U.S. Department of Energy
Hydrogen Program

2022 Annual Merit Review and Peer Evaluation Report

June 6–8, 2022

U.S. DEPARTMENT OF ENERGY

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NOTICE

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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 offices: 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 hydrogen activities across other federal and state agencies involved in key hydrogen- and fuel-cell-related activities.

The Fiscal Year (FY) 2022 AMR was held online as a virtual meeting June 6–8, 2022. It focused on a high-level peer review of subprograms within HFTO and included opportunities for reviewers to comment on the Department-wide Program, as well as on interdepartmental collaboration on hydrogen and fuel cells. The full peer review results, shown in Appendix A of this report, consist of comments and scores provided by reviewers in response to presentations on Program and project progress. Summaries of the review comments are also included in the body of report (in the Program Peer Review Summary chapter and in the chapters for each HFTO subprogram). A representative selection of hydrogen and fuel cell programs and projects funded by other DOE offices in the Program were also presented—but not reviewed—at the AMR. All AMR presentations are available to the public in the 2022 AMR Proceedings.[1]

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

The goals of the AMR include the following:

- Review and evaluate FY 2022 accomplishments and outyear plans for HFTO subprograms, including rigorous and systematic tracking of progress against targets and metrics.
- Present an opportunity for stakeholders (hydrogen and fuel cell system developers and manufacturers, component developers, integrators, end users, and others) to provide input to help shape the Program so that it addresses the highest-priority barriers, facilitates technology transfer and market impact, and continually improves its effectiveness in making progress toward national goals.
- Foster interactions among national laboratories, industry, and universities conducting research, development, demonstration, and deployment (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 though 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, and inclusion as well as engagement within the energy and environmental justice community.
- Provide transparency regarding the use and impact of taxpayer funding, including on concrete deliverables such as innovations, patents, commercialized or near-commercial technologies, and enabling activities such as manufacturing, safety, codes and standards, and workforce development.

[1] DOE, "2022 Annual Merit Review Proceedings," energy.gov, https://www.hydrogen.energy.gov/annual-review/annual_review22_proceedings.html.

Organization of the Report

This report is organized as follows:

- The **Introduction** provides a brief overview of the Program, highlights key accomplishments since the previous AMR (held in June 2021), and summarizes activities and accomplishments within each Program office.
- The **Program Peer Review Summary** describes the FY 2022 AMR peer review process and provides a summary of Program-level peer review comments and recommendations.
- The following **HFTO subprogram chapters** provide summaries of key activities and accomplishments since the preceding AMR, summaries of projects presented orally during this year's AMR, and a summary of peer reviewer comments on the subprogram:
  - Hydrogen Technologies
  - Fuel Cell Technologies
  - Technology Acceleration
  - Safety, Codes and Standards
  - Systems Analysis.
- **Appendix A** provides the complete set of review comments received from the AMR program reviewers.
- **Appendix B** provides a complete list of the meeting participants.
- **Appendix C** provides the evaluation criteria used for the reviews.
- **Appendix D** provides a complete list of projects that were presented at the AMR (in both oral and poster format), including those funded by other DOE offices or external stakeholders.
- **Appendix E** provides details on the Program's funding opportunity announcements (FOAs) and project selections since the 2021 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[2] and the Energy Act of 2020.[3] 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 activities, which are determined based on technical, economic, and environmental analyses; stakeholder workshops; requests for information; and merit-reviewed project proposals that may be selected through competitive 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-pollution-free electricity by 2035, and a net-zero-emissions economy by 2050.[4] 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 durability and reliability of hydrogen

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[2] Energy Policy Act of 2005 (EPACT 2005) Public Law 109-58, Title VIII – HYDROGEN, Sections 801 to 816 (42 USC Sections 16151 to 16165), August 5, 2005, as amended by the Infrastructure Investment and Jobs Act, Public Law 117-58 (November 15, 2021).

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

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

technologies, while also enabling scale-up of clean hydrogen production. Progress in these areas is key to jump-starting new markets for clean hydrogen, including heavy-duty transportation applications, decarbonized industrial and chemical processes, and energy storage and power generation.

In FY 2022, Congress appropriated a total of $318.8 million for DOE hydrogen and fuel cell activities (see Table 1 below). This includes $163.4 million for EERE activities and $113 million for FECM activities. Funding for hydrogen and fuel cell activities in NE and SC amounted to $23 million and $17.4 million, respectively, with an additional $2 million in hydrogen-related funding within ARPA-E.

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.[5] 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 2021 (enacted)	FY 2022 (enacted)	FY 2023 (enacted)
Energy Efficiency and Renewable Energy	**$155.9**	**$163.4**	**$216.2**
Hydrogen and Fuel Cell Technologies Office	$150.0	$157.5	$170.0
Vehicle Technologies Office	$0.0	$0.0	$10.0
Advanced Materials and Manufacturing Technologies Office	$5.9	$0.0	$25.0
Solar Energy Technologies Office	$0.0	$5.1	$7.5
Wind Energy Technologies Office	$0.9	$0.0	$1.1
Water Power Technologies Office	$0.0	$0.8	$2.6
Fossil Energy and Carbon Management	**$88.7**	**$113.0**	**$128.0**
Carbon Management Technologies	$87.0	$88.0	$101.0
Resource Sustainability	$1.7	$20.0	$26.0
Energy Asset Transformation	$0.0	$5.0	$1.0
Nuclear Energy	**$23.0**	**$23.0**	**$23.0**
Crosscutting Technology Development	$13.0	$10.0	$12.0
Light Water Reactor Sustainability	$10.0	$13.0	$11.0
Science	**$17.0**	**$17.4**	**$50.3**
Advanced Research Program Agency–Energy	**$34.3**	**$2.0**	**TBD[a]**
TOTAL	**$318.9**	**$318.8**	**$417.5**

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

[5] Infrastructure Investment and Jobs Act, Public Law 117-58, November 15, 2021, https://www.congress.gov/bill/117th-congress/house-bill/3684.

Background: H2@Scale – A Guiding Framework

H2@Scale is a DOE initiative that provides 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 1 below. The main priorities of this vision include:

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

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

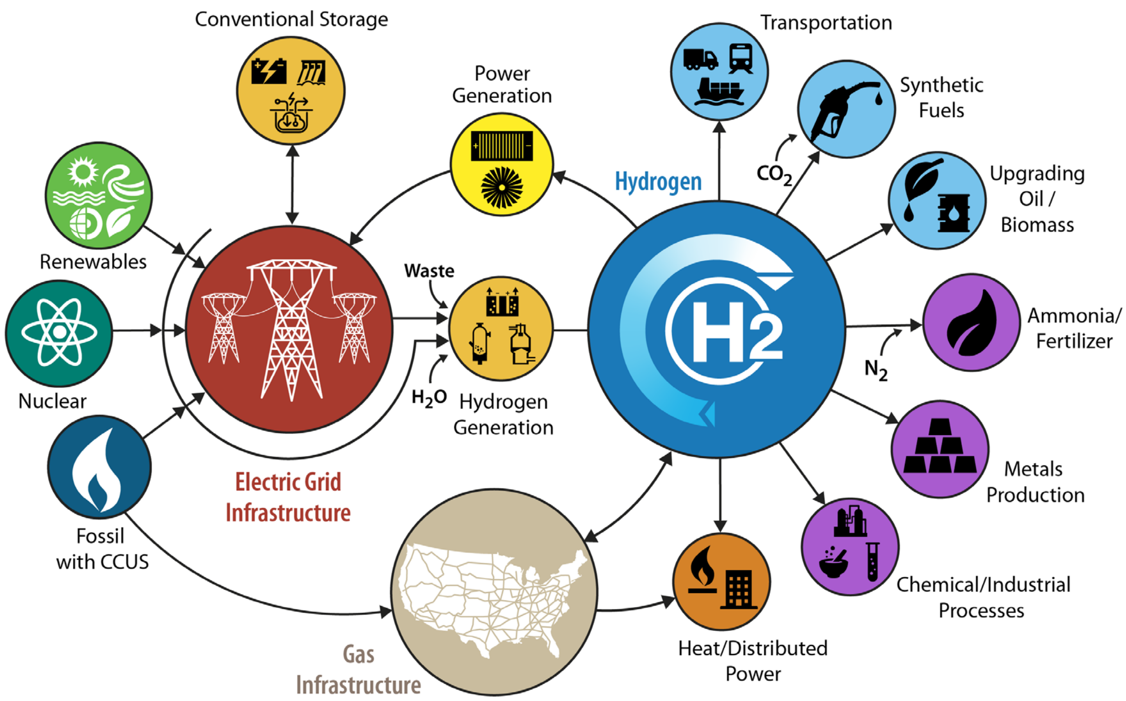

Figure 1. Schematic of H2@Scale

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

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

Program Highlights

Global interest and investment in clean hydrogen technologies continued to grow rapidly in the past year. The Program also has been accelerating its efforts in all areas, as demonstrated by the 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 Program actions in FY 2022.

- **DOE National Clean Hydrogen Strategy and Roadmap:** On September 22, 2022, DOE released the draft *DOE National Clean Hydrogen Strategy and Roadmap* for public comment.[8] The document provides a snapshot of hydrogen production, transport, storage, and use in the United States today. It explores the potential for clean hydrogen to contribute to national goals across multiple sectors, identifying opportunities for expansion of domestic clean hydrogen production to 10 million metric tons (MMT) per year by 2030, 20 MMT/year by 2040, and 50 MMT/year by 2050. Public comments were collected via email through December 1, 2022. Feedback received will be used to finalize the document and develop updates as required by the BIL. The *Strategy and Roadmap* will be finalized in early 2023 and updated at least every three years (as required by the BIL).
- **Regional Clean Hydrogen Hubs:** On September 22, 2022, DOE released a funding opportunity announcement (FOA) for up to $7 billion to establish six to ten regional clean hydrogen hubs (H2Hubs) across America.[9] The FOA, which was developed by OCED in collaboration with HFTO and other Program offices, is one of the largest funding opportunities ever issued by DOE. The H2Hubs will create regional networks of hydrogen producers, consumers, and local connective infrastructure to accelerate the use of hydrogen as a clean energy carrier. To lay the groundwork for development and implementation of this FOA, on February 15, 2022, HFTO issued a Request for Information (RFI) on Regional Clean Hydrogen Hubs Implementation Strategy.[10] Together with the RFI for BIL provisions on Clean Hydrogen Manufacturing, Recycling, and Electrolysis (see below), these RFIs generated more than 5,000 pages of responses. Feedback has also been collected through workshops and listening sessions. HFTO also developed the H2 Matchmaker tool,[11] which will help to realize H2Hubs by identifying potential matches among hydrogen producers, suppliers, users, and other stakeholders (see additional information under "Reports, Program Records, and Tools" below).
- **Electrolysis RD&D and Clean Hydrogen Manufacturing and Recycling RD&D:** To support effective implementation of these BIL provisions, on February 15, 2022, HFTO issued an RFI on Clean Hydrogen Manufacturing, Recycling and Electrolysis.[12] Stakeholder feedback from this RFI, along with information gathered through workshops and listening sessions, is being used to inform development of initial FOAs for these topics.
- **Clean Hydrogen Production Standard:** On September 22, 2022, DOE released the draft guidance for a Clean Hydrogen Production Standard, which was posted for public comment through November 14,

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[8] DOE, *DOE National Clean Hydrogen Strategy and Roadmap* (draft), September 22, 2022, https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf.

[9] DOE, DE-FOA-0002779: Bipartisan Infrastructure Law: Additional Clean Hydrogen Programs (Section 40314): Regional Clean Hydrogen Hubs Funding Opportunity Announcement, 2022 (modified January 2023), https://oced-exchange.energy.gov/Default.aspx#FoaId4dbbd966-7524-4830-b883-450933661811.

[10] DOE, DE-FOA-0002664: Bipartisan Infrastructure Law (BIL) – 2022 Regional Clean Hydrogen Hubs Implementation Strategy RFI, 2022, https://oced-exchange.energy.gov/Default.aspx#FoaIdb2ae7a4e-b071-4e77-9694-dba3c9ab0333.

[11] DOE EERE, H2 Matchmaker, accessed 2023, https://www.energy.gov/eere/fuelcells/h2-matchmaker.

[12] DOE EERE, DE-FOA-0002698: RFI on Clean Hydrogen Manufacturing, Recycling and Electrolysis, February 15, 2022, https://govtribe.com/opportunity/federal-grant-opportunity/bipartisan-infrastructure-law-bil-rfi-on-clean-hydrogen-manufacturing-recycling-and-electrolysis-defoa0002698.

2022.[13] This initial proposal establishes a target of 4.0 $kgCO_2e/kgH_2$ for life cycle (i.e., "well-to-gate") greenhouse emissions associated with hydrogen production.

Hydrogen Shot and Related Developments

Since the launch of the Hydrogen Shot in June 2021, in addition to ramping up Program-wide efforts to meet the aggressive goal of $1 per kilogram of clean hydrogen in one decade, the Program has also implemented a number of actions and initiatives focused on Hydrogen Shot.

- The first **DOE Hydrogen Shot Summit**[14] convened more than 3,000 stakeholders on August 31 and September 1, 2021, to identify concrete actions and innovations needed to achieve the Hydrogen Shot goal and to rally the global community on the urgency of tackling the climate crisis. Key themes that emerged during the summit included the need to collaborate across all sectors, to leverage clean hydrogen to lift up communities in need, and to identify opportunities for scale as a way to bring down costs. The Summit breakout sessions focused on specific technical areas, including electrolysis, thermal conversion with carbon capture, and advanced hydrogen production pathways. Breakout session discusssions included diverse representation from stakeholders representing industry, research, national laboratories, tribal nation leaders, members of the environmental justice community, government agencies, international organizations, and non-governmental agencies. Feedback and insights from breakout session discussions are being used to help guide Program activities.
- The **Hydrogen Shot Fellowship**[15] was launched during the Hydrogen Shot Summit to recruit diverse talent who can contribute to making Hydrogen Shot a reality. Funded through HFTO, Hydrogen Shot fellows engage in related work from one or more HFTO technical programs, including Hydrogen Technologies, Fuel Cell Technologies, Technology Acceleration, and Systems Analysis, as well as other functional areas including communications, workforce development, and stakeholder engagement and inclusion.
- The **Hydrogen Shot Incubator Prize**[16] is a $2.6 million competition to foster innovative concepts for producing clean hydrogen (see "Funding, Prizes, and Loans" below).

Funding, Prizes, and Loans

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.

- **Hydrogen-related FOAs and project selections:** Since the preceding AMR, DOE announced more than $350 million in FOAs (not including the $6 billion–$7 billion announced by OCED for the demonstration and deployment of regional clean hydrogen hubs) and more than $230 million in project selections for hydrogen-related RDD&D funded by offices across DOE: HFTO, FECM, NE, SC, ARPA-E, the Vehicle Technologies Office, the Advanced Manufacturing and Materials Technologies and Industrial Efficiency & Decarbonization Offices (formerly the Advanced Manufacturing Office), and the Solar Energy Technologies Office. See Appendix E for more details on these FOAs and project selections.
- **Loan Guarantees:** On June 8, 2022, LPO issued a $504.4 million loan guarantee to finance Advanced Clean Energy Storage, a facility capable of providing long-duration seasonal energy storage.[17] Located in Delta, Utah, it will be the nation's largest hydrogen production and storage facility—combining 220 MW of alkaline electrolysis with two 4.5-million-barrel salt caverns to store clean hydrogen. On December 23, 2021, LPO offered a conditional commitment to guarantee a loan of up to $1.04 billion to Monolith Nebraska, LLC, to establish the first-ever commercial-scale deployment of methane pyrolysis technology,

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[13] DOE, U.S. Department of Energy Clean Hydrogen Production Standard (CHPS) Draft Guidance, September 22, 2022, https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-production-standard.pdf.

[14] DOE EERE, "Hydrogen Shot Summit," accessed 2023, https://www.energy.gov/eere/fuelcells/hydrogen-shot-summit.

[15] HFTO, "DOE Launches the Hydrogen Shot Fellowship," August 31, 2021, https://www.energy.gov/eere/fuelcells/articles/doe-launches-hydrogen-shot-fellowship.

[16] DOE EERE, "U.S. Department of Energy Announces Hydrogen Shot Incubator Prize," June 6, 2022, https://www.energy.gov/eere/articles/us-department-energy-announces-hydrogen-shot-incubator-prize.

[17] DOE, "DOE Announces First Loan Guarantee for a Clean Energy Project in Nearly a Decade," June 8, 2022, https://www.energy.gov/articles/doe-announces-first-loan-guarantee-clean-energy-project-nearly-decade.

which will convert natural gas into carbon black and hydrogen.[18] Carbon black can be used in manufacturing tires and other rubber products, and the hydrogen produced by this facility will be used in the decarbonized production of ammonia fertilizer.

- **Prize Competitions:** On October 5, 2021, HFTO launched the first ever Hydrogen Business Case Prize Competition, which challenges teams to develop user-friendly analysis tools to identify regional business cases where clean hydrogen can add value to specific sectors and technology applications.[19] Prize awards include internships at industry, nonprofit, and national laboratory locations. Cash awards and sponsored travel were also provided to winners of the competition,[20] who gave presentations at the 2022 AMR. During the 2022 AMR, HFTO launched the Hydrogen Shot Incubator Prize, a $2.6 million competition to foster innovative concepts for producing clean hydrogen.[21] Nine phase-1 winners were announced on October 11, 2022.[22] Winners of the next phase 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.

Reports, Program Records, and Tools

- **Reports:** In February 2022, EERE released seven deep-dive assessments of clean energy manufacturing supply chains, including several relevant to hydrogen and fuel cell technologies.[23] Each assessment focuses on a different technology or resource that will aid in achieving the Biden Administration's goal of net-zero carbon emissions by 2050. HFTO contributed to the Water Electrolyzers and Fuel Cells Supply Chain Deep Dive Assessment, identifying key considerations that will help to meet the future demand for hydrogen production.[24] In April 2022, SC released the report of the Basic Energy Sciences Roundtable: Foundational Science for Carbon-Neutral Hydrogen Technologies**,** a virtual roundtable held in August 2021.[25] The event was hosted by the Office of Basic Energy Sciences within SC, in coordination with EERE, FECM, and NE. The roundtable addressed barriers for carbon-neutral hydrogen production, storage, transport, utilization, and conversion, and participants identified priority research opportunities to address associated scientific and technical challenges.
- **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 2021 AMR, including Life Cycle Greenhouse Gas Emissions for Small Sport Utility Vehicles,[26] Hydrogen Production Potential from Nuclear Power,[27] Electrolyzer

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[18] LPO, "Open For Business: LPO Issues New Conditional Commitment for Loan Guarantee," December 23, 2021, https://www.energy.gov/lpo/articles/open-business-lpo-issues-new-conditional-commitment-loan-guarantee.

