electrolyzers of Water (H2NEW) Low-Temperature Electrolysis: Durability and Accelerated Stress Test Development	Rangachary Mukundan	Lawrence Berkeley National Laboratory
P-196b	Hydrogen from Next-generation Electrolyzers of Water (H2NEW) Low-Temperature Electrolysis: Benchmarking and Performance	Deborah Myers	Argonne National Laboratory
P-196c	Hydrogen from Next-generation Electrolyzers of Water (H2NEW) Low-Temperature Electrolysis: Manufacturing, Scale-Up, and Integration	Scott Mauger	National Renewable Energy Laboratory
P-196d	Hydrogen from Next-generation Electrolyzers of Water (H2NEW) Low-Temperature Electrolysis: System and Techno-Economic Analysis – Hydrogen from Next-Generation Electrolyzers	Alex Badgett	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
P-196e	Hydrogen from Next-generation Electrolyzers of Water (H2NEW) High-Temperature Electrolysis: Durability and Accelerated Stress Test Development	Olga Marina	Pacific Northwest National Laboratory
P-196f	Hydrogen from Next-generation Electrolyzers of Water (H2NEW) High-Temperature Electrolysis: Cell Characterization	David Ginley	National Renewable Energy Laboratory
P-196g	Hydrogen from Next-generation Electrolyzers of Water (H2NEW) High-Temperature Electrolysis: Multiscale Degradation Modeling	Brandon Wood	Lawrence Livermore National Laboratory
P-196h	Hydrogen from Next-generation Electrolyzers of Water (H2NEW) High-Temperature Electrolysis: Liquid Alkaline Water Electrolysis	Bryan Pivovar	National Renewable Energy Laboratory
P-205	Metal–Organic Framework-Based Heterostructure Electrocatalysts with Tailored Electron Density Distribution for Cost-Effective and Durable Fuel Cells and Electrolyzers	Sreeprasad Sreenivasan	University of Texas, El Paso
P-206	Single-Walled Carbon Nanotubes with Confined Chalcogens as the Catalysts and Electrodes for Oxygen Reduction Reaction in Fuel Cells	Juchen Guo	University of California, Riverside
P-207	Megawatt-Scale Low-Temperature Electrolyzer Research Capability	Daniel Leighton	National Renewable Energy Laboratory
PRA-001	Mitigation and Diagnosis of Pin-Hole Formation in Polymer Electrolyte Membrane Fuel Cells	Audrey Taylor	National Renewable Energy Laboratory
PRA-002	Advanced Porous-Transport-Layer Interface Design for Proton Exchange Membrane Electrolyzers	Jason Lee	Lawrence Berkeley National Laboratory
PRA-003	Thin-Film Catalyst Fuel Cell Electrodes with Improved Durability	Wipula Liyanage	Los Alamos National Laboratory
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
SA-187	Heavy-Duty Hydrogen Fueling Station Corridors	Mark Chung	National Renewable Energy Laboratory
SA-188	Sustainability Criteria for Hydrogen Deployments	Mark Chung	National Renewable Energy Laboratory
SA-189	Fiscal Year 2022 Small Business Innovation Research (SBIR) I: Siting Hydrogen for Equity and Energy Justice	Erin Middleton	Carbon Solutions LLC