[19] DOE American Made, "Hydrogen Business Case Prize," accessed 2022, https://americanmadechallenges.org/challenges/h2businesscase/index.html.

[20] DOE American Made, "Congratulations Hydrogen Business Case Prize Winners!" accessed 2022, https://www.herox.com/h2businesscase/update/4792.

[21] DOE American Made, "H-Prize: Hydrogen Shot Incubator," accessed 2022, https://americanmadechallenges.org/challenges/hydrogen-shot/.

[22] HFTO, "U.S. Department of Energy Announces Winners of the First Phase of the Hydrogen Shot Incubator Prize," October 11, 2022, https://www.energy.gov/eere/fuelcells/articles/us-department-energy-announces-winners-first-phase-hydrogen-shot-incubator.

[23] DOE EERE, "U.S. Department of Energy Issues Comprehensive Plan to Strengthen America's Clean Energy Supply Chains and Bolster Domestic Manufacturing," February 24, 2022, https://www.energy.gov/eere/articles/us-department-energy-issues-comprehensive-plan-strengthen-americas-clean-energy.

[24] DOE, Water Electrolyzers and Fuel Cells Supply Chain: Supply Chain Deep Dive Assessment, Response to Executive Order 14017, "America's Supply Chains," February 24, 2022, https://www.energy.gov/sites/default/files/2022-02/Fuel%20Cells%20%26%20Electrolyzers%20Supply%20Chain%20Report%20-%20Final.pdf.

[25] SC, Basic Energy Sciences Roundtable: Foundational Science for Carbon-Neutral Hydrogen Technologies, August 8, 2021, https://www.osti.gov/biblio/1834317/.

[26] Offices of Vehicle Technologies, Hydrogen and Fuel Cell Technologies, and Bioenergy Technologies, "Life Cycle Greenhouse Gas Emissions for Small Sport Utility Vehicles," Program Record #21003, September 8, 2021, https://www.hydrogen.energy.gov/pdfs/21003-life-cycle-ghg-emissions-small-suvs.pdf.

[27] DOE Hydrogen Program, "Hydrogen Production Potential from Nuclear Power," Program Record #20003, September 1, 2020, https://www.hydrogen.energy.gov/pdfs/20003-h2-production-potential-nuclear-power.pdf.

Capacity Installations in the United States,[28] and Increased Design Life for High-Pressure Stationary Hydrogen Storage Vessels through Development of Empirically Based Design Curves.[29] The complete list of Program Records (published since 2005) is available on the Program website.[30]

- **Tools:** On December 9, 2021, HFTO introduced the H2 Matchmaker tool, which was later released for public use in January 2022.[31] This tool is designed to help hydrogen producers, suppliers, users, and other stakeholders identify opportunities for partnering on hydrogen projects to grow the hydrogen ecosystem and create regional hydrogen hubs. H2 Matchmaker allows users to self-identify so they can reach out to other stakeholders in their region, aligning potential hydrogen needs in a specific geographic area within the United States.

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 the BIL provisions. Below are examples of the many workshops HFTO hosted in 2021–2022 (most of which were virtual or hybrid because of health and safety concerns):

- Mission Innovation Off-Road Equipment and Vehicles Workshop
- H2-PACE: Power and Control Electronics for Hydrogen Technologies Experts Meeting
- Advanced Liquid Alkaline Electrolysis Experts Meeting
- Bulk Storage of Gaseous Hydrogen Workshop
- Liquid Hydrogen Technologies Workshop
- High-Temperature Electrolysis Manufacturing Workshop
- H2-AMP: Advanced Materials for Proton Exchange Membrane Electrolyzers Workshop
- Manufacturing Automation and Recycling for Clean Hydrogen Technologies Experts Meeting.

A complete list of all workshops held by HFTO, including links to the proceedings of each workshop, can be found on the HFTO website.[32]

Interagency Collaboration

The Hydrogen and Fuel Cells Interagency Working Group (IWG), coordinated by HFTO, continued to convene federal agencies to share information on their hydrogen-related RDD&D programs, perform gap analyses, and collaborate on joint projects. During monthly meetings, IWG member agencies provide updates on their hydrogen and fuel cell programs and identify opportunities for collaboration. Participating agencies currently include DOE, the U.S. Environmental Protection Agency, the National Science Foundation, the U.S. Postal Service, NASA, and the U.S. Departments of Agriculture, Commerce, Defense, Transportation, Homeland Security, and the Interior. Examples of recent and ongoing collaborative IWG activities include:

- Updating the national standards for hydrogen metering (DOE, Commerce – National Institute of Standards and Technology)
- Deploying fuel cell lift trucks and related hydrogen infrastructure (DOE, U.S. Postal Service)
- Supporting fuel cell vehicle and hydrogen demonstration projects in Hawaii (DOE, Defense – U.S. Air Force, Interior – National Park Service)

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[28] DOE Hydrogen Program, "PEM Electrolyzer Capacity Installations in the United States," Program Record #22001, May 16, 2022, https://www.hydrogen.energy.gov/pdfs/22001-electrolyzers-installed-in-united-states.pdf.

[29] DOE Hydrogen Program, "Increased Design Life for High-Pressure Stationary Hydrogen Storage Vessels through Development of Empirically Based Design Curves," Program Record #21004, May 5, 2021, https://www.hydrogen.energy.gov/pdfs/21004-increased-life-pressure-vessel-tanks.pdf.

[30] DOE Hydrogen Program, "Program Records," accessed 2023, https://www.hydrogen.energy.gov/program_records.html.

[31] DOE EERE, H2 Matchmaker, accessed 2023, https://www.energy.gov/eere/fuelcells/h2-matchmaker.

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

- Developing a hydrogen energy system as a grid frequency management tool (DOE, Defense – U.S. Navy)
- Demonstrating a fuel cell system for shore power at the Scripps Institution of Oceanography (DOE, Interior – National Oceanic and Atmospheric Administration, Transportation – Maritime Administration)
- Evaluating a fuel cell train refueling concept (DOE, Transportation)
- Developing and demonstrating a fuel-cell–battery-powered hybrid emergency relief truck (DOE, Defense – U.S. Army Corps of Engineers, Defense – Army Ground Vehicle Power and Mobility, Defense – Naval Research Laboratory, Homeland Security – Science and Technology Directorate, Homeland Security – Federal Emergency Management Agency).

Other focus areas include hydrogen infrastructure (pipelines, buses, rail, marine, aviation), microgrids and resilience, cryogenic hydrogen systems, metering, diagnostics, emissions analyses, a clean hydrogen production standard, and supply chain considerations.

DOE is also collaborating with other agencies on a variety of hydrogen-related policy and regulatory considerations:

- U.S. Environmental Protection Agency: clean hydrogen standard
- U.S. Department of the Treasury: tax credits
- U.S. Department of Transportation: infrastructure, codes and standards.

International Collaboration

HFTO leads the Program in continuing to engage with hydrogen and fuel cell efforts around the world through a range of global multilateral partnerships. A key priority is to create and sustain a coordinated framework for international engagement that will accelerate technical and market progress; the approach is to leverage complementary activities and identify gaps while avoiding duplication of efforts. The Program has taken a leadership role in this area by co-chairing the **Hydrogen Breakthrough** (along with counterparts from the United Kingdom). The Hydrogen Breakthrough, one of the initiatives of the Breakthrough Agenda,[33] 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." One of the priority actions of the Hydrogen Breakthrough is to improve coordination and transparency across the landscape of international hydrogen initiatives.

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; 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; the Center for Hydrogen Safety; and others.

Recent international activities include:

- **Global Clean Energy Action Forum (GCEAF):** On September 22, 2022, Secretary of Energy Jennifer M. Granholm gave the opening public remarks at GCEAF. She announced both the FOA for the Regional Clean Hydrogen Hubs and the release of the draft *DOE National Clean Hydrogen Strategy and Roadmap*. In partnership with the DOE Office of International Affairs, HFTO convened a GCEAF Hydrogen Roundtable comprising leaders from ten government agencies, spanning five continents, and nine executives from organizations with significant international interests in the hydrogen industry. Secretary Granholm chaired the roundtable, and participants identified several priority areas for actions that will increase supply and demand (including demand certainty) for clean hydrogen. Participants also came to a general consensus to support a call to action: *within the next 12 to 24 months, identify or expand national targets that accelerate the growth of the clean hydrogen market.* HFTO also worked with multiple international partners to help organize 11 high-level side events focused on hydrogen.
- **Hydrogen Breakthrough Priority Actions:** In September and October 2022, the Program helped coordinate input and reach consensus among major international partnerships on five priority actions for the Hydrogen

[33] The Breakthrough Agenda (https://racetozero.unfccc.int/system/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.

Breakthrough for 2023.[34] These actions, which emerged from recommendations in the 2022 Breakthrough Agenda Report,[35] were endorsed by several nations and officially launched at COP27 in November 2022.

- **H2 Twin Cities:** In November 2021, the Program, in collaboration with Clean Energy Ministerial members, announced the launch of the H2 Twin Cities[36] program during the COP26[37] Climate Summit. H2 Twin Cities is a global initiative that connects cities and communities around the world to deploy clean hydrogen solutions. The result is self-assembled, international community partnerships that share ideas, mentor and learn from one another, build communities of hydrogen best practices, and strengthen global commitment to environmental justice, social equity, and clean energy jobs, particularly at the city level. Secretary Granholm announced the 2022 winners[38] as part of COP27 activities in Sharm el-Sheikh, Egypt.
- **International Greenhouse Gas Emissions Methodology:** With participation by Program staff, the IPHE's Hydrogen Production Analysis (H2PA) working group developed a mutually agreed upon methodology for determining the greenhouse gas emissions and other pollutants associated with the production of hydrogen.[39] Application of this methodology is expected to facilitate market valuation and international trade in clean hydrogen.
- **Mission Innovation Off-Road Equipment and Vehicles Virtual Workshop:**[40] On September 22–24, 2021, HFTO co-hosted this workshop—in collaboration with international partners—with the goal of sharing information on the status of hydrogen and fuel cell technologies in heavy-duty off-road equipment and vehicle applications in agriculture, construction, and mining.
- **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.[41] The Summit convened representatives from government, industry, and a wide range of stakeholder groups from across the America to identify opportunities to advance the growth of clean hydrogen markets and industry in the Americas.

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

The Program continued its efforts to improve diversity, equity, inclusion, and accessibility (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 2021 AMR included the following:

- **Funding for minority-serving institutions:** In November 2022, HFTO awarded $1.5 million to five projects at three different minority-serving institutions 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 at these establishments. A key goal of these projects is to give participating students direct exposure to cutting-edge research, which includes engagement with DOE national laboratory researchers while supporting their work.

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[34] "Hydrogen Breakthrough: Priority International Actions for 2023," 2022, https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fclimatechampions.unfccc.int%2Fwp-content%2Fuploads%2F2022%2F11%2FHydrogen-Breakthrough-Priority-International-Actions-for-2023-final1.docx&wdOrigin=BROWSELINK.

[35] International Energy Agency, *2022 Breakthrough Agenda Report*, September 2022, https://www.iea.org/reports/breakthrough-agenda-report-2022.

[36] DOE EERE, "H2 Twin Cities," accessed 2023, https://www.energy.gov/eere/h2twincities/h2-twin-cities.

[37] COP26 was the 26th United Nations Climate Change Conference of the Parties.

[38] DOE EERE, "H2 Twin Cities 2022 Winners," accessed 2023, https://www.energy.gov/eere/h2twincities/h2-twin-cities-2022-winners.

[39] IPHE, "Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen," Release of the IPHE Working Paper Version 1, October 2021, https://www.iphe.net/iphe-working-paper-methodology-doc-oct-2021.

[40] HFTO, "Mission Innovation Hydrogen Fuel Cell Off-Road Equipment and Vehicles Virtual Workshop," accessed 2023, https://www.energy.gov/eere/fuelcells/mission-innovation-hydrogen-fuel-cell-road-equipment-and-vehicles-virtual-workshop.

[41] Hydrogen Americas 2023 Summit & Exhibition, Washington, DC, October 2–3, 2023, https://www.hydrogen-americas-summit.com/.

- **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 winners of this award during the 2022 AMR.[42] The current round of this award is in progress and will be announced at the 2023 AMR.
- **Webinars:** HFTO conducts a free monthly webinar series, covering a variety of hydrogen-related topics.[43] In the past year, the following webinars were specifically focused on DEIA, environmental justice, or workforce development topics:
  - Overview of DOE Requests for Information Supporting Hydrogen BIL Provisions, and Environmental Justice Priorities[44]
  - Exploring Hydrogen and Fuel Cell Projects in Disadvantaged Communities[45]
  - Workforce Development in Hydrogen and Fuel Cells.[46]

Office Overviews and Updates

Hydrogen and Fuel Cell Technologies Office

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, from research and development to demonstration and deployment.

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

- Conduct RD&D to advance technologies for the production, delivery, and storage of clean hydrogen.
- Conduct RD&D to advance fuel cell technologies for multiple applications.
- 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.

HFTO's RDD&D activities are organized into the following subprogram and activity areas in this report: Hydrogen Technologies; Fuel Cell Technologies; Technology Acceleration; Safety, Codes and Standards; and Systems Analysis. Overviews of the subprograms are provided below, and highlights of key HFTO RDD&D accomplishments and progress are shown in Table 2. More detailed information on the subprograms is provided in their respective chapters.

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[42] HFTO, "Hydrogen and Fuel Cell Technologies Office Postdoctoral Recognition Award: 2022," 2022, https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-postdoctoral-recognition-award-2022.

[43] HFTO, "Hydrogen and Fuel Cell Technologies Office Webinars," accessed 2023, https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-webinars.

[44] HFTO, H2IQ Hour: Overview of DOE Requests for Information Supporting Hydrogen BIL Provisions, and Environmental Justice Priorities, February 24, 2022, https://www.energy.gov/eere/fuelcells/2022-hydrogen-and-fuel-cell-technologies-office-webinar-archives#02242022.

[45] HFTO, H2IQ Hour: Exploring Hydrogen and Fuel Cell Projects in Disadvantaged Communities, August 31, 2022, https://www.energy.gov/eere/fuelcells/2022-hydrogen-and-fuel-cell-technologies-office-webinar-archives#date08312022.

[46] HFTO, October H2IQ Hour: Workforce Development in Hydrogen and Fuel Cells, October 6, 2022, https://www.energy.gov/eere/fuelcells/2022-hydrogen-and-fuel-cell-technologies-office-webinar-archives#10062022.

Hydrogen Technologies

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

- **Hydrogen Production** addresses low-cost, highly efficient, clean hydrogen production technologies that use diverse sustainable domestic sources of energy and feedstocks. RD&D activities include advanced water-splitting technologies leveraging clean energy sources (solar, wind, nuclear, etc.) and innovative concepts such as biological hydrogen production from biomass or waste streams. The work on water-splitting technologies is coordinated predominantly through the HydroGEN Advanced Water Splitting Materials consortium (HydroGEN) and the Hydrogen from Next-generation Electrolyzers of Water consortium (H2NEW) to accelerate RD&D of advanced water-splitting technologies for clean, sustainable hydrogen production.
- **Hydrogen Infrastructure** addresses efficient and rugged low-cost options for moving hydrogen from the point of production to the point of use. RD&D activities investigate liquefaction, pipelines, chemical carriers, and tube trailers to transport hydrogen over long distances, as well as compressors, pumps, dispensers, and auxiliary components to support the development of hydrogen stations serving medium- and heavy-duty fuel cell electric vehicles. The Hydrogen Materials Compatibility Consortium (H-Mat) coordinates RD&D on accelerated test methods and novel, low-cost, durable metals and polymers for use in hydrogen infrastructure. The HyBlend effort 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 and development of breakthrough hydrogen storage materials.

Fuel Cell Technologies

The Fuel Cell Technologies subprogram conducts innovative RD&D to advance key technologies to enable a diverse portfolio of low-cost, durable, and efficient fuel cells that are competitive with incumbent and emerging technologies across applications.

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

The subprogram also strategically addresses crosscutting challenges for fuel cell development, with a focus on:

- Materials and components, especially low-platinum-group-metal (low-PGM) and PGM-free catalysts and electrodes
- Systems integration, including stacks, system design, and balance-of-plant components
- Analysis and modeling.

Technology Acceleration

The Technology Acceleration subprogram[47] aims to enable the H2@Scale vision and support the Hydrogen Energy Earthshot through targeted hydrogen and fuel cell system integration and demonstration activities.

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[47] In the congressional budget request, the Technology Acceleration subprogram is referred to as Systems Development and Integration.

The subprogram:

- Identifies hydrogen applications and system configurations that can provide more affordable and reliable clean energy.
- Validates and tests integrated energy systems.
- Bridges the gaps between component-level RD&D and commercialization by integrating technologies into functional systems, reducing costs, and overcoming barriers to deployment.

The subprogram is currently focused on three technology application areas: grid energy storage and power generation, chemical and industrial processes, and transportation, including medium- and heavy-duty vehicles.

To support market growth and deployment of clean hydrogen technologies, the subprogram also conducts activities to develop lower-cost, scalable manufacturing processes and technologies; support the growth of supply chains; and facilitate the evolution of a skilled domestic workforce.

Safety, Codes and Standards

The Safety, Codes and Standards (SCS) activity area, as part of the Technology Acceleration portfolio, supports RD&D to improve the fundamental understanding of the physics related to hydrogen safety and to provide the critical safety data and information needed to develop and revise technically sound and defensible codes and standards. These codes and standards will 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 used to define requirements.
- Conducting the underlying scientific research to close knowledge gaps in codes and standards in a timely manner.
- Identifying and promoting best safety practices, including developing and disseminating information resources.

Systems Analysis

The Systems Analysis subprogram conducts crosscutting analyses in collaboration with other HFTO subprograms, DOE offices, and external stakeholders to inform RDD&D priorities. These analyses help to identify technology pathways that can enable 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 uses a diverse portfolio of both focused and integrated models and tools that characterize technology costs, performance, impacts, and cross-sector market potential. These tools and capabilities are continuously updated and enhanced, while new tools are also developed as needed. The subprogram's current focus areas are:

- **Scenario analysis of hydrogen demand and its impacts**, which includes examining demand scenarios in key sectors to enable a net-zero greenhouse gas emissions economy by 2050, updating market and sustainability models across EERE offices, and collaborating with other EERE offices to assess the potential role of hydrogen in the trucking sector.
- **Techno-economic and life cycle analysis**, which includes detailed assessments of the environmental impacts and economics of various clean hydrogen production, delivery, storage, and use pathways; harmonization of DOE analysis with the international community; and climate impact assessments of hydrogen releases.
- **Tool development, updates, and support** activities, which provide and sustain useful tools to the hydrogen community and other stakeholders. These activities include development and updating of the user-friendly Hydrogen Analysis (H2A) tool for cost analysis and the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) tool for emissions analysis, as well as globalization of the GREET life cycle analysis platform.

Table 2. Selected Examples of HFTO RDD&D Progress and Accomplishments since the 2021 AMR

Hydrogen Technologies

Hydrogen Production

- ✓ Developed thin (50 µm) polymer electrolyte membrane (PEM) with an integrated gas recombination layer specific for electrolyzer technology that is compatible with roll-to-roll fabrication processes.
- ✓ Made important advances in the understanding of iridium dissolution, using a combination of experimental, modeling, and analysis techniques, through the H2NEW consortium. (Iridium dissolution significantly affects the cost and degradation of PEM electrolyzers.)
- ✓ Demonstrated 20% solar-to-hydrogen conversion efficiency in a hydrophobic perovskite photoelectrochemical cell with a platinum–graphite barrier lifetime of 100 hours.
- ✓ Used computational modeling to guide selection of promising high-entropy perovskite oxides for solar thermochemical hydrogen production; synthesized and characterized over 150 compositions and demonstrated production of >400 µmol H_2/g perovskite.
- ✓ Hosted workshops on liquid alkaline electrolyzers, advanced materials for PEM electrolyzers, and high-temperature electrolyzer manufacturing in collaboration with the National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory.
- ✓ Demonstrated 90% Faradaic efficiency for a proton-conducting solid oxide electrolyzer cell operating at commercially relevant conditions (1.0 A/cm^2, 600°C, 70% steam), with stable operation over 5,000 hours.

Hydrogen Storage

- ✓ Hosted multiple workshops, including two focusing on liquid hydrogen storage, in collaboration with NASA, and one on bulk gaseous hydrogen storage, in collaboration with FECM.
- ✓ Developed several design concepts for the world's largest liquid hydrogen storage tank and down-selected to two concepts for detailed evaluation.
- ✓ Demonstrated high-pressure hydrogen release from hydrogen carriers—formic acid and formic acid–methanol blends—with capacities as high as 5.3 wt.% and good catalyst stability.
- ✓ Achieved a 75% increase in volumetric capacity (due to a significant increase in packing density) for a porous cage–metal-organic framework (MOF) composite compared to the MOF alone, without sacrificing adsorption behavior.
- ✓ Demonstrated a PEM fuel cell membrane electrode assembly (MEA) with a 40 wt.% Pt/Mn-N-C catalyst that meets end-of-life performance and durability targets after a 150,000-cycle accelerated stress test (AST) under heavy-duty vehicle conditions.

Hydrogen Infrastructure

- ✓ Completed commissioning of a high-flow hydrogen fueling system at the NREL Energy Systems Integration Facility; executed a test, representative of fueling a heavy-duty vehicle, that achieved a 76 kg fill in under six minutes. (This test had an average flow rate of nearly 13 kg per minute and a peak rate of over 23 kg per minute.)
- ✓ Initiated validation efforts for the publicly accessible Hydrogen Filling Simulation (H2FillS) model with high-flow test data up to approximately 80 MPa. The model allows users to simulate the impact of varying fueling methods on the thermodynamics of fueling equipment and onboard hydrogen storage.
- ✓ Demonstrated accelerated techniques to characterize the life of materials in hydrogen twice as fast as traditional approaches.
- ✓ Demonstrated high-throughput techniques to test thin-film metals in hydrogen.
- ✓ Completed a technical report summarizing ASME and National Fire Protection Association (NFPA) codes and standards relevant to hydrogen blending in pipelines.

Fuel Cell Technologies

- ✓ Developed intermetallic platinum–cobalt and platinum–nickel catalysts that outperformed the baseline commercial catalyst for heavy-duty fuel cells by >25% at beginning of life and by >45% after a 90,000-cycle AST.
- ✓ Demonstrated a novel ionomer that has 2× the oxygen permeability of the conventional ionomer, improves catalyst mass activity by 60%, and lowers local O_2 transport resistance by 50%.
- ✓ Demonstrated membranes with immobilized radical scavengers (heteropoly acid; dispersed cerium zirconium oxide nanofibers). The membranes are not prone to failure due to migration and have enhanced durability compared with membranes with no additives.
- ✓ Developed fuel cell ASTs that are representative of the high durability requirements for heavy-duty vehicle operation and account for degradation of catalysts, catalyst supports, and membranes.
- ✓ Improved the performance of PGM-free cathode catalysts in a hydrogen–air fuel cell by 25% over the FY 2021 baseline, as validated using ElectroCat-developed test protocols.
- ✓ Reduced PGM loadings to 0.2 mg PGM/cm^2 for anion exchange membrane fuel cells while maintaining performance (100 mW/cm^2 at 0.8 V with back pressure under 250 kPa in H_2–air scrubbed to 2 ppm CO_2).
- ✓ Developed a new fuel cell catalyst support, based on doped carbon with optimized "accessible" pore structure and tuned hydrophobicity, meeting the DOE end-of-life target (1.07 A/cm^2 @ 0.7V) after heavy-duty AST while also achieving target power performance of >1 W/cm^2.

Table 2 (cont.)

Technology Acceleration

- ✓ In collaboration with OCED, completed numerous tasks to enable release of the Regional Clean Hydrogen Hub FOA, including stakeholder engagement, public webinars, and release of the request for information and notice of intent.
- ✓ Awarded three SuperTruck III projects (Daimler, General Motors, and Ford), which will demonstrate a total of 11 medium-/heavy-duty hydrogen fuel cell trucks with driving ranges, payloads, and fueling times competitive with incumbent technologies.
- ✓ Awarded six new H2@Scale Cooperative Research and Development Agreement projects to support the NREL Advanced Research on Integrated Energy Systems (ARIES) facility, including integrated hydrogen energy system testing and validation as well as risk mitigation and sensor testing.
- ✓ Completed over 7,000 cumulative hours of high-temperature electrolyzer system testing at Idaho National Laboratory (INL) and commissioned a simulated test of a high-temperature electrolysis test facility with a nuclear power plant.
- ✓ Completed the procurement and design for a 1.25 MW electrolyzer installation at the Nine Mile Point nuclear power plant.
- ✓ Completed conversion of ten United Parcel Service (UPS) vans into fuel cell hybrid electric delivery vans, which are entering into service in disadvantaged communities in California to reduce local air pollution.
- ✓ Supported the launch of the Mission Innovation global initiative, including the Clean Hydrogen Mission (held a workshop and established the International Off-Road Working Group for hydrogen and fuel cell vehicles) and the Zero-Emission Shipping Mission.

Safety, Codes and Standards

- ✓ Utilized bulk cryogenic hydrogen behavior validation data to enable a 40% reduction in the footprint of hydrogen stations, based on NFPA 2.
- ✓ Performed safety, codes and standards gap assessments for large-scale hydrogen applications, including bulk storage and rail.
- ✓ Along with the European Commission, hosted the Clean Hydrogen JU (Joint Undertaking) Expert Workshop on Environmental Impacts of Hydrogen to identify technical needs and next steps for monitoring and mitigating hydrogen releases into the atmosphere.

Systems Analysis

- ✓ Developed a user-friendly version of GREET to enable life cycle analysis of user-defined systems.
- ✓ Developed the H2A Lite tool to provide an easy-to-use tool to characterize the cost of hydrogen production with user-defined technology and electricity costs.
- ✓ Collaborated within the IPHE Hydrogen Production Analysis (H2PA) task force on the release of draft guidance regarding mutually agreed-upon methods of life cycle analysis of hydrogen production.
- ✓ Launched the Hydrogen Business Case Prize competition and selected four winning university teams.

Workforce Development and Diversity, Equity, and Inclusion

- ✓ Held six listening sessions with environmental justice and tribal stakeholders on hydrogen provisions in the BIL.
- ✓ Awarded $1.5 million in funding for minority-serving institutions to advance clean hydrogen technologies while growing the skills and knowledge of students from historically underrepresented communities.
- ✓ Launched five professional workforce development courses, covering basic hydrogen science as well as production, storage, end use, and safety, through the Hydrogen Education for a Decarbonized Global Economy (H2EDGE) initiative; expanded H2EDGE to include partners from historically black colleges and universities. H2EDGE collaborates with universities to develop and train a workforce for the emerging hydrogen technology industry and its end-use applications.
- ✓ Held three H2IQ (HFTO educational resources) hours focusing on environmental justice, energy equity, and workforce development topics.
- ✓ Included a feature in the H2 Matchmaker tool allowing users to identify as (or screen for) communities or groups that are relevant to the Justice 40 Initiative's intent to increase benefits and reduce harm in disadvantaged communities.

Office of Clean Energy Demonstrations

OCED was established in December 2021 as part of the BIL to accelerate clean energy technologies from the lab to market and fill a critical innovation gap on the path to achieving our nation's climate goals of net-zero emissions by 2050. The OCED mission is to deliver clean energy demonstration projects at scale in partnership with the private sector to accelerate deployment, market adoption, and the equitable transition to a decarbonized energy system.

The OCED portfolio includes demonstrations of clean hydrogen, carbon management, advanced nuclear reactors, long-duration energy storage, industrial decarbonization, and demonstrations in rural areas and on current and former mine land, with BIL appropriations as follows:

- Advanced Reactor Demonstration Projects ($2.5 billion)[48]
- Carbon Capture Large-Scale Pilot Projects ($937 million)[49]
- Carbon Capture Demonstration Projects Program ($2.5 billion)[50]
- Clean Energy Demonstration Program on Current and Former Mine Land ($500 million)[51]
- Energy Improvements in Rural or Remote Areas ($1 billion)[52]
- Industrial Demonstrations Program ($6.3 billion)[53]
- Long-Duration Energy Storage Demonstrations ($505 million)[54]
- Regional Clean Hydrogen Hubs ($8 billion)[55]
- Regional Direct Air Capture Hubs ($3.5 billion).[56]

Office of Fossil Energy and Carbon Management

In FY 2022, FECM hydrogen-focused funding was $113.5 million. The Office's hydrogen focus areas were:

- Low-cost, carbon-neutral hydrogen production and utilization technologies—including turbines, gasification, reforming/pyrolysis, solid oxide fuel cells, and point source carbon capture
- Low-cost, reliable, and safe options for bulk hydrogen transport (pipelines) and sub-surface storage.

Key activities and accomplishments through September 2022 included the following:

- Applied hydrogen combustion fundamentals, pilot testing, and analysis tools to enable low-nitrogen-oxide hydrogen combustor designs and zero-carbon, dispatchable power generation.

48 OCED, "Advanced Reactor Demonstration Projects," accessed 2023, https://www.energy.gov/oced/advanced-reactor-demonstration-projects.

49 OCED, "Carbon Capture Large-Scale Pilot Programs," accessed 2023, https://www.energy.gov/oced/carbon-capture-large-scale-pilot-programs.

50 OCED, "Carbon Capture Demonstration Projects Program," accessed 2023, https://www.energy.gov/oced/carbon-capture-demonstration-projects-program.

51 OCED, "Clean Energy Demonstration Program on Current and Former Mine Land," accessed 2023, https://www.energy.gov/oced/clean-energy-demonstration-program-current-and-former-mine-land.

52 OCED, "Energy Improvements in Rural or Remote Areas," accessed 2023, https://www.energy.gov/oced/energy-improvements-rural-or-remote-areas-0.

53 OCED, "Industrial Demonstrations Program," accessed 2023, https://www.energy.gov/oced/industrial-demonstrations-program.

54 OCED, "Long-Duration Energy Storage Demonstrations," accessed 2023, https://www.energy.gov/oced/long-duration-energy-storage-demonstrations.

55 OCED, "Regional Clean Hydrogen Hubs," accessed 2023, https://www.energy.gov/oced/regional-clean-hydrogen-hubs.

56 OCED, "Regional Direct Air Capture Hubs," accessed 2023, https://www.energy.gov/oced/regional-direct-air-capture-hubs.

- Conducted successful commercial demonstration of the world's largest clean hydrogen facility (in Port Arthur, Texas), which is based on steam methane reforming with carbon capture and utilization and has been in operation for seven years.
- Developed ceramic matrix composite materials to increase the temperature capability of gas turbine hot gas path components for use in hydrogen turbines and to improve turbine efficiency.
- Completed pre-front-end engineering design studies for a clean hydrogen production facility, which is now shifting the design to using waste coal, biomass, and plastic feedstocks.
- Developed several pre-combustion CO_2/H_2 separation technologies at a small pilot scale.
- Developed reversible solid oxide fuel cell technologies to produce either hydrogen or electricity, depending on grid demand.
- Released a report, Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies, to provide a basis for FECM research and development (R&D) program planning to reduce the levelized cost of hydrogen and reduce the greenhouse gas footprint of future carbon-based feedstock-to-hydrogen plants.[57]
- Released a report, Subsurface Hydrogen and Natural Gas Storage: State of Knowledge and Research Recommendations, to inform the public about the safe and effective deployment of industrial-scale underground hydrogen storage in the United States.[58]
- Issued funding opportunity: Clean Hydrogen Production, Storage, Transport and Utilization to Enable a Net-Zero Carbon Economy.[59]

Office of Nuclear Energy

In FY 2022, NE continued to focus on RD&D to support hydrogen production applications for the existing nuclear fleet and advanced reactors. Ongoing activities include five projects in collaboration with HFTO: four projects to demonstrate hydrogen production capabilities at existing nuclear power plants and one project validating high-temperature steam electrolysis (HTSE) system performance and durability at INL. Additional ongoing activities include testing human interfaces for integrated plant operation using real operators in a control room environment, validating and demonstrating HTSE operation and control, and standing up the Hydrogen Regulatory Research and Review Group to engage industry stakeholders on the review of license and license-amendment requirements for integrating hydrogen and nuclear plants.

Key activities and accomplishments in FY 2022 include the following:

- Completed high-fidelity modeling for integrated design and operation of energy systems (electricity, hydrogen, and hydrogen utilization) to support techno-economic assessment using a suite of dynamic analysis and optimization tools. Energy systems modeled include hydrogen storage for delayed power production, hydrogen utilization pathways for synthetic fuel production (Fischer–Tropsch pathway), and carbon conversion to higher-value products.
- Conducted techno-economic analysis illustrating the potential for clean hydrogen production using nuclear energy to achieve the DOE target of $2/kg hydrogen with high-volume production and deployment of HTSE.

[57] National Energy Technology Laboratory, *Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies*, DOE/NETL-2022/3241, April 12, 2022, https://netl.doe.gov/projects/files/ComparisonofCommercialStateofArtFossilBasedHydrogenProductionTechnologies_041222.pdf.

[58] A. Goodman Hanson et al., *Subsurface Hydrogen and Natural Gas Storage (State of Knowledge and Research Recommendations)*, April 1, 2022, https://www.osti.gov/biblio/1846632.

[59] FECM, "Funding Notice: Clean Hydrogen Production, Storage, Transport and Utilization to Enable a Net-Zero Carbon Economy," October 2022, https://www.energy.gov/fecm/funding-notice-clean-hydrogen-production-storage-transport-and-utilization-enable-net-zero.

- Developed multiple dynamic physics models for thermal energy storage systems and advanced nuclear reactor concepts to support techno-economic assessment of multiple integrated systems, including those for hydrogen production and utilization.
- Formed the Hydrogen Regulator Research Review Group—comprising experienced nuclear utility design and licensing lead personnel, DOE laboratory research leads, contracted architect engineering companies, nuclear plant operators, and licensing experts—to identify the technical and safety risks for integrating hydrogen and nuclear plants.
- Completed a comparative study across four capacity expansion models (developed by NREL, the Electric Power Research Institute, the U.S. Energy Information Administration [a DOE agency], and the U.S. Environmental Protection Agency) to evaluate the adequacy of their assumptions for modeling advanced nuclear energy systems and integrated energy systems with multiple energy use options, such as the electric grid, hydrogen production, and hydrogen utilization markets.
- Confirmed system design and conducted probabilistic risk assessment of commercial-scale heat delivery and hydrogen production at a nuclear plant site.
- Completed the development of a full-scope simulator for a nuclear power plant coupled to a high-temperature steam electrolysis hydrogen plant.
- Developed a prototype human–system interface and used it to test operating concepts for dispatching thermal energy and electrical power to a high-temperature steam electrolysis plant. An interdisciplinary team of operations experts, nuclear engineers, and human factors experts evaluated the performance of previously licensed nuclear plant operators who were enlisted to test operational factors involved with integrating a nuclear reactor to a hydrogen plant.
- In collaboration with EERE, NE installed hardware to connect a thermal energy distribution system to solid oxide electrolyzer cell testing platforms at INL. The system was designed to emulate a heat distribution network that would couple a nuclear microreactor to energy users.
- Initiated design of a flexible thermal energy utilization network that will allow demonstration of thermal energy storage and a controllable thermal load (which could be used to emulate hydrogen production systems, chemical processes, etc.) alongside future microreactor demonstrations at INL.

Office of Science, Basic Energy Sciences

Since the 2021 AMR, SC hydrogen activities have focused 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. Recent accomplishments include the following:

- Enabled the discovery of semiconductor surface modifications that increase the efficiency of light-driven water splitting by a factor of ~100, through mechanistic understanding of detrimental charge recombination processes in a dye-sensitized photochemical hydrogen production system.
- Demonstrated how controlled manipulation of structures, using a combination of ab initio simulations and precision synthesis of a Pd-containing intermetallic catalyst, can be used to increase the efficiency of hydrogenation reactions by orders of magnitude.

In August 2021, SC led the **Roundtable on Foundational Science for Carbon-Neutral Hydrogen Technologies**, in coordination with EERE, FECM, and NE.[60] The roundtable identified four high-priority basic science research opportunities that could enable a carbon-neutral, hydrogen-based energy and chemical infrastructure:

- Discover and control materials and chemical processes to revolutionize electrolysis systems.
- Manipulate hydrogen interactions to harness the full potential of hydrogen as a fuel.

[60] DOE, Office of Science, Basic Energy Sciences, *Foundational Science for Carbon-Neutral Hydrogen Technologies*. Full report: https://www.energy.gov/sites/default/files/2022-05/Hydrogen_Roundtable_Report.pdf, Brochure: https://science.osti.gov/-/media/bes/pdf/reports/2021/Hydrogen_Roundtable_Brochure.pdf.