Project ID	Project Title	Principal Investigator Name	Organization
SA-190	Patent and Technology Portfolios Resulting from Hydrogen and Fuel Cell Technologies Office Research and Development Funding	Lindsay Steele	Pacific Northwest National Laboratory
SA-SCS000	Analysis, Codes and Standards Subprogram Overview	Neha Rustagi	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
SCS-034	Large-Scale Hydrogen Storage – Risk Assessment – Seattle City Light and Port of Seattle	Arun Veeramany	Pacific Northwest National Laboratory
SCS-035	Modeling and Risk Assessment of Hydrogen/ Natural Gas Blends	Austin Glover	Sandia National Laboratories
SDI-000	Systems Development and Integration Subprogram Overview	Jesse Adams	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
SDI-001a	Integrated Modeling, Techno-Economic Analysis, and Reference Design for Renewable Hydrogen to Green Steel and Ammonia	Jennifer King	National Renewable Energy Laboratory
SDI-005	HYdrogen systems for PERformance-based Value stacking (HYPER-V)	Rishabh Jain	National Renewable Energy Laboratory
SDI-006	Energy Technology Proving Ground	Richard Boardman	Idaho National Laboratory
SETO-001	Concentrating Solar–Thermal Power Program Overview	Matt Bauer	U.S. Department of Energy, Solar Energy Technologies Office
SETO-002	Technology for Electrically Enhanced Thermochemical Hydrogen (TEETH)	Jim Miller	Arizona State University
SETO-003	Solar Hydrogen from Water Splitting Using Liquid Metal Oxidation/Reduction Cycles Promoted by Electrochemistry	Anthony McDaniel	Sandia National Laboratories
ST-001	System-Level Analysis of Hydrogen Storage Options	Rajesh Ahluwalia	Argonne National Laboratory
ST-008	Hydrogen Storage System Modeling: Public Access, Maintenance, and Enhancements	Sam Sprik	National Renewable Energy Laboratory
ST-135	National Institute of Standards and Technology–National Renewable Energy Laboratory Overview	Ryan Klein	National Institute of Standards and Technology
ST-148	Novel Plasticized Melt Spinning Process of Polyacrylonitrile (PAN) Fibers Based on Task-Specific Ionic Liquids	Sheng Dai	Oak Ridge National Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
ST-201	Hydrogen Materials Advanced Research Consortium (HyMARC) – SLAC Activities	Nicholas Strange	SLAC National Accelerator Laboratory
ST-202	HyMARC – National Renewable Energy Laboratory Activities	Tom Gennett	National Renewable Energy Laboratory
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-209	HyMARC Seedling: Theory-Guided Design and Discovery of Materials for Reversible Methane and Hydrogen Storage	Omar Farha	Northwestern University
ST-210	HyMARC Seedling: Metal–Organic Frameworks Containing Frustrated Lewis Pairs for Hydrogen Storage at Ambient Temperature	Shengqian Ma	University of North Texas
ST-211	HyMARC Seedling: Optimal Adsorbents for Low-Cost Storage of Natural Gas and Hydrogen: Computational Identification, Experimental Demonstration, and System-Level Projection	Adam Matzger	University of Michigan
ST-212	HyMARC Seedling: Methane and Hydrogen Storage with Porous-Cage-Based Composite Materials	Eric Bloch	University of Delaware
ST-213	HyMARC Seedling: Uniting Theory and Experiment to Deliver Flexible Metal–Organic Frameworks for Superior Methane (Natural Gas) Storage	Brian Space	North Carolina State University
ST-214	HyMARC Seedling: Heteroatom-Modified and Compacted Zeolite-Templated Carbons for Gas Storage	Nicholas Stadie	Montana State University
ST-216	HyMARC Seedling: Hydrogen Release from Concentrated Media with Reusable Catalysts	Travis Williams	University of Southern California
ST-217	HyMARC Seedling: A Reversible Liquid Hydrogen Carrier System Based on Ammonium Formate and Captured Carbon Dioxide	Hongfei Lin	Washington State University
ST-218	HyMARC Seedling: High-Capacity Step-Shaped Hydrogen Adsorption in Robust, Pore-Gating Zeolitic Imidazolate Frameworks	Michael McGuirk	Colorado School of Mines
ST-224	HyMARC – Lawrence Berkeley National Laboratory Activities	Jeffrey Long	Lawrence Berkeley National Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
ST-225	HyMARC – Lawrence Berkeley National Laboratory Advanced Light Source Activities	David Prendergast	Lawrence Berkeley National Laboratory
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
ST-235	Hydrogen Storage Cost and Performance Analysis	Cassidy Houchins	Strategic Analysis, Inc.
ST-242	Dimethyl Ether as a Renewable Hydrogen Carrier: Innovative Approach to Renewable Hydrogen Production	Michael Heidlage	Los Alamos National Laboratory
ST-243	FueL Additives for Solid Hydrogen (FLASH) Carriers for Electric Aviation	Noemi Leick	National Renewable Energy Laboratory
TA-009	Maritime (Pierside Power) Fuel Cell Generator Project	Lennie Klebanoff	Sandia National Laboratories
TA-013	Fuel Cell Bus Evaluations	Matthew Post	National Renewable Energy Laboratory
TA-030	Demonstration of Integrated Hydrogen Production and Consumption for Improved Utility Operations	Paul Brooker	Orlando Utilities Commission
TA-051	Low Total Cost of Hydrogen by Exploiting Offshore Wind and Proton Exchange Membrane Electrolysis Synergies	Judith Lattimer	Giner, Inc.
TA-054	Anion Exchange Membrane Water Electrolyzer for Hydrogen Production from Offshore Wind	Richard Masel	Alchemr, Inc.
TA-061	Optimal Wind Turbine Design for Hydrogen Production	Chris Bay	National Renewable Energy Laboratory
TA-063	High-Efficacy Validation of Hydride Mega Tanks at the ARIES [Advanced Research on Integrated Energy Systems] Lab (HEVHY METAL)	Katherine Hurst	National Renewable Energy Laboratory
TA-064	Hydrogen Production, Grid Integration, and Scaling for the Future	Sam Sprik	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
VTO-001	Accelerating the Development of Hydrogen Internal Combustion Engines – Vehicle Technologies Office/Decarbonization of Off-Road, Rail, Marine, and Aviation (DORMA) Projects	Gurpreet Singh	U.S. Department of Energy, Vehicle Technologies Office
WETO-001	Integrated Wind–Hydrogen Systems	Jian Fu	U.S. Department of Energy, Wind Energy Technologies Office
WPTO-001	Water Power Technologies Office: Potential Connections with Hydrogen Generation	Bill McShane	U.S. Department of Energy, Water Power Technologies Office