- Elucidate the structure, evolution, and chemistry of complex interfaces for energy and atom efficiency.
- Understand and limit degradation processes to enhance the durability of hydrogen systems.

Advanced Research Projects Agency–Energy

In FY 2022, ARPA-E funding for hydrogen-related activities was $1.5 million. ARPA-E catalyzes transformational energy technologies to enhance the economic and energy security of the United States. The agency funds high-potential, high-impact projects that are at too early a development stage for private-sector investment but could disruptively advance the ways energy is generated, stored, distributed, and used. Some programs at ARPA-E have sought to develop technologies involving renewable energy, carbon-neutral liquid fuels, and natural gas, with applications in the transportation, commercial, and industrial power sectors; in these areas, there are a number of efforts related to hydrogen. R&D programs having projects relevant to hydrogen or related technologies include:

- Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH)[61]
- Duration Addition to electricitY Storage (DAYS)[62]
- Methane Pyrolysis Cohort
- Innovative Natural-gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-generation (INTEGRATE)[63]
- Integration and Optimization of Novel Ion-Conducting Solids (IONICS)[64]
- Renewable Energy to Fuels through Utilization of Energy-dense Liquids (REFUEL)[65]
- Seeding Critical Advances for Leading Energy Technologies with Untapped Potential 2021 (SCALEUP 2021)[66]
- OPEN 2021.[67]

In Closing…

Since the 2021 AMR, the Program has continued to make significant progress toward its goals, while also doing extensive groundwork to prepare for the release of FOAs required by the BIL and supporting Regional Clean Hydrogen Hubs (released in September 2022), the Clean Hydrogen Electrolysis Program, and Clean Hydrogen Technology Manufacturing and Recycling RD&D. Together, these initiatives will represent the largest U.S. public investment in hydrogen to date. Global momentum on hydrogen has also continued as countries begin to implement their national hydrogen strategies and public–private consortia across the world announce large-scale hydrogen deployment projects.

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

New flagship initiatives such as the Hydrogen Energy Earthshot and Clean Hydrogen Hubs will pave the way to success in enabling low-cost hydrogen and realizing its potential to decarbonize applications across multiple sectors. Since the 2021 AMR:

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61 ARPA-E, "REEACH," accessed 2023, https://arpa-e.energy.gov/technologies/programs/reeach.

62 ARPA-E, "DAYS," accessed 2023, https://arpa-e.energy.gov/technologies/programs/days.

63 ARPA-E, "INTEGRATE," accessed 2023, https://arpa-e.energy.gov/technologies/programs/integrate.

64 ARPA-E, "IONICS," accessed 2023, https://arpa-e.energy.gov/technologies/programs/ionics.

65 ARPA-E, "REFUEL," accessed 2023, https://arpa-e.energy.gov/technologies/programs/refuel.

66 ARPA-E, "SCALEUP 2021," accessed 2023, https://arpa-e.energy.gov/technologies/scaleup/scaleup-2021.

67 ARPA-E, "OPEN 2021," accessed 2023, https://arpa-e.energy.gov/open-2021.

- The first-ever DOE Hydrogen Shot Summit rallied the global community on the urgency of tackling the climate crisis through concrete actions and innovation.
- The Program launched new prize competitions, such as the Hydrogen Shot Incubator Prize and the Hydrogen Business Case Prize, to spur innovation and entrepreneurship.
- The Program held numerous workshops to inform upcoming FOAs and educate stakeholders on hydrogen and fuel cell challenges and opportunities.
- Collaboration across government, industry, labs, academia, and the environmental and energy justice communities—with emphasis on diversity, equity, and inclusion—set the stage for continued progress.

DOE will continue to work in close collaboration with key stakeholders and will continue its strong commitment to effective stewardship of taxpayer dollars in support of its mission to enable the energy, environmental, and economic security of the nation.

Program Peer Review Summary

The U.S. Department of Energy (DOE) Hydrogen Program Fiscal Year 2022 Annual Merit Review and Peer Evaluating Meeting (AMR) included overview presentations on the DOE Hydrogen Program (the Program), as well as oral presentations of 58 Hydrogen and Fuel Cell Technologies Office (HFTO)-funded projects and poster presentations of 137 HFTO-funded projects. Project-level presentations were provided by the Office of Fossil Energy and Carbon Management (FECM), the Office of Nuclear Energy (NE), the Office of Science (SC), the Advanced Research Projects Agency–Energy (ARPA-E), and other offices within the Office of Energy Efficiency and Renewable Energy (EERE). Of these hydrogen- and fuel-cell-related projects, 11 were presented orally and 28 were presented with posters.

While individual projects were not reviewed at the 2022 AMR, a group of reviewers was asked to provide feedback on the overall Program and HFTO subprograms, taking into account both plenary and poster presentations. Panel members included experts from a variety of backgrounds related to hydrogen and fuel cells (see Appendix A). Each reviewer was screened for conflicts of interest, as prescribed by the EERE Peer Review Guide. A summary of reviewer comments and recommendations that are applicable across the entire Program is provided in the next section. Summaries of comments and recommendations that apply to specific subprograms, as well as summaries of the projects that were presented orally at the AMR, are provided in subsequent sections of this report, grouped by subprogram. The full set of Program review results, including scores, comments, and recommendations, is included in Appendix A.

Summary of Reviewer Comments

This section provides a summary of the program review comments received. The content reflects those inputs only and not the views of Program management.

Reviewers stated that, overall, the Program has a comprehensive portfolio and is well-managed. It has been very effective in driving hydrogen and fuel cell technology performance and cost improvements through research, development, and demonstration (RD&D) activities. The Program uses a well-coordinated RD&D strategy and input from multiple stakeholders to address key challenges (e.g., high costs) that prevent clean hydrogen and fuel cell technologies from being implemented comprehensively—and that restrain consumers' acceptance of those technologies. In addition, the Program responded quickly to the Administration's emphasis on concerns related to environmental justice, ensuring they were included in Program scope.

Even after the technology and cost goals are achieved, challenges will remain, and deploying the technologies will require broad acceptance across stakeholders: regulators, industry, and the public. Therefore, it is important to identify and address those remaining obstacles by devoting more resources to discussing barriers, assessing risks to overcome barriers, and defining and prioritizing the challenges. In addition, a clearer and more detailed breakdown of funding for different Program offices would help in understanding what RD&D priorities are being addressed.

Reviewers also noted that the Program plans for the funding provided under the Bipartisan Infrastructure Law are promising and well-formulated. The goals of these plans align well with efforts already under way, though one reviewer commented that the published expectations for the Clean Hydrogen Hubs could be made clearer, citing the well-articulated structure and goals of the Hydrogen Shot as an example. Continuity across all these efforts is key to the success. Notices of intent to issue funding opportunity announcements (FOAs) made the Program plans clearer (especially for the Clean Hydrogen Electrolysis Program and the Clean Hydrogen Manufacturing and Recycling Program) and allowed potential FOA applicants to prepare. The FOAs and the subsequent program management should be as streamlined and simple as possible, with minimal administrative burden (i.e., reporting and data collection requirements).

The Program should focus on making consistent progress and keeping a line of sight on ultimate goals, rather than trying to reach cost parity with fossil-based transportation technologies. The Program's portfolio of projects seems appropriately balanced between near-, mid-, and long-term goals. However, the challenges and many unknowns make it difficult to determine whether decisions on the distribution of projects were truly appropriate. The Program would benefit from continued leveraging of lessons learned from past successes and evaluating what aspects and achievements have led to commercialization.

The Program's portfolio has expanded in terms of more mature technologies (i.e., those with higher technology readiness levels [TRLs] that will soon be ready to enter the commercial sphere), which were under-represented until recently. Reviewers had mixed views on the portfolio's balance. Some reviewers felt that projects working on lower-TRL technologies were less likely to meet goals and that focusing on higher-TRL activities with coordination across DOE offices would be beneficial in the near term, making hydrogen hubs and commercialization successful. Even with existing high-TRL technologies, though, some felt that the funding allocated to developing hydrogen hubs across the United States may not be adequate. Some reviewers felt that near-term research should not completely displace mid- and long-term research, noting that the lower-TRL efforts should remain an important part of a balanced portfolio.

Across the portfolio, additional testing infrastructure and increased investment in component development will be critical in the next two to four years. Furthermore, Program goals include development of a domestic supply chain, yet several projects with industry did not appear to include domestic supply chain considerations. Some reviewers suggested that "manufactured in America" should be a goal included in all subprograms. More attention should be paid to the materials infrastructure needed to enable a successful energy transition. In particular, a domestic supply of raw materials would provide cost-effectiveness, long-term jobs, and energy security. One reviewer, however, urged the Program not to overemphasize the need to improve the domestic supply chain, noting that the world's economies are integrated and allies such as Europe, the United Kingdom, Japan, and South Korea manufacture systems and components in the United States and serve as key consumers of U.S. products.

Reviewers also commended the Program's individual subprograms, describing them as extremely well-managed. Subprogram goals, milestones, and quantitative metrics are clearly articulated, providing a rational framework for coordinating complementary activities and reducing organizational redundancies. However, metrics could have been further emphasized and made clearer at the individual subprogram level. A semi-quantitative assessment of the risks remaining to overcome barriers and probability of achieving goals could also be useful. One concern is that the focus on the Hydrogen Shot and the hydrogen hubs may leave many legacy research areas somewhat "orphaned" and not as strongly tied to Program priorities. These legacy research efforts, such as HydroGEN, remain important and should continue.

The Program aligns well with industry and stakeholder needs, having extensive cooperation with a diverse range of stakeholders from the community, industry, states, international organizations, and other partners. However, to improve the probability of achieving technological breakthroughs, more industry engagement would be helpful, with industry accepting some financial risk but receiving greater rewards, such as through exclusive patents. Engaging actively with demonstrated technology disruptors and innovators at the incubator level is also a good pathway for fostering the implementation of groundbreaking technology. The Program could further enhance these engagements by providing additional guidance on a variety of avenues:

- Siting and deployment to enable technology integration into communities.
- Education and coordination to identify market opportunities related to stationary applications (combined heat and power, mission-critical facilities, microgrids, etc.); transportation applications (light- and heavy-duty vehicle fleets, materials handling, aircraft, etc.); refueling applications (in coordination with renewable feedstock producers); and utilities (electric and natural gas).
- Means of addressing concerns of distressed communities, underserved cities, and opportunity zones, consistent with both state and federal policies and goals for community investment.
- Alliance-building with local industry, supply chain partners, and community resources.
- Environmental performance, safety, and economic projection of the impact on consumer energy costs and the utility rate base.
- Coordinating with non-hydrogen stakeholders on overall integration with other technologies.
- Developing mechanisms for coordination and communication among renewable feedstock producers, energy (electric and gas) producers and grids, and energy markets for storage, transport, and dispatch of hydrogen.

In future reviews, reviewers would like to see comparisons between hydrogen and fuel cell technologies and incumbent and emerging technologies (especially batteries); such comparisons would provide useful context for assessing the future impacts and advantages/disadvantages of Program RD&D in relation to other renewable energy options.

Hydrogen Shot

The Hydrogen Shot initiative provides well-formulated, concise, and challenging goals and focus for the Program, but other notable challenges should not be de-emphasized. In working toward the Hydrogen Shot goal, progress would likely be evolutionary, so intermediate goals should be set accordingly, and progress should be quantified. To speed commercialization and reach Hydrogen Shot goals, the Program should focus on developing tools to support and enable industrial partners and stakeholders (for example, industry-vetted reference models for all promising clean hydrogen production pathways that would help determine which innovations would have the greatest impacts in terms of reaching the Hydrogen Shot goal). Also, more collaboration with the European Union, including direct partnerships on projects, could leverage knowledge and progress relating to the use of electrolyzers, strengthening efforts of the United States on the path to meeting the ambitious Hydrogen Shot goal.

Clean Hydrogen Hubs

Reviewers stated that the proposed investment in hydrogen hubs is meaningful, with potential to build confidence in the private sector and encourage investments to propel the envisioned hydrogen economy. The hubs have the potential to enable innovation in demonstrations, deployments, education, outreach, and approaches to working with states. The focus on regional markets and supply chains supports industry, perhaps encouraging the private sector to accept some initial risks. The strategy articulated by the Program will help spread hydrogen infrastructure into different regions.

The Program must focus on the long-term viability of the hubs, beyond the five-year period of the hydrogen hub investment. Projects and sites should be required to provide clear evidence of plans for commercial sustainability. In addition, Program management should think critically about the scale of hydrogen production, distribution, and use that will be supported by the Bipartisan Infrastructure Law provisions and funds, relative to the size of the overall energy market. One reviewer noted that the full cost of building out hydrogen hubs across the United States may approach $100 billion–$500 billion[1] and suggested that DOE focus the $8 billion in Bipartisan Infrastructure Law funding for maximum impact.

Furthermore, it is not clear that there is sufficient private-sector demand or market pull for the clean hydrogen that the hubs will produce. The H2 Matchmaker tool, which helps hydrogen suppliers identify hydrogen off-takers, might be of use for identifying potential off-takers.

Awarding, contracting, permitting, and building the hubs in the stated timeframe will be difficult and time-consuming. Many technical reviewers and experienced project managers will be needed. The Program should clearly detail the specific administrative, technical, or regional goals of the hydrogen hubs before releasing the FOA. Additionally, funding may not be smooth: industry and states may struggle to meet the planned 50% cost share requirement, and DOE will have to obligate funds quickly.

Clean Hydrogen Electrolysis Program

Reviewers agreed that plans for the Clean Hydrogen Electrolysis Program are well-thought-out and clearly articulated. One reviewer recommended strong continued support for advanced concepts to improve the chances of meeting the Hydrogen Shot goal; another recommended increasing the emphasis on hydrogen compression to improve system-level reliability for the electrolysis program.

Clean Hydrogen Manufacturing and Recycling Program

Reviewers expressed support for the Clean Hydrogen Manufacturing and Recycling Program. This program is perhaps less well-defined than the Clean Hydrogen Electrolysis Program, but that is to be expected, given the breadth of the manufacturing and recycling program and its early development stage. However, funding for clean

[1] E. Larson, C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, EJ Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan. "Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report." Princeton University, Princeton, NJ, October 29, 2021. https://netzeroamerica.princeton.edu/the-report.

manufacturing may be too low to address all the technical barriers, and so critical items should be prioritized. The proposed material recycling and end-of-life effort is a necessary and significant step toward achieving the Program's goals. One reviewer noted the importance of learning from equipment demonstrations and suggested that equipment suppliers be "required" to receive, dispose of, and learn from used equipment as a condition of receiving DOE funding. Another suggested emphasizing refurbishment of fuel cells rather than recycling, as many fuel cell components, such as advanced catalysts and bipolar plates, may be made from lower-value materials, so their value is mainly in their structure.

Consortia

The research consortia approach addresses critical challenges; it is successful, efficient, innovative, very well-organized, and a valuable catalyst to innovation and progress. One reviewer stated that "bringing multiple labs together with appropriate industrial and academic participation supercharges ideation and knowledge creation necessary to support the applications at hand." Using lab facilities and other research capabilities to support competitively selected DOE-funded projects is an effective way to accelerate learning and progress. The Program has created an effective model for integrating seedling and push projects into the larger consortium framework. However, programs involving numerous principal investigators present management challenges. The Program must avoid coordination difficulties and redundancies and ensure the lead researchers have time for research and development (R&D). Moreover, it would be helpful in future reviews to clarify differences in related consortia objectives and directions, as well as the role of Tech Teams.

The Program could enhance the visibility of the consortia by better advertising them to academia and U.S. businesses, particularly small businesses. Recommendations for improving the consortia include sharing lessons learned among the different consortia, conducting an anonymous survey of lab personnel and industry and university partners to identify best practices and areas for improvement, initiating periodic third-party reviews of the consortia to assess operation and effectiveness, and increasing the number of basic, high-risk–high-reward projects supported under the consortia.

Diversity, Equity, Workforce Development and STEM Education

The Program funds projects at universities and national laboratories, thereby playing an important role in science, technology, engineering, and mathematics (STEM) education. Reviewers were divided as to whether the Program is doing enough to advance goals for workforce development and STEM education; some stated that these activities merit increased funding because of their importance in meeting the Program's near- and long-term goals. However, all applauded the Program's efforts to ensure diversity in STEM student populations and in the workforce and the Program's collaborations with historically black colleges and universities and minority-serving institutions.

STEM education needs to span all levels of education, from elementary school to graduate programs. Needs include incorporation of hydrogen and fuel cells in standard curricula, targeted grants and scholarships for undergraduate and graduate programs, and a balanced approach that highlights both the benefits of cleaner fuels and the practical challenges to widescale adoption. Specific recommendations include:

- Promoting the teaching of life cycle analysis and the enhancement of communication skills.
- Encouraging inclusion of STEM educational activities in research proposals.
- Reaching out to state educational groups.
- Assessing the number of hydrogen-related graduate programs.
- Establishing programs to train teachers and trainers.
- Advancing internships and co-op programs for university students.
- Promoting job shadowing for high school students.

The DOE Justice 40 initiative provides a solid plan and an excellent framework for addressing critical issues associated with workforce development in disadvantaged communities and collaboration with minority-serving institutions. The talent pipeline for researchers with graduate degrees is important to the Program mission. The Program has appropriate plans to fund universities for workforce development, and Los Alamos National Laboratory's involvement of undergraduate students in its research is commendable. National laboratories could conduct further activities in workforce development:

- Increasing graduate student funding for summer fellowships at national laboratories.
- Recognizing and rewarding workforce development activities at the national laboratories.
- Developing specific resources to help scientists with workforce development, such as assisting with job searches and linking community colleges to research universities.

Outside of academia, there is a need to provide auto mechanics, utility workers, and other technicians with specialized training in hydrogen energy systems. Education and training efforts are already under way through the Hydrogen Education for a Decarbonized Global Economy (H2EDGE) project and the Center for Hydrogen Safety. Additional recommended efforts include:

- Establishing two-year training courses focused on hydrogen and fuel cell technology at community colleges.
- Developing a certification program, similar to the Electric Vehicle Infrastructure Training Program, for technicians working with hydrogen technologies.

Other support could be identified through workforce analysis, which would provide a better understanding of the demographics, geography, infrastructure needs (e.g., high-speed internet access), and training needs of the workforce and its ability to support the transition to a hydrogen economy. Universities should work with industry to ensure that workforce development results in skills valued by industry, and there is a similar need for coordination between original equipment manufacturers and institutions providing mechanic training. More workforce development efforts at the state and regional levels are encouraged, and DOE could coordinate with other agencies with specific workforce development expertise.

DOE’s workforce training should address energy efficiency, system durability and lifetimes, capital expenditure evaluation, ways to decrease the cost of electricity, and energy systems integration. When creating e-learning systems for training the workforce, project developers should be included as partners to ensure that the training systems will meet their needs and that they will attract and retain a skilled workforce. One reviewer identified deficiencies in the modules available through the DOE website: they are static pages, do not necessarily interact and change with the progress of the online learner/instructor communities, may in some cases be out of date, and may in some cases require DOE employees to deliver the modules.

Intra-Agency Collaboration

DOE programs and offices have increased collaboration, which will help advance systemic approaches and favorable technology couplings. A welcome and promising evolution of a well-structured and well-managed Program, these cooperative efforts should be continued to reduce duplication, break down barriers between groups, and find solutions that help all and achieve policy goals. However, a challenge remains: stakeholders must be shown how these collaborations can lead to meaningful advancements and impacts. While overall communications between the offices are effective, offices could work together to develop a dashboard that tracks project status and strengthens information-sharing. Of less value are the numerous (time-consuming) meetings that senior researchers and program managers must attend to facilitate inter-office coordination. Perhaps an alternative approach, such as international postdoctoral fellow exchanges or rotations/details to the different offices, could reduce this burden.

The following are recommendations specific to collaborations with the various DOE offices:

- ***Basic Energy Sciences (BES) Office:*** The BES hydrogen R&D budget request has increased, emphasizing the continued need for basic, high-risk research and recognizing the Office’s role in workforce development. Advances in high-strength materials, such as carbon fiber, for high-pressure tanks is important for transportation applications. A joint EERE–BES materials discovery program could move beyond current levels of incremental technology progress and help to address cost-related challenges.
- ***Office of Energy Efficiency and Renewable Energy (EERE):*** Program strengths include coordination and co-funding between HFTO and other offices in EERE, such as the Advanced Manufacturing Office’s Roll-to-Roll consortium. The Program should increase support and resources for manufacturing R&D to lower technology cost for clean hydrogen technologies, thereby addressing a significant gap in high-speed, low-cost manufacturing technologies in the United States.
- ***Office of Fossil Energy and Carbon Management (FECM):*** Almost all current domestic and global hydrogen supply comes from fossil fuel sources, which may remain true beyond the next decade. Thus,

attaining Hydrogen Shot goals may require significant advances in large-scale, low-carbon hydrogen production from fossil fuels. Many approaches are predicated on the existence of a credible, commercial-scale carbon capture and storage technology, yet this technology has not yet been proven to be cost-effective at scale. FECM may require more funding to demonstrate technical feasibility to meet ambitious hydrogen cost and emissions targets and timelines. However, it is not clear whether continued research on fossil-based hydrogen production pathways is in line with stakeholder needs. One reviewer recommended that DOE assess how much fossil-based hydrogen production with carbon capture will be needed as a transition approach, and at what cost. Continued R&D on solid oxide fuel cells and hydrogen turbines is clearly needed. Also of interest is further discussion of the methods for reducing nitrogen oxide emissions from hydrogen turbines.

- ***Office of Electricity (OE):*** During the review, the Program highlighted that maximizing hydrogen's impact on the grid (e.g., through electrolysis) will require grid modernization. To this end, more emphasis should be given to engaging with OE. One area for collaboration is integration of renewable power, grid capacity, and hydrogen production at the point of use.
- ***Office of Nuclear Energy (NE):*** Collaborations between HFTO and NE are commendable, and the Program has clearly articulated the challenges and opportunities associated with integrating hydrogen production with nuclear energy. It should be noted that different rating systems may be needed for high-TRL technologies (such as alkaline electrolysis using solar power sources) vs. low-TRL technologies (such as solid oxide electrolysis cells integrated with into nuclear power plants). Integrating hydrogen production with nuclear plants may take five to ten years for permitting, testing, and training, so it would be useful to clarify how different TRLs will be treated in the Program. Another recommendation is to capture learnings as they occur for utilization in training systems.

Some of the collaborative efforts should focus on breakthrough technologies. The U.S. Department of Defense provides examples of successful approaches, such as the Navy and its science advisors through the Office of Naval Research.

Hydrogen Technologies – 2022

Subprogram Overview

Introduction

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

- Hydrogen Production addresses low-cost, highly efficient, clean hydrogen production technologies that use diverse sustainable domestic sources of energy and feedstocks. RD&D activities include advanced water splitting and innovative concepts such as biological hydrogen production. The former is predominantly coordinated through the HydroGEN Advanced Water Splitting Materials consortium (HydroGEN) and the Hydrogen from Next-generation Electrolyzers of Water consortium (H2NEW) to accelerate RD&D of advanced water-splitting technologies for clean, sustainable hydrogen production.
- Hydrogen Infrastructure addresses low-cost, high-efficiency technologies to move hydrogen from the point of production to the point of use. RD&D activities investigate liquefaction, pipelines, chemical carriers, and tube trailers to transport hydrogen over long distances, as well as compressors, pumps, dispensers, and auxiliary components to support the development of hydrogen stations serving medium- and heavy-duty fuel cell electric vehicles. The Hydrogen Materials Compatibility Consortium (H-Mat) coordinates RD&D on accelerated test methods and novel, low-cost, durable metals and polymers for use in hydrogen infrastructure. The HyBlend effort 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 and development of breakthrough hydrogen storage materials.

Since the Fiscal Year (FY) 2021 Annual Merit Review, the BIL has been enacted. The law includes a provision for clean hydrogen electrolysis for production of clean, low-carbon hydrogen. With this provision, all of the electrolysis activities under the Hydrogen Production category are being shifted under the BIL. The Hydrogen Production funding from annual appropriations will focus on non-electrolysis technologies at lower technology readiness levels (TRLs), such as photoelectrochemical, solar thermochemical, and biological hydrogen production processes. Key activities kicked off in the past year for the Hydrogen Infrastructure and Hydrogen Storage categories include the HyBlend effort on hydrogen–natural gas blending, four projects on low-cost carbon fiber (CF) for high-pressure tanks, and an ultra-large-scale liquid hydrogen (LH2) storage vessel project.

Goals

The Hydrogen 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 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 \$1/kg H_2 by 2031 (the Hydrogen Shot target).
- 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 Technologies subprogram has key milestones for each of the technology areas:

- 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 polymer electrolyte membrane (PEM) electrolyzer technologies with stack targets of ≥70% electrical efficiency, ≤\$100/kW, and a lifetime of ≥80,000 hours by 2026; and develop stacks using oxide-ion-conducting solid oxide electrolysis cells (O^{2-} SOECs) with ≥ 98% electrical efficiency, ≤ \$100/kW and a lifetime of ≥ 60,000 hours by 2026.
- 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 either 700 bar compressed or LH2 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.

FY 2022 Technology Status and Accomplishments

Production

- Documented in a Program Record that the clean hydrogen production cost with current PEM electrolyzer technology can be less than \$4/kg H_2 in regionally specific cases.
- Developed a thin (50 µm) PEM membrane with an integrated gas recombination layer specific to electrolyzer technology that is compatible for roll-to-roll fabrication processes.
- Used a combination of experimental, modeling, and analysis techniques to achieve important advances in the understanding of Ir dissolution, which has significant impacts on the cost and degradation of PEM electrolysis.
- Demonstrated 20% solar-to-hydrogen in a hydrophobic perovskite photoelectrochemical cell with a Pt/graphite barrier lifetime of 100 hours.
- Used computational modeling to guide selection of promising high-entropy perovskite oxides for solar thermochemical hydrogen production; synthesized and characterized over 150 compositions and demonstrated production of >400 µmol H_2/g perovskite.
- Collaborated with the National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory to host workshops on liquid alkaline electrolyzers, advanced materials for PEM electrolyzers, and high-temperature electrolyzer manufacturing.
- Demonstrated 90% Faradaic efficiency for a proton-conducting SOEC operating at commercially relevant conditions (1.0 A/cm^2, 600°C, 70% steam), with stable operation over 5,000 hours.

Infrastructure

- Completed commissioning of a high-flow hydrogen fueling system at the NREL Energy Systems Integration Facility and achieved a 76 kg fill in under six minutes, as determined by conducting a test representative of fueling a heavy-duty vehicle. This test had an average flow rate of nearly 13 kg/minute and a peak rate of over 23 kg/minute.
- Initiated validation efforts for the publicly accessible H2FillS model with high-flow test data up to approximately 80 MPa. The model allows users to simulate the impact of varying fueling methods on the thermodynamics of fueling equipment and onboard hydrogen storage.
- Demonstrated accelerated techniques to characterize the life of materials in hydrogen twice as fast as traditional approaches.
- Demonstrated high-throughput techniques to test thin film metals in hydrogen.
- Completed a technical report summarizing ASME and National Fire Protection Agency codes and standards relevant to hydrogen blending in pipelines.

Storage

- Hosted multiple workshops, including two focusing on LH2 storage (in collaboration with NASA) and one focusing on bulk gaseous hydrogen storage (in collaboration with the DOE Office of Fossil Energy and Carbon Management).
- Developed several design concepts for the world's largest LH2 storage tank and down-selected to two concepts for detailed evaluation.
- Demonstrated high-pressure hydrogen release from hydrogen carriers—formic acid and formic acid–methanol blends—with capacities as high as 5.3 wt % and good catalyst stability.
- Showed a 75% increase in volumetric capacity for a composite of a porous cage and metal–organic framework (MOF) compared to the MOF alone. A significant increase in packing density allowed for the increased capacity without sacrificing adsorption behavior.

New Project Selections

Funding Opportunity Announcement DE-FOA-0002446

Production

- Nextech Materials, Ltd.: Low-Cost Manufacturing of High-Temperature Electrolysis Stacks
- Cummins Inc.: Automation of Solid Oxide Electrolyzer Cell and Stack Assembly
- Southern Company Services, Inc.: Novel Microbial Electrolysis System for Conversion of Biowastes into Low-Cost Renewable Hydrogen
- Pennsylvania State University: Novel Microbial Electrolysis Cell Design for Efficient Hydrogen Generation from Wastewaters
- Strategic Analysis, Inc.: Hydrogen Production Cost and Performance Analysis

Infrastructure

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

Storage

- Strategic Analysis, Inc.: Hydrogen Storage Cost and Performance Analysis

Technology Commercialization Fund

Production

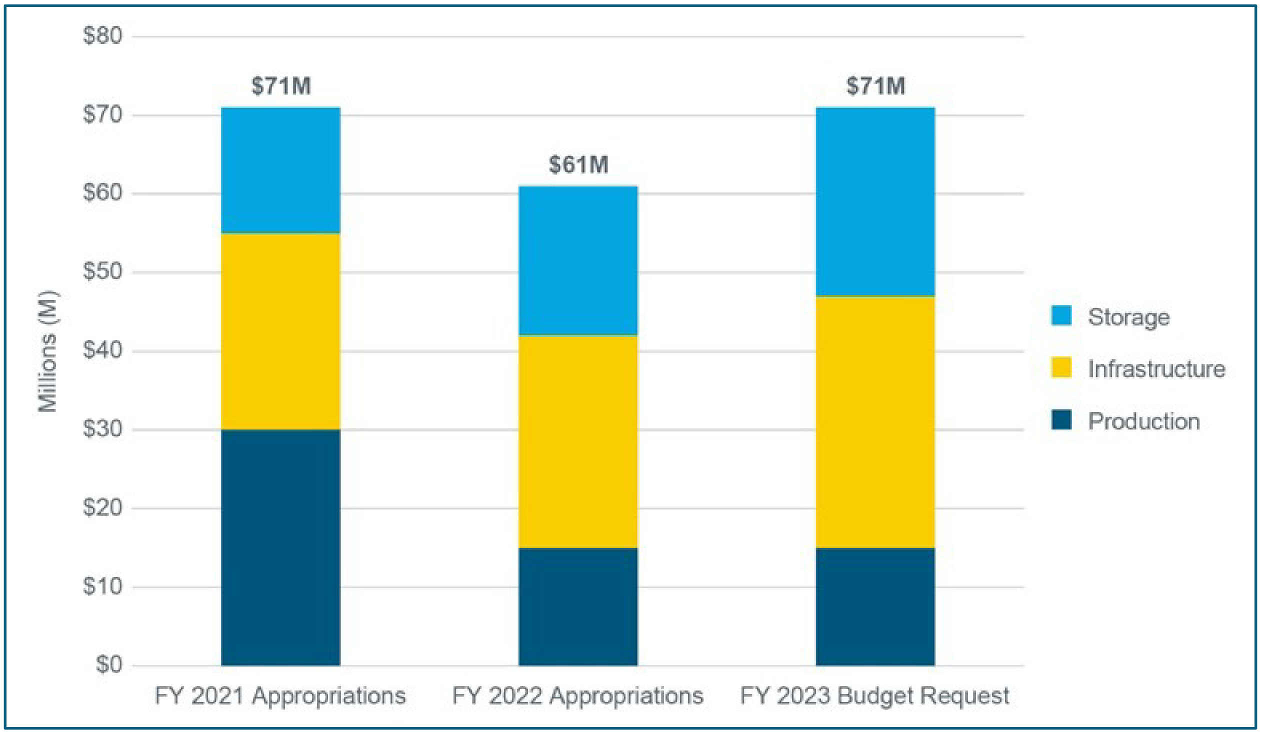
- Sandia National Laboratories and Giner, Inc.: Alkaline Water Electrolysis
- Lawrence Berkeley National Laboratory, Nel Hydrogen, and De Nora Tech., Inc.: Porous Transport Electrodes for Proton Exchange Membrane Electrolyzers
- NREL and Eaton Corporation: Hydrogen-based Power grid support using ElectrolyzeRs with Value stacking (HYPER-V)

Storage

- NREL and Honeywell Aerospace: FueL Additives for Solid Hydrogen (FLASH) Carriers for Electric Aviation
- Los Alamos National Laboratory and Oberon, Inc.: Dimethyl Ether as a Renewable Hydrogen Carrier: An Innovative Approach to Renewable Hydrogen Production

Budget

Enacted on November 15, 2021, the BIL includes the Clean Hydrogen Electrolysis Program, with $1 billion of new funding. As noted above, electrolysis-related activities were shifted to BIL funding, so the Hydrogen Production category's budget was reduced from $30 million in FY 2021 to $15 million in FY 2022. For Hydrogen Infrastructure, the budget was increased from $25 million to $27 million, and for Hydrogen Storage, the budget was increased from $16 million to $19 million.



Project Summaries

Below are brief Hydrogen Technologies project summaries of oral presentations given during the 2022 Annual Merit Review. The full list of projects, including oral and poster presentations, is provided in Appendix D.

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

Huyen Dinh, National Renewable Energy Laboratory

DOE Contract #	WBS 2.7.0.518 and 2.7.0.513
Start and End Dates	6/1/2016
Partners/Collaborators	• HydroGEN Consortium

Project Goal and Brief Summary

The HydroGEN consortium's objective is to facilitate collaborations between federal laboratories, academia, and industry to evaluate and accelerate 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, solar thermochemical, low-temperature electrolysis, and high-temperature electrolysis. 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 #P-196: H2NEW Consortium: Hydrogen from Next-Generation Electrolyzers of Water

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

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

Project Goal and Brief Summary

The H2NEW consortium is a comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable, and efficient electrolyzers that can achieve <$2/kg H_2 by 2025. H2NEW is studying both low-temperature electrolysis, based on an acidic PEM, and high-temperature electrolysis, based on oxide-ion-conducting solid electrolyte. The core H2NEW national laboratory team is addressing components, materials integration, and manufacturing R&D. 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 #P-197: Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzers: Oxygen Evolution Reaction Catalysts and Electrodes

Andy Steinbach, 3M

DOE Contract #	DE-EE0009237
Start and End Dates	1/1/2021–3/30/2024
Partners/Collaborators	• Giner, Inc. • Plug Power Inc. • National Renewable Energy Laboratory • Oak Ridge National Laboratory

Project Goal and Brief Summary

This project aims to develop manufacturing processes for reproducible and uniform PEM water electrolysis components at commercial scale, specifically for an oxygen evolution reaction 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 PEM electrolysis and reduced manufacturing costs for the necessary components.

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

Christopher Capuano, Nel Hydrogen

DOE Contract #	DE-EE0009238
Start and End Dates	10/1/2020–9/30/2023
Partners/Collaborators	• National Renewable Energy Laboratory • Oak Ridge National Laboratory • De Nora • University of California, Irvine

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 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 in service of advancing electrolyzers toward the DOE cost goal of $2/kg.

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

Monjid Hamdan, Plug Power Inc.

DOE Contract #	DE-EE0009236
Start and End Dates	8/1/2021–7/31/2024
Partners/Collaborators	• University of Tennessee • Colorado School of Mines • Oak Ridge National Laboratory • National Renewable Energy Laboratory

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, the most expensive components in an electrolyzer stack. Researchers will create a single-piece anode support structure 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 #IN-015: Optimizing the Heisenberg Vortex Tube for Hydrogen Cooling

Jacob Leachman, Washington State University

DOE Contract #	DE-EE0008429
Start and End Dates	1/23/2019–6/30/2023
Partners/Collaborators	• Plug Power Inc.

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

Devin Halliday, Gas Technology Institute

DOE Contract #	DE-EE0008431
Start and End Dates	1/1/2019–12/31/2022
Partners/Collaborators	• Center for Electromechanics (University of Texas at Austin) • Argonne National Laboratory

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 #IN-034: HyBlend: Pipeline Cooperative Research and Development Agreement – Cost and Emissions Analysis

Mark Chung, National Renewable Energy Laboratory; Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	8.6.2.1
Start and End Dates	10/1/2021–9/31/2023
Partners/Collaborators	• Sandia National Laboratories • Pacific Northwest National Laboratory

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 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 #IN-035: HyBlend: Pipeline Cooperative Research and Development Agreement – Materials Research and Development

Kevin Simmons, Pacific Northwest National Laboratory; Chris San Marchi, Sandia National Laboratories

DOE Contract #	8.6.4.2
Start and End Dates	10/1/2021–9/31/2023
Partners/Collaborators	• Argonne National Laboratory • National Renewable Energy Laboratory

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

Xiaodong "Chris" Li, University of Virginia

DOE Contract #	DE-EE0009239
Start and End Dates	10/1/2021–9/30/2026
Partners/Collaborators	• Oak Ridge National Laboratory • Savannah River National Laboratory • Cytec Engineered Materials (Solvay) • Hexagon R&D LLC

Project Goal and Brief Summary

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

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

Dylan Winter, Hexagon R&D LLC

DOE Contract #	DE-EE0009240
Start and End Dates	10/1/2021–9/30/2026
Partners/Collaborators	• Cytec Engineered Materials (Solvay) • Oak Ridge National Laboratory • Pacific Northwest National Laboratory • Newhouse Technology • Kenworth R&D

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 CNG, and CF 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 CF with a demonstrated cost of less than $15/kg, tensile strength of 700 ksi, and tensile modulus of 35 Msi. CF 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 #ST-238: Low-Cost, High-Strength Hollow Carbon Fiber for Compressed Gas Storage Tanks

Matthew C. Weisenberger, University of Kentucky Center for Applied Energy Research

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.