Appendix E. Funding Opportunity Announcements and Selections – Examples

This appendix lists examples of Hydrogen Program Funding Opportunity Announcements (FOAs) and selections, October 2022–December 2023.

Funding Selection Announcement Examples

This list comprises examples of funding selections from FOAs that solicited hydrogen and fuel cell projects exclusively. Additional hydrogen and fuel cell projects selected through FOAs with a broader technological focus are not included in this list.

- $7.0 billion to launch seven Regional Clean Hydrogen Hubs (H2Hubs) across the nation and accelerate the commercial-scale deployment of low-cost, clean hydrogen, funded by the Office of Clean Energy Demonstrations (OCED) (October 13, 2023)
- $59.1 million for 22 projects to advance critical technologies for producing, storing, and deploying clean hydrogen, and to establish a new North American university research consortium that will help states and tribal communities implement grid resilience programs and achieve decarbonization goals, funded by the Hydrogen and Fuel Cell Technologies Office (HFTO) (May 22, 2023)
- $47.7 million for 16 projects to lower technology costs, enhance hydrogen infrastructure, and improve the performance of hydrogen fuel cells, funded by HFTO (September 20, 2023)
- $34.0 million for 19 projects to advance cutting-edge technology solutions to make clean hydrogen a more available and affordable fuel for electricity generation, industrial decarbonization, and transportation, funded by the Office of Fossil Energy and Carbon Management (FECM) (August 17, 2023)
- $8.6 million for 43 Phase I Small Business Innovation Research – Small Business Technology Transfer hydrogen and fuel cell projects across 16 states, funded by HFTO (July 26, 2023)
- $1.5 million for 5 projects to advance key clean-hydrogen technologies while growing the skills and knowledge of science and engineering students at Minority Serving Institutions, jointly funded by HFTO through an amendment to a funding opportunity from FECM (November 10, 2022)
- Funding for two (2) industry-led projects aimed at expanding clean hydrogen production with nuclear energy, funded by the Office of Nuclear Energy and HFTO (May 9, 2023)

FY 2023 DOE Hydrogen-Related FOA Examples

The table below comprises examples of recently released FOAs supporting one or more hydrogen and fuel cell topics.

FOA/Lab Call Number	FOA/Lab Call Title	Issuing DOE Office	Funding	Date Released
DE-FOA-0002922	Bipartisan Infrastructure Law: Clean Hydrogen Electrolysis, Manufacturing, and Recycling	EERE HFTO	$750,000,000	March 15, 2023
DE-FOA-0003187	Demand-Side RFP for Independent Entity	OCED	$500,000,000 to $1,000,000,000	September 14, 2023
DE-FOA-0002920	Hydrogen and Fuel Cell Technologies Office FOA in Support of Hydrogen Shot	EERE HFTO	$47,000,000	January 27, 2023
DE-FOA-0002784 (Modification 08)	Exploratory Topics	ARPA-E	$20,000,000	September 7, 2023
DE-FOA-0002400 (Modification 0000010)	Clean Hydrogen Production, Storage, Transport and Utilization to Enable a Net-Zero Carbon Economy	FECM	$19,000,000	September 12, 2023