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 #ST-239: Melt-Spun Polyacrylonitrile Precursor for Cost-Effective Carbon Fibers in High-Pressure Compressed Gas Tankage

Felix Paulauskas, Oak Ridge National Laboratory

DOE Contract #	DE-EE0009242
Start and End Dates	10/15/2021–9/30/2026
Partners/Collaborators	• Collaborative Composites Solutions • Virginia Tech • JR Automation • High Energy Sales LLC • Hexagon R&D LLC, Prescott Composites

Project Goal and Brief Summary

CF accounts for nearly 50% of total vehicle high-pressure storage system costs. Currently, high-tensile-strength CF is produced exclusively from polyacrylonitrile (PAN) precursor made via solution spinning, which requires extensive capital investment for fiber formation and solvent recovery. In comparison, melt-spinning of PAN offers significant advantages: reduced solvent and energy use, faster line speeds, fewer defects, and a much smaller spinning equipment footprint. This project aims to demonstrate that melt-spun PAN precursor can reduce 700 ksi CF cost by 25% of the cost of conventional solution spinning. The project will also show that the process can effectively scale to the pre-production levels necessary to make finished CF, which will then be validated in multiple high-pressure tanks. Commercialization of the resultant technology for producing cost-effective CF is a long-term goal of partner company, Prescott Composites.

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

Amit Naskar, Oak Ridge National Laboratory

DOE Contract #	4.3.0.605
Start and End Dates	4/1/2021–3/31/2024
Partners/Collaborators	• Pacific Northwest National Laboratory • 4XGroup LLC

Project Goal and Brief Summary

This project aims to manufacture low-cost, high-strength CF costing 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 CF costs, so the project aims to employ both novel precursor and new high-performance processing technologies to manufacture low-cost, high-strength CF. Researchers will conduct foundational research to enhance processability of newly synthesized 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 CF manufacture will lead to higher utilization of hydrogen in vehicles.

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

Jo-Tsu Liao, Shell International Exploration and Production, Inc.

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

Project Goal and Brief Summary

One of three priorities in the 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 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.

Annual Merit Review of the Hydrogen Technologies Subprogram

Summary of Hydrogen Technologies Subprogram Reviewer Comments

This section provides a summary of the reviewers' remarks. The content reflects those inputs only and not the views of Program management. The complete set of review comments received is provided as Appendix A.

Hydrogen Shot Goal

The Hydrogen Shot goal of $1/kg hydrogen by 2030 is clear, well-aligned and -formulated, concise, appropriately ambitious, and aggressive, while also being tremendously challenging. The intermediate goals, e.g., $2/kg by 2026, make the Hydrogen Shot goal more manageable, and the goal makes sense given the current TRL of hydrogen production technology. However, some reviewers suggested that the Hydrogen Shot goal is more aggressive than necessary. Being able to meet the goal will depend on electricity cost, which is outside the Program's control, and specific articulated pathways to achieve the goal have not yet been identified. It would be useful to develop tools for quantifying and communicating progress toward the Hydrogen Shot goal, such as a total cost of ownership/techno-economic analysis model and dashboards.

Strategy, Targets, and Metrics

The Program has developed a comprehensive strategy on a national scale to achieve the Hydrogen Shot goal, including R&D, demonstration, deployment, education, and outreach. The Hydrogen Technologies subprogram has clearly defined targets, a clear mission and strategy, and a logical and effective organization. One reviewer, however, noted a mismatch between the stated materials and performance goals of industry and those of the national laboratories. Suggestions include:

- Adding more detailed metrics and targets at the component level, using multiple parameters, similar to the fuel cell targets.
- Measuring the success of the subprogram's activities against a metric describing how much they accelerate the hydrogen industry rather than the degree to which the subprogram's technologies are adopted by industry.
- Developing strategies for maintaining reliable energy supply during the transition to hydrogen and, in the longer term, with dependence on fewer energy sources.

Hydrogen Technologies Subprogram Portfolio

The Hydrogen Technologies subprogram's portfolio of projects is appropriately balanced across research areas to help achieve its mission and goals. It has an appropriate balance between near-, mid-, and long-term R&D and a good balance of TRLs. The following recommendations are applicable across the Hydrogen Technologies subprogram's portfolio:

- Prioritize the use of domestic materials in projects funded by the subprogram, and consider the projects' impacts on the domestic supply chain.
- Concentrate resources in the next three to five years to address critical barriers on hydrogen production, storage, transport, and fueling infrastructure to achieve the 2026 hydrogen cost target.
- Conduct component analysis to develop component-level metrics.
- Quantify performance tradeoffs for the technologies being developed within the subprogram.
- Determine which legacy projects within the subprogram were most successful and identify their most critical elements.
- Prioritize the use of safe, secure, economical, and reliable sources of materials.
- Increase the amount of research conducted on near-term, high-TRL technologies without reducing the amount of research on mid- and long-term, lower-TRL technologies.
- Critically evaluate projects to be funded through the BIL for their ability to accelerate industry's implementation of large-scale hydrogen production, distribution, and use.

In the Hydrogen Production category, reviewers commended the subprogram for adding alkaline and anion exchange membrane electrolyzers to the portfolio. Reviewers confirmed that R&D of the following topics remains necessary:

- Both basic and applied electrolyzer R&D
- Assessment of trade-offs between performance and durability for electrolyzers from a deployed system capital expenditure perspective

- R&D on platinum-group-metal (PGM) catalysts for PEM electrolysis, as well as R&D to enable thinner PEMs with lower hydrogen crossover and higher mechanical strength, R&D on PTLs, and identification of optimal material properties for PEM electrolysis
- Expanded R&D on alkaline electrolyzers, including development of thinner separators
- R&D on balance of plant to improve efficiency
- R&D on biomass/waste pathways
- Materials development for stable Ir-based catalysts at low loadings
- Advanced characterization, modeling, baselining, and focused materials development to enable electrolyzer operation at current density of 5 A/cm^2 or higher
- Accelerated R&D on anion exchange membrane electrolyzers, including durable ionomers
- Continued early-stage R&D in areas such as proton-conducting SOECs.

The Program is encouraged to use new funding through the BIL for new applied projects in key electrolyzer components and system concepts, including investment in high-TRL electrolyzers that can move beyond R&D to process development and scale-up to reduce capital costs. While one reviewer questioned whether there is sufficient benefit to warrant continued research into fossil-fuel-based hydrogen production, another cautioned the Program not to penalize “gray” hydrogen. Similarly, there were conflicting opinions regarding the appropriate amount of R&D on non-PGM catalysts for electrolysis to include in the portfolio. Individual reviewers made the following remarks for consideration:

- The major Chinese electrolyzer manufacturers could be benchmarked as a measure of U.S. competitiveness in the electrolyzer market.
- Universities are underfunded relative to the national laboratories, despite their advantages in tackling certain fundamental issues.
- Funding should be more equitably distributed between low-temperature and high-temperature electrolysis.

In addition to research needs, individual reviewers had suggestions regarding hydrogen production analysis needs:

- The electricity cost assumption used in the electrolysis analyses is too low and should include transmission and distribution costs.
- The entire value chain should be analyzed to ensure viable goals and accurate cost status, including buffering costs when hydrogen is made from intermittent electricity sources yet downstream users require uninterrupted feed for continuous operations.
- The war in Ukraine and the drought conditions and scarcity of water have impacts on hydrogen analyses.

Additional recommendations related to the Hydrogen Production portfolio include implementing a prize where the award is a federal fleet off-take agreement for the first organization to demonstrate $1/kg production with a hydrogen price that can compete with conventional fuel; implementing seed programs for high-risk, high-reward research; and focusing on supply chain development.

In the Hydrogen Infrastructure category, reviewers recommended analysis of the integration of renewable power, grid capacity, and hydrogen production at the point of use to understand how to minimize transport of hydrogen. R&D and materials testing for hydrogen pipelines should accelerate. Small engineered underground hydrogen storage, LH2 storage, liquefaction technology, fueling interfaces for LH2, and transport and distribution of hydrogen are underrepresented in the Hydrogen Technologies subprogram portfolio.

In the Hydrogen Storage category, reviewers identified the need for accelerated development of hydrogen storage technologies, liquid carriers, and materials for high-pressure tanks. Also needed are new approaches to reducing the cost of CF for fiber-reinforced tanks. One suggestion is a joint materials discovery program for high-strength materials for high-pressure tanks; the co-sponsors would be the Office of Energy Efficiency and Renewable Energy and the Office of Basic Energy Sciences. One reviewer cautioned against de-emphasizing hydrogen storage and carriers in light of the focus on meeting the Hydrogen Shot goal. Another reviewer suggested that successful development of solid-state hydrogen storage would warrant the investment.

Challenges

While some reviewers felt the challenges to the Program goals were well-articulated and plans were adequately formulated, others felt more discussion of barriers, assessment of risks to overcome barriers, and definition and prioritization of the challenges would be useful. The Program could address the specifics of the R&D steps to achieve the goals, present a detailed pathway for achieving the progression of TRLs, and illustrate the relative TRL and manufacturing readiness level of its accomplishments. More discussion of quantifying and controlling emissions from hydrogen projects would be welcome; there is a need to identify the challenges in overcoming the energy and greenhouse gases involved in producing hydrogen at large scales. According to one reviewer, hydrogen storage remains a critical issue and should receive more attention at the Annual Merit Review.

Another challenge is the lack of a clear pathway to unsubsidized renewable energy to produce hydrogen at $1/kg. There was no mention of the significant materials-related infrastructure that is needed to meet the goals. It was not clear that the targets address return on investment and operating costs. One reviewer observed insufficient involvement and support for (1) the smooth transition of energy technologies without significant disruption and (2) economic and secure supply chains that benefit all stakeholders. There is a need for improved and increased coordination with stakeholders, industry, communities, supply chains, and others.

Clean Hydrogen Electrolysis Program

The Clean Hydrogen Electrolysis Program has well-thought-out and well-articulated plans. One reviewer recommended more strongly favoring advanced concepts to improve the chances of meeting the Hydrogen Shot goal; another recommended increasing the emphasis on hydrogen compression to improve system-level reliability for the electrolysis program.

Consortia

As noted in the Hydrogen Program Overview, reviewers praised the Program's consortia approach for its efficiency, innovation, and success and encouraged the Program to enhance the visibility of its consortia, while cautioning that care must be taken to avoid management and coordination challenges. Industry engagement with the HydroGEN and H2NEW consortia is important; such collaboration would help advance electrolyzer technology to meet the Program's goals. HydroGEN is an extremely effective consortia model, though one reviewer felt that some of the lab node collaborations in HydroGEN are not very effective and recommended development of a clear set of metrics for evaluation and feedback of the lab nodes program. Although HydroGEN's important work should continue, it is unlikely to contribute to achievement of the Hydrogen Shot goal; perhaps the consortium's research focuses should be reconsidered. H2NEW has "unparalleled technical understanding and capabilities" (to quote one reviewer), although technical efforts within H2NEW and HydroGEN seem to overlap.

The HyMARC consortium was not discussed in detail during the Annual Merit Review. It was unclear whether the consortium's research priorities have changed or any of its research directions have been or will be discontinued. One reviewer remarked that HyMARC continues to focus on material evaluation to meet long-term goals for low cost and high volumetric and gravimetric efficiencies, while another commented that it is difficult to see a clear path to any material that will meet the goals. One reviewer recommended that HyMARC consider developing specific hydrogen storage materials for the less challenging applications beyond passenger vehicles, including one-way hydrogen storage materials for hydrogen cartridges.

International

The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) provides a vehicle for U.S. experts to participate in development of an international low-carbon or renewable hydrogen standard, addressing the need for alignment and standardization of clean hydrogen production and distribution evaluation methods, metrics, targets, and implementation. Verifiable, trusted, certified, and consistent hydrogen life cycle performance is needed, as well as international alignment on strategies and use cases for support of or preference for certain hydrogen distribution and use life cycles, especially concerning methods of transport, distribution, and hydrogen delivery. Also needed are more standard methods and terminology related to environmental performance and the engineering and technology language used. The Program is encouraged to share and spread the consortia approach in other countries to create bridges and to leverage electrolysis progress and knowledge outside the United States through international collaboration.

Fuel Cell Technologies – 2022

Subprogram Overview

Introduction

Fuel cells convert the chemical energy of hydrogen or other fuels into electricity and deliver power for applications across multiple sectors. Fuel cells also provide long-duration energy storage for the grid in reversible systems. The Fuel Cell Technologies (FCT) subprogram applies innovative research, development, and demonstration (RD&D), with the main goal of developing a diverse portfolio of low-cost, durable, and efficient fuel cells that are competitive with incumbent and emerging technologies across applications.

The subprogram's RD&D strategy is target-driven, with technical targets developed for different fuel cell technologies, specifically considering end-use requirements. In this holistic approach, the subprogram develops targets based on the ultimate life cycle cost of using fuel cell systems in diverse applications. Building on previously developed comprehensive technical targets in areas such as light-duty vehicles, the subprogram continues to develop and refine additional 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 focus is primarily on heavy-duty vehicles, which have more stringent durability requirements than light-duty vehicles. Advances in heavy-duty vehicle fuel cells will also offer transferrable benefits for light-duty, medium-duty, and stationary power fuel cell applications.

The subprogram strategically addresses crosscutting challenges for fuel cell development through focus on materials and components (especially low-platinum-group-metal [low-PGM] and PGM-free catalysts and electrodes); systems integration (stacks, system design, and balance-of-plant [BOP] components); and analysis and modeling.

Goals

The FCT subprogram's goal is to develop fuel cell technologies that are competitive with incumbent and emerging technologies across diverse applications.

Specific objectives of the subprogram include:

- Developing fuel cell systems, including stack and BOP components, with an emphasis on systems that are highly durable, efficient, and low-cost, while meeting the needs and constraints of varied heavy-duty transportation applications for the near to mid-term.
- Developing new materials and components for next-generation fuel cell technologies for transportation, distributed power, and long-duration grid-scale energy storage, emphasizing innovative mid- to long-term approaches.

Key Milestones

By 2030

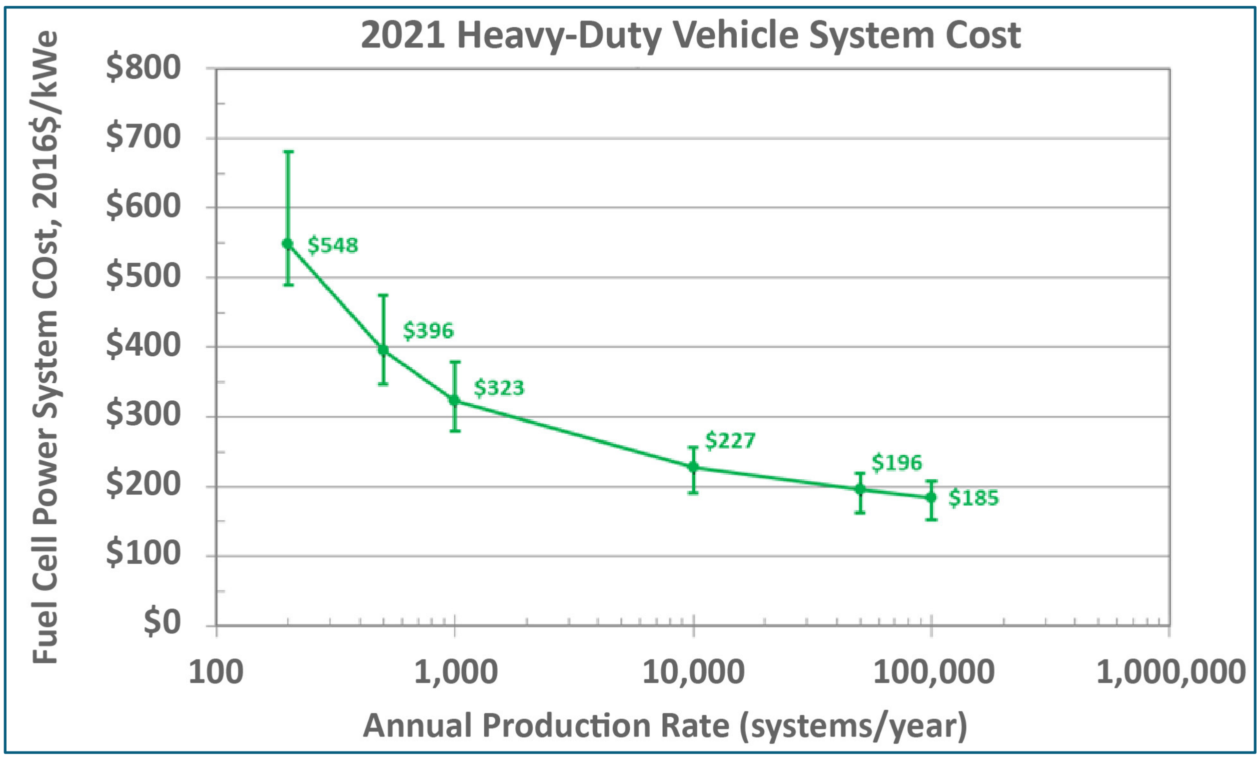
- Develop a 68% (ultimately 72%) peak-efficient direct hydrogen fuel cell power system for heavy-duty trucks that can achieve durability of 25,000 hours (ultimately 30,000 hours) and be mass-produced at a cost of $80/kW (ultimately $60/kW).
- Develop medium-scale distributed generation fuel cell power systems (100 kW–3 MW) operating on renewable fuels, such as renewable natural gas or biogas, that achieve 65% electrical efficiency and 80,000-hour durability at a cost of $1,000/kW.
- Develop reversible fuel cells for energy storage applications that can achieve 40,000-hour durability at a cost of $1,800/kW ($0.20/kWh levelized cost of storage).

Fiscal Year 2022 Technology Status and Accomplishments

One of the most important metrics used to guide the FCT subprogram's RD&D efforts is the projected high-volume manufacturing cost for fuel cells, which is tracked for a range of production volumes. The chart below shows projected costs, based on production volume, of a 275 kW_{net} polymer electrolyte membrane fuel cell (PEMFC) system for a Class 8 long-haul heavy-duty truck based on next-generation laboratory technology[1] and operating on direct hydrogen. Estimates decrease from $323/$kW_{net}$ for a volume of 1,000 units/year to $196/$kW_{net}$ for a volume of 50,000 units/year to $185/$kW_{net}$ for a volume of 100,000 units/year.

These costs include design aspects for enhanced durability anticipated to achieve the one million miles (25,000 hours) of fuel cell system performance needed for long-haul trucks. Durability aspects include stack oversizing (allowing for fuel cell degradation), the use of mono-metallic Pt cathode catalyst at a high loading, 20-micron-thick membranes, and BOP replacement costs.

The subprogram is targeting a cost reduction for heavy-duty vehicle fuel cells to $80/kW by 2030. Long-term competitiveness with alternative powertrains is expected to require further cost reduction to $60/kW, which represents the subprogram's ultimate cost target. To meet these targets, further improvements are needed through RD&D efforts to enhance fuel cell power density and durability, lower PGM loading, and demonstrate manufacturing innovations to enable economies of scale.



Modeled cost of a 275 kW_{net} PEMFC system based on projection to high-volume manufacturing (100,000 units per year) for 2021.

[1] The projected cost status is based on an analysis of state-of-the-art components that have been developed and demonstrated through the U.S. Department of Energy (DOE) Hydrogen Program at the laboratory scale. Additional efforts would be needed for integration of components into a complete commercial vehicle system that meets durability requirements in real-world conditions.

Million Mile Fuel Cell Truck Consortium (M2FCT)

The mission of the M2FCT consortium is to advance PEMFC efficiency and durability and to lower PEMFC cost, thereby enabling PEMFC commercialization for heavy-duty vehicle applications. M2FCT consists of a core lab team, affiliate labs, and industry and university partners selected through competitive solicitations (funding opportunity announcements [FOAs]).[2] A "team-of-teams" approach is being used, featuring collaborative groups in analysis, durability, integration, and materials development. The objective for fuel cell development efforts under this consortium combines efficiency, durability, power density, and (implicitly) cost in a single metric: 2.5 kW/gPGM power (1.07 A/cm^2 current density at 0.7 V) after 25,000 hour-equivalent accelerated stress tests (ASTs).

The consortium has achieved the following:

- M2FCT labs established a baseline catalyst and membrane electrode assembly (MEA) performance, based on commercially available Pt/C, to meet heavy-duty durability requirements.
- Los Alamos National Laboratory (LANL) and Brookhaven National Laboratory (BNL) developed intermetallic PtCo and PtNi catalysts that outperformed the baseline commercial catalyst for heavy-duty fuel cells by >25% at beginning of life and by >45% after a 90,000-cycle AST (A/cm^2 at 0.8 V).
- Carnegie Mellon University and partners demonstrated a novel high-oxygen permeability ionomer. It has twice the oxygen permeability of the conventional ionomer, improves catalyst mass activity by 60%, and lowers local O_2 transport resistance by 50%. Conventional ionomers have restricted O_2 transport that can reduce performance and durability over long heavy-duty vehicle lifetimes.
- General Motors and partners addressed the issue of fuel cell degradation by introducing approaches to tackle cerium migration. Cerium is used in radical scavengers to improve chemical stability, but cerium salt-based additives migrate during operation. The project demonstrated membranes with immobilized radical scavengers (heteropoly acid, dispersed cerium zirconium oxide nanofibers) with enhanced durability compared to membranes with no additives.
- M2FCT developed fuel cell ASTs that are representative of heavy-duty vehicle operation and consider catalyst, catalyst support, and membrane degradation. Temperature and potential cycling were used as primary acceleration factors in a 500-hour H_2/air AST to simulate the high durability requirements (25,000 hours) of heavy-duty vehicle operation.

ElectroCat 2.0

The mission of the Electrocatalysis Consortium (ElectroCat) is to develop durable PGM-free catalysts for PEMFCs and for low-temperature electrolyzers as low-cost alternatives to PGM catalysts, addressing critical mineral supply challenges. The ElectroCat core lab team includes ANL, LANL, NREL, and ORNL. In Fiscal Year (FY) 2022, the performance of PGM-free cathode catalysts in H_2/air was improved by 25% over the FY 2021 baseline using ElectroCat-developed test protocols.

Anion Exchange Membrane (AEM) Fuel Cell Development

AEM fuel cell RD&D continued in FY 2022 with two main projects at LANL and NREL. Efforts resulted in reducing PGM loadings to 0.2 mg PGM/cm^2 for AEM fuel cells while maintaining performance (100 mW/cm^2 at 0.8 V with back pressure under 250 kPa in H_2/air scrubbed to 2 ppm CO_2).

Small Business Innovation Research (SBIR)/Small Business Technology Transfer Research

Two small business projects, one led by pH Matter, LLC, and one by Giner, Inc., attained noteworthy results. The former project developed a new fuel cell catalyst support showing improved durability while maintaining performance and cost. The pH Matter team achieved the end-of-life target (1.07 A/cm^2 at 0.7 V) after heavy-duty

[2] The core labs are Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), Argonne National Laboratory (ANL), National Renewable Energy Laboratory (NREL), and Oak Ridge National Laboratory (ORNL). The affiliate labs are Brookhaven National Laboratory, Pacific Northwest National Laboratory, and National Institute of Standards and Technology.

ASTs and outperformed commercial catalysts tested under similar conditions. Target power performance of over 1 W/cm^2 was also achieved with this MEA. This multifunctional catalyst support is based on doped carbon with optimized "accessible" pore structure and tuned hydrophobicity.

Giner worked with partner University of Buffalo to demonstrate a fuel cell MEA using Giner's 40 wt % Pt/Mn-N-C catalyst. The MEA was a combination of a highly stable catalyst incorporated with a novel Mn-N-C support and a high O_2 permeability ionomer. The resulting product meets end-of-life performance and durability targets after a 150,000-cycle AST under heavy-duty vehicle conditions (equivalent to 25,000-hour lifetime).

Minority Serving Institutions Partnership Program (MSIPP)

In FY 2022, LANL developed the MSIPP to grow the interest of minority-serving institutions (MSIs) in participating in hydrogen- and fuel-cell-related research and to help produce more qualified candidates from underrepresented colleges and universities for the hydrogen and fuel cell workforce. The MSIPP fosters relationships between MSIs, the national lab, and industry partners. Efforts are ongoing to formalize collaborations with commercial entities such as Pajarito Powder, Plug Power Inc., and Chemours through memorandums of understanding.

In its inaugural year, the program welcomed and supported eight participants who were awarded summer internships and helped perform cutting-edge fuel cell research at LANL. Lab staff planned several additional activities to help grow MSI participation, including fall and spring internships, MSI campus tours, and a hydrogen and fuel cell week at LANL.

New Project Selections

FY 2022 SBIR Phase II

- pH Matter, LLC (Columbus, Ohio): Multi-Functional Catalyst Supports (Phase IIC)
- Giner, Inc. (Newton, Massachusetts): Durable High-Efficiency Membrane and Electrode Assemblies for Heavy-Duty Fuel Cell Vehicles (Phase II)

FY 2022 SBIR Phase I

- Supercool Metals (Branford, Connecticut): Durable Bulk Metallic Glass Catalysts for Medium- and Heavy-Duty PEM [Polymer Electrolyte Membrane] Fuel Cells

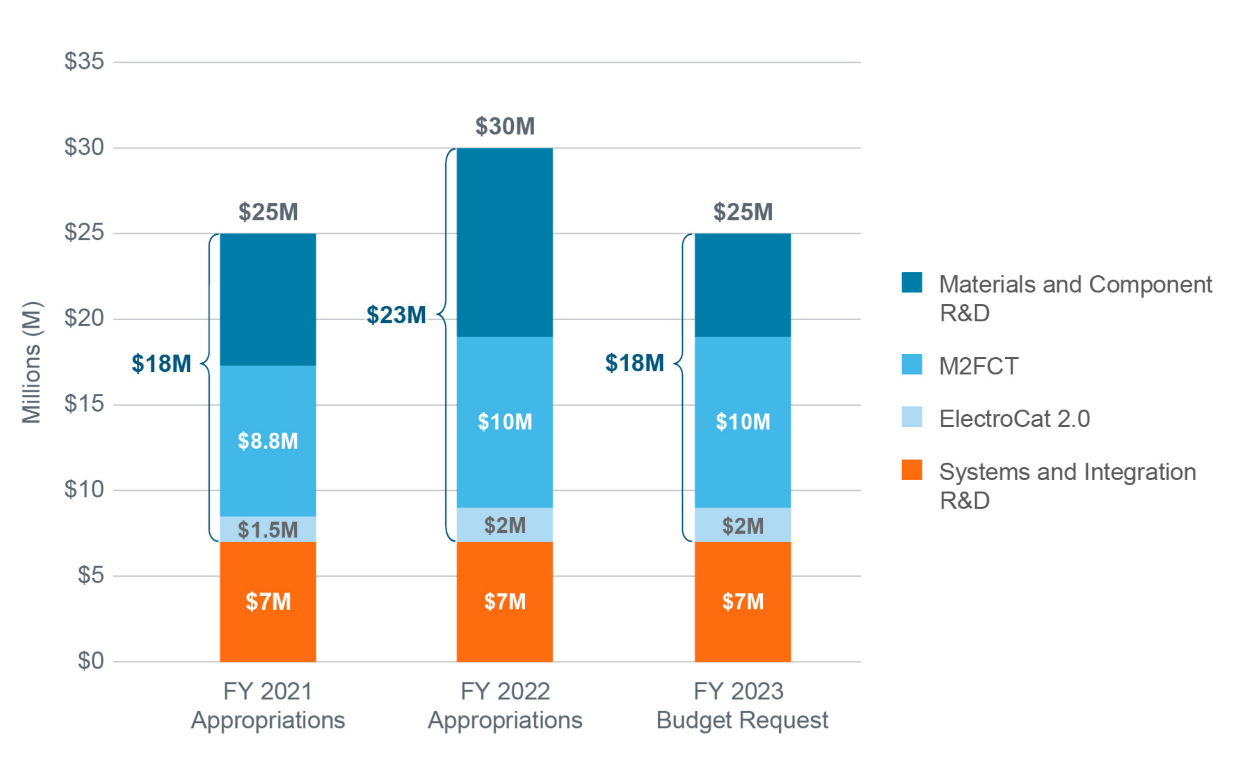
FY 2022 Hydrogen and Fuel Cell Technologies Office FOA

- Planned for release in early FY 2023, this FOA will cover fuel cell components and materials.

Budget

The FY 2021 appropriation was $25 million. The FCT subprogram funded RD&D efforts in two key areas: (1) materials and components and (2) systems integration. Funding was dedicated to the two national laboratory consortia, M2FCT and ElectroCat 2.0, with M2FCT receiving most of the consortia funding (see the chart below). Funding for research into fuel cell materials and components focused on areas such as novel, low-cost manufacturable bipolar plates, MEA components with enhanced durability, and PGM-free catalysts/electrodes. Funding for research into fuel cell systems integration focused on stacks, BOP components (for air management), and systems cost and performance analysis.

The FY 2022 appropriation was $30 million. The FCT subprogram continued its support, at FY 2021 funding levels, of M2FCT and ElectroCat 2.0. Funding for research into fuel cell materials and components focused on additional development of novel, high-performing, durable, low-PGM catalysts incorporated into MEAs for fuel cell trucks. Funding for systems integration primarily supported the newly awarded SuperTruck III projects that included fuel cell technologies as part of these advanced medium-duty truck demonstrations.



The Bipartisan Infrastructure Law adds Section 815 to the Energy Policy Act to support the clean hydrogen supply chain. In response, the FCT subprogram initiated plans in FY 2022 to implement a new clean hydrogen manufacturing and recycling RD&D program, funded (in accordance with Section 815) at $100 million per year over the next five years for a total of $500 million. The planning activities included several workshops and a request for information—both to gather stakeholder input—and coordination with other DOE offices. Additionally, a supply chain analysis was completed, per White House directive, that provided useful information on availability of critical minerals and other materials and components for the clean hydrogen and fuel cell industry in the United States.

Project Summaries

Below are brief FCT project summaries of oral presentations given during the 2022 Annual Merit Review. The full list of projects, including oral and poster presentations, is provided in Appendix D.

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	10/1/2021–9/30/2024
Partners/Collaborators	• National Renewable Energy Laboratory • Oak Ridge National Laboratory

Project Goal and Brief Summary

ElectroCat, which was created as part of the Energy Materials Network, aims to accelerate the development of next-generation catalysts and electrodes that are free of the PGMs currently required for good performance and durability. ElectroCat has focused its efforts on oxygen reduction reaction catalysis for PEMFCs and has established a portfolio of unique synthesis, experimental, characterization, and modeling capabilities. ElectroCat 2.0 has increased focus on improving catalyst durability, investigating electrode engineering, and further advancing high-throughput catalyst synthesis and characterization capabilities coupled with machine learning while still working to improve catalyst performance. The consortium has also expanded its catalyst portfolio to include the development of PGM-free catalysts for low-temperature electrolysis with an emphasis on alkaline exchange membrane oxygen evolution catalysts.

Project #FC-167: Fiscal Year 2020 Small Business Innovation Research Phase IIA: Multi-Functional Catalyst Support

Minette Ocampo, pH Matter, LLC

DOE Contract #	DE-SC0017144
Start and End Dates	05/22/2018–05/20/2022
Partners/Collaborators	• Giner, Inc. • National Renewable Energy Laboratory • Shyam Kocha Consulting

Project Goal and Brief Summary

The research team developed a multi-functional catalyst support for use in PEMFCs to enhance durability. Researchers demonstrated catalyst performance and durability required of MEAs for heavy-duty vehicle applications. The project will continue to optimize the synthesis of the catalyst support to enable higher power and extended durability performance. Heavy-duty ASTs were performed to evaluate the catalyst durability, and the MEA met the DOE 2025 M2FCT end-of-life target of 1.07 A/cm^2 at 0.7 V.

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	10/1/2019–2/28/2023
Partners/Collaborators	• 3M Company • Pajarito Powder, LLC • Colorado School of Mines • Cornell University • Million Mile Fuel Cell Truck Consortium

Project Goal and Brief Summary

This project aims to develop highly stable catalysts and more durable membrane materials for use in direct hydrogen-fed PEMFC MEAs in medium-duty and heavy-duty truck applications. The materials will feature low cost (using less PGM), 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 #FC-326: Durable Membrane Electrode Assemblies for Heavy-Duty Fuel Cell Electric Trucks

Vivek Murthi, Nikola Motor Company

DOE Contract #	DE-EE0008820
Start and End Dates	Q3 2020–Q3 2023
Partners/Collaborators	• Georgia Institute of Technology • Northeastern University • Carnegie Mellon University • Los Alamos National Laboratory • National Renewable Energy Laboratory • Oak Ridge National Laboratory

Project Goal and Brief Summary

This project will fabricate, characterize, and evaluate an MEA with a novel catalyst layer incorporating a "nanocapsule" electrode structure that separates ionomer and platinum to maximize activity while allowing ionic transport. If successful, this project will allow for better use of highly active and/or highly durable catalysts and the bridging of the activity gap between rotating disk electrodes and MEAs.

Project #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	10/1/2019–1/31/2023
Partners/Collaborators	• The Chemours Company • Ballard Power Systems, Inc. • Million Mile Fuel Cell Truck Consortium

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 an MEA, and (3) optimize the design of the ionomer for commercialization. If successful, the project will facilitate low platinum loadings in an advanced MEA cathode catalyst layer for heavy-duty vehicles.

Project #FC-333: Advanced Membranes for Heavy-Duty Fuel Cell Trucks

Vivek Murthi, Nikola Motor Company

DOE Contract #	DE-EE0009243
Start and End Dates	Q3 2021–Q3 2024
Partners/Collaborators	• The Chemours Company • Million Mile Fuel Cell Truck Consortium

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 MEAs in heavy-duty fuel cell vehicles, reduce the lifetime operational expenses of heavy-duty fuel cell systems, and improve their commercial viability relative to diesel energy sources. Nikola Motor Company is collaborating with The Chemours Company and M2FCT on this project.

Project #FC-334: Extending Perfluorosulfonic Acid Membrane Durability through Enhanced Ionomer Backbone Stability

Michael Yandrasits and Gregg Dahlke, 3M Company

DOE Contract #	DE-EE0009244
Start and End Dates	1/1/2021–12/31/2023
Partners/Collaborators	• National Renewable Energy Laboratory • General Motors

Project Goal and Brief Summary

This project aims to increase membrane lifetimes by improving the inherent chemical stability of perfluorinated membrane ionomers. If successful, the project will increase fuel cell lifetimes and allow fuel cells to meet the DOE 2030 heavy-duty transportation target of 25,000 hours of operation.

Project #FC-335: Additive Functionalized Polymers for Extended Heavy-Duty Polymer Electrolyte Membrane Lifetimes

Tom Corrigan, The Lubrizol Corporation

DOE Contract #	DE-EE0009245
Start and End Dates	Q2 2021–Q3 2023
Partners/Collaborators	• National Renewable Energy Laboratory

Project Goal and Brief Summary

The Lubrizol Corporation will work with NREL to develop membranes with enhanced chemical durability, with the goal of improving the lifetimes of PEMFCs for heavy-duty vehicles. The research team will identify novel additives to mitigate chemical degradation and find strategies to immobilize these additives, thereby addressing radical scavenger shortcomings. The improved membrane durability could enable PEMFC heavy-duty vehicle lifetimes that achieve the DOE target of 25,000 hours (one million miles for long-haul trucks).

Project #FC-336: A Systematic Approach to Developing Durable Conductive Membranes for Operation at 120°C

Tom Zawodzinski, University of Tennessee, Knoxville

DOE Contract #	DE-EE0009246
Start and End Dates	10/1/2020–1/31/2024
Partners/Collaborators	• Oak Ridge National Laboratory • Akron Polymer Systems

Project Goal and Brief Summary

This project aims to develop membranes with sufficient performance and lifetime to meet the requirements of long-term applications of PEMFCs for heavy-duty 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 that reflect operating conditions in heavy-duty 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.

Project #FC-337: Cummins Polymer Electrolyte Membrane Fuel Cell System for Heavy-Duty Applications

Darren Hickey, Cummins Inc.

DOE Contract #	DE-EE0009247
Start and End Dates	8/1/2021–7/31/2024
Partners/Collaborators	• Cummins Hydrogenics • Argonne National Laboratory • W.L. Gore & Associates, Inc. • Dana Incorporated • Cummins Turbo Technologies

Project Goal and Brief Summary

The objective of this project is to develop and demonstrate a new standardized, modular, and scalable 100 kW PEMFC stack that meets performance, efficiency, durability, and affordability requirements for heavy-duty applications. 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; ANL; W.L. Gore & Associates, Inc.; and Dana Incorporated.

Project #FC-338: Domestically Manufactured Fuel Cells for Heavy-Duty Applications

John Lawler, Plug Power Inc.

DOE Contract #	DE-EE0009248
Start and End Dates	5/1/2021–5/1/2024
Partners/Collaborators	• Argonne National Laboratory

Project Goal and Brief Summary

Plug Power Inc. is working with ANL to develop a heavy-duty 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 and 100 kW modular stack systems to create a reliable and efficient stack with improved durability, cost-effectiveness, and performance.

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	• Los Alamos National Laboratory • Lawrence Berkeley National Laboratory • Argonne National Laboratory • National Renewable Energy Laboratory • Oak Ridge National Laboratory • Pacific Northwest National Laboratory • Brookhaven National Laboratory

Project Goal and Brief Summary

The project team is working to construct fuel cells that provide 2.5 kW of power per gram of PGM after a 25,000-hour-equivalent accelerated durability test. The purpose is to create durable and efficient fuel cell designs suitable for adoption by the heavy-duty vehicle market.

Project #FC-353: Fuel Cell Cost and Performance Analysis

Brian D. James, Strategic Analysis, Inc.

DOE Contract #	DE-EE0009628
Start and End Dates	10/01/2021–09/30/2025
Partners/Collaborators	• National Renewable Energy Laboratory • Argonne National Laboratory

Project Goal and Brief Summary

This project's primary goal is to develop fuel-cell-centric technoeconomic analysis models based on Design for Manufacture and Assembly, 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 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 #FC-354: L'Innovator Program

Emory S. De Castro, Advent Technologies, Inc.

DOE Contract #	Multiple
Start and End Dates	04/1/2021–03/31/2023
Partners/Collaborators	• Los Alamos National Laboratory • Brookhaven National Laboratory • National Renewable Energy Laboratory

Project Goal and Brief Summary

The L'Innovator ("Lab Innovator") was developed to enable a robust domestic fuel cell industry by assembling bundles of unique, state-of-the-art national lab intellectual property and facilitating their development by a commercialization partner. This pilot project for L'Innovator, led by Advent Technologies, focuses on demonstrating a minimum viable product of high-temperature, polymer electrolyte MEAs, using LANL's ion-pair coordinated membrane and MEA technology and BNL's core catalyst technology. With the technology's viability confirmed, the project team will scale up these next-generation MEAs and demonstrate their benefits in stacks or systems. Anticipated outcomes include lower costs, better durability, higher efficiency, and higher power density.

Project #FC-356: Durable High-Efficiency Membrane Electrode Assemblies for Heavy-Duty Fuel Cell Vehicles

Hui Xu, Giner, Inc.

DOE Contract #	DE-SC0021671 (SBIR)
Start and End Dates	06/28/2021–06/27/2022
Partners/Collaborators	• University at Buffalo (State University of New York) • Compact Membrane Systems • Indiana University and Purdue University Indianapolis • University of Connecticut • Oak Ridge National Laboratory of the Million Mile Fuel Cell Truck Consortium

Project Goal and Brief Summary

This project aims to develop robust MEAs for heavy-duty vehicles. Researchers will develop a catalyst using highly active and stable Pt or PtCo nanoparticles, with well-controlled particle size and composition for enhanced performance and durability. The catalyst will be integrated with a high oxygen permeability ionomer to improve fuel cell performance. Researchers will then determine the optimal variables for preparing inks and MEAs using the newly developed catalysts. The developed MEAs will be evaluated using M2FCT ASTs.

Annual Merit Review of the Fuel Cell Technologies Subprogram

Summary of Fuel Cell Technologies Subprogram Reviewer Comments

This section provides a summary of the reviewers' remarks. The content reflects those inputs only and not the views of Program management. The complete set of review comments received is provided as Appendix A.

Fuel Cell Technologies Subprogram Portfolio and Technology Applications

Overall, the FCT subprogram is well-balanced across near-, mid-, and long-term research and development and is consistently strong, appropriately aligning priorities and investments. While significant innovation in fuel cells has traditionally been fostered and important challenges have clearly been identified, more work is needed to prioritize and connect these challenges to the process of meeting the goals.

The decrease in the Program's 2023 FCT budget request, when the overall Program budget is increasing, is a concern. Although outstanding progress has been made in improving fuel cell performance and reducing costs, the shift in focus from light-duty vehicles to medium- and heavy-duty vehicles makes cost goals more challenging to achieve, as durability requirements are also increased. Moreover, despite advancements in light-duty fuel cell vehicles, improvements are still needed, especially in durability and costs. Furthermore, reducing funding for fuel cell research and development is premature, as significant performance and cost challenges remain for heavy-duty vehicle applications. Thus, the budget for fuel cell research should be increased to achieve the more challenging goals.

The heavy-duty vehicle market alone may not generate the demand needed in the transportation sector to reduce the cost of hydrogen to the Hydrogen Shot goal or to enable widespread commercialization. Researchers should also consider cost breakthroughs needed to achieve a cost-effective heavy-duty fuel cell system. The FCT subprogram is focusing on decreasing the fuel cell stack cost by 80% and has identified which components will need to be improved to meet this goal; however, during the Annual Merit Review, there was no clear expression of how much cost reduction would actually be possible with each component. Moreover, light-duty fuel cell vehicles could remain a zero-emission-vehicle option for fleet vehicles and for drivers whose vehicle range and refueling needs are not met by battery electric vehicles. The subprogram should communicate clearly where the advances in one application may or may not be transferrable to the other and to keep stakeholders appropriately informed.

Research Focus

The research focus of the FCT subprogram has been changing in the past couple years, with some previous achievements being put aside to some extent, which could result in losing capabilities that could benefit both fuel cells and electrolyzers.

Some research areas are underrepresented, while others have too much focus:

- Non-PGM catalysts are over-represented. While these catalysts hold great promise for addressing cost in the long term, they also remain far from commercial viability. Also, the effect of decreased performance of non-PGM catalysts compared to PGM-based catalysts might bring forth different design considerations, such as larger fuel cell stacks, more bipolar plates, or more membranes.
- Off-road fuel cell electric vehicles are underrepresented.
- The fuel cell BOP should have greater emphasis.
- The reduced emphasis on solid oxide fuel cell research is concerning. Industry is still interested in commercializing the technology, and these higher-temperature fuel cells have a vital role to play in stationary power generation applications and do not require the use of precious metals. However, there are many important challenges to overcome, requiring supportive funding and more emphasis on the current state of solid oxide fuel cell technology. Furthermore, the split between low-temperature fuel cells (with higher technology readiness levels) and high-temperature fuel cells (with lower technology readiness levels) seems out of balance; future funding and research should be more balanced.

Regarding sub-cell and cell-level fuel cell research, there is a need to reevaluate the tradeoff between near-term high performance and long-term stability, as the techniques that achieve high-performing electrochemical cells often do not persist and may require replacing the expensive electrochemical hardware more frequently.

Recycling of fuel cell components is another matter of interest. While it is a longer-term issue, recycling fuel cell stacks, systems, and vehicles could receive more focus. There should be more emphasis on refurbishing fuel cells rather than recycling them, as most of the value (other than the PGMs) is in the structure of the materials, rather than in the metal. This is particularly true of bipolar plates and of advanced catalysts with no PGMs.

Consortia

The consortium approach is innovative and enables timely progress toward addressing challenging problems. However, the consortia need more visibility. Many of the small businesses that are only tangentially related to the hydrogen and fuel cell industry are unaware of these consortia and the potential benefits of participating. Such businesses may be more likely to change their business models to support the hydrogen economy if they could leverage the consortia to modify their products to address emerging opportunities.

In addition, the focus of the ElectroCat consortium could be shifted toward developing PGM-free catalysts for AEM electrolyzers over the next three to five years.

Technology Acceleration – 2022

Subprogram Overview

Introduction

The Technology Acceleration subprogram aims to enable the H2@Scale vision and support the Hydrogen Energy Earthshot through targeted hydrogen and fuel cell system integration and demonstration activities. To achieve this mission, Technology Acceleration focuses on:

- Identifying hydrogen applications and system configurations that can provide affordable and reliable clean energy.
- Validating and testing 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's (DOE) Hydrogen Program subprograms. 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 remaining subprogram activities—including manufacturing RD&D; safety, codes and standards; and workforce development—fill out an integrated portfolio that addresses other significant barriers.

The Technology Acceleration subprogram focuses its activities on key emerging markets and technology applications based on preliminary findings of the Systems Analysis subprogram, which identifies technologies and markets with the potential to enable economies of scale for hydrogen and fuel cell systems in alignment with the H2@Scale vision. Based on this analysis, the Technology Acceleration subprogram is currently focused on four technology application areas:

- **Grid energy storage and power generation** applications focus on grid integration and 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.
- **Chemical and industrial processes** are focused on decarbonizing hard-to-decarbonize industrial sectors through integration of hydrogen technologies. These end uses include iron- and steelmaking and ammonia, fuel, and chemical production, among others. The integration of clean hydrogen will reduce greenhouse gas emissions, add jobs, and provide environmental justice in these energy-intensive processes.
- **Transportation** includes medium- and heavy-duty trucks, maritime, rail, 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 fueling to support these transportation modes. Analysis will also be conducted to determine total cost of ownership (TCO) and future targets needed to compete with incumbent technologies.
- **Enabling activities** include manufacturing RD&D; safety, codes and standards; and workforce development. Manufacturing RD&D projects aim (1) to identify and pursue high-value processing routes to accelerate scaling and (2) to develop techniques to produce advanced components and sub-systems to enable multi-megawatt-scale hydrogen systems at high production volumes. These demonstrations also focus on developing technology and analysis tools for quality control and reliability issues. The Safety, Codes and Standards activity area develops codes and standards to enable bulk utilization of hydrogen, as well as safety and permitting guidance to enable deployment of hydrogen for novel applications (see the Safety, Codes and Standards section of this report for more details). Workforce development activities support the development of training programs to enable the safe and effective deployment, use, and maintenance of hydrogen and fuel cell technologies across various applications.

Goals

The overarching goals of the Technology Acceleration 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 Technology Acceleration subprogram are summarized below.

Grid Energy Storage and Power Generation

- Validate large-scale electrolysis systems for energy storage, grid stabilization, resilience, and dispatch management of electric grid systems with high renewable energy penetration.
- Validate efficiency, costs, and benefits of hydrogen production systems 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 (HTE) 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 up to 2 MW.
- 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

- Validate 80,000-hour electrolyzer lifetime and verify clean hydrogen system cost and technical performance comparable with incumbent technologies for metals production.
- Validate 80,000-hour electrolyzer lifetime and demonstrate green ammonia production processes for emission reductions; verify costs and validate technical performance.
- Integrate emerging concepts with industrial processes for production of synthetic fuels and chemicals; verify costs and validate technical performance.
- 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

- Validate 25,000-hour durability and 68% peak efficiency for fuel cells in in heavy-duty truck applications.
- Validate integrated portside power systems and a 35,000-hour durability target for ferry boat shipboard applications.
- Validate onboard hydrogen storage and locomotive power systems for long-distance trains, including a 35,000-hour durability target.
- Validate technical and economic potential of hydrogen and fuel cells for off-road applications.
- 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.

Enabling Activities

- Develop manufacturing and supply innovations to commercialize multi-megawatt-scale electrolyzers that can produce hydrogen at <$1/kg.
- Develop crosscutting low-cost manufacturing processes with scalability in mind to support domestic supply chains.
- Identify opportunities for standardization of components, reduce dependence on critical materials, and foster a robust supply chain.

- Establish a skilled workforce to respond effectively to the expected growth in hydrogen-supported industries.
- See the Safety, Codes and Standards section of this report for additional enabling activity targets.

Fiscal Year 2022 Accomplishments

Subprogram-Level Accomplishments

Technology Acceleration Fiscal Year (FY) 2022 accomplishments are summarized below.

Overall

- Released the $7 billion Regional Clean Hydrogen Hub Funding Opportunity Announcement in collaboration with DOE's Office of Clean Energy Demonstrations, along with extensive stakeholder engagement, public webinars, a request for information, and a notice of intent.

Grid Energy Storage and Power Generation

- Completed over 7,000 cumulative hours of high-temperature electrolyzer system testing and commissioned a simulated integration of an HTE test facility with a nuclear power plant (Idaho National Laboratory [INL]).
- Completed the procurement and design for a 1.25 MW electrolyzer installation at the Nine Mile Point nuclear plant (Constellation).
- Awarded a new project to demonstrate a high-temperature solid oxide electrolyzer integrated with a simulated nuclear plant using electricity and waste heat (FuelCell Energy and INL).
- Awarded two Small Business Innovation Research (SBIR) Phase 2 wind-to-hydrogen projects to model pathways and optimize designs for coupling hydrogen electrolyzers to offshore wind turbines (Giner, Inc. and Alchemr, Inc.).
- Facilitated international collaboration between the United States and Netherlands, including a techno-economic analysis and assessment of knowledge gaps for multiple pathways for offshore-wind-to-hydrogen.
- Commenced building out megawatt-scale hydrogen infrastructure and capabilities at the National Renewable Energy Laboratory's (NREL's) Flatirons campus to enable integrated hydrogen energy system RD&D (e.g., to demonstrate grid services, energy storage, renewable hydrogen production, and innovative end-use applications).
- Awarded four H2@Scale cooperative research and development agreement (CRADA) projects that will leverage NREL's Advanced Research on Integrated Energy System (ARIES) facilities and capabilities to perform integrated hydrogen energy system testing and validation (NREL and industry partners).
- Awarded a new project to develop and demonstrate a grid-forming fuel cell inverter for a microgrid with the potential to enable higher solar photovoltaic penetration and replace the current diesel-powered backup generators at a disadvantaged community in Borrego Springs, California (NREL and San Diego Gas and Electric).

Chemical and Industrial Processes

- Designed and began constructing a direct iron reduction pilot plant facility that will have a production rate of one tonne of iron per week. The pilot system will be capable of operating with hydrogen, natural gas, and various mixtures and will be used to evaluate using hydrogen to decarbonize iron and steelmaking processes to help de-risk industrial investments (Missouri University of Science and Technology).
- Developed system models for hydrogen direct reduction, integrating a solid oxide electrolysis cell (SOEC) module with a direct reduced iron (DRI) furnace, indicating potential energy intensity of less than 8 GJ/ton (crude steel) compared to 19–20 GJ/ton for a traditional blast furnace and basic oxygen furnace (University of California, Irvine).
- Initiated a new modeling and analysis effort focused on reducing cost, improving efficiency, and accelerating renewable energy penetration for integrated clean hydrogen pathways that include hydrogen production from solar or wind energy, optimized to support industrial end-use applications for hydrogen (NREL).

Transportation

- Awarded three SuperTruck 3 projects (Daimler North America, General Motors, and Ford), which will demonstrate a total of 11 medium-/heavy-duty hydrogen fuel cell electric trucks with driving ranges, payloads, and fueling times competitive with incumbent technologies.
- Built ten fuel cell hybrid electric United Parcel Service (UPS) delivery vans entering service in disadvantaged communities in California to reduce local air pollution (Center for Transportation and the Environment).
- Modeled the TCO for hydrogen fuel cell passenger ferry and rail, multiple medium-duty applications, and mining trucks to provide the basis for developing targets necessary to meet incumbent technology performance (Argonne National Laboratory [ANL]).
- Through Mission Innovation Clean Hydrogen, co-hosted the Hydrogen Fuel Cell Off-Road Equipment and Vehicles Workshop focused on mining, construction, and agriculture equipment and established the International Off-Road Working Group for hydrogen and fuel cell vehicles.
- Demonstrated the >10 kg/min average hydrogen fueling rate necessary for heavy-duty transportation applications (NREL).

Enabling Activities

- Engaged in SOEC manufacturing workshops to identify quality assurance/quality control (QA/QC) gaps and performed post-mortem stack characterization on commercial stacks to identify operational and manufacturing issues (Pacific Northwest National Laboratory [PNNL]).
- With the European Commission, co-hosted the Clean Hydrogen JU [Joint Undertaking] Expert Workshop on Environmental Impacts of Hydrogen to identify technical needs and next steps for monitoring and mitigating hydrogen releases into the atmosphere.
- Through Hydrogen Education for a Decarbonized Global Economy (H2DGE) (Electric Power Research Institute [EPRI]), launched five professional workforce development courses, covering basic hydrogen science as well as production, storage, end use, and safety.
- Accelerated progress on safety, codes and standards (see Safety, Codes and Standards section for specific program- and project-level accomplishments).

Project-Level Accomplishments

Grid Energy Storage and Power Generation

Constellation Corporation is integrating a 1.25 MW polymer electrolyte membrane (PEM) electrolyzer at the Nine Mile Point nuclear power plant in New York to provide cost-effective supply of in-house hydrogen. The initial engineering design is 60% complete, while an electrolyzer supplied by Nel Hydrogen has gone through acceptance testing (NREL), demonstrating less than 0.1% degradation over 500 hours of operation. Initial market demand analysis for similar deployments at various sites has been conducted by ANL, and INL developed a front-end controller for optimal electrolyzer dispatching.

Idaho National Laboratory is advancing the state of the art of HTE technology. Over the past year, this project commissioned an HTE test stand integrated with a nuclear power plant emulator and initiated testing of a 100 kW Bloom Energy system, attaining over 7,000 hours to date of cumulative HTE stack testing. INL continues to work with several industry partners—including Bloom Energy, Nexceris, OxEon, FuelCell Energy, Xcel Energy, and Haldor Topsoe—to independently validate stack performance and provide nuclear-simulated integration and testing with the goal of over 10,000 hours of stack and system testing to be completed by the end of 2022.

Pacific Northwest National Laboratory, in collaboration with INL, is addressing important HTE manufacturing issues that adversely affect stack performance and durability and reduce stack manufacturing costs. Over the past year, PNNL developed a process to produce 300 cm^2 active-area SOECs. The project team tested single cells over 2,800 hours at 750°C with minimal degradation, established a stack repeat unit fabrication process, and assembled and tested two 1 kW short stacks with a goal of building and testing a 5 kW stack. SOEC manufacturing workshops were conducted to identify QA/QC gaps, and post-mortem stack characterization on commercial stacks was performed to identify operation and manufacturing issues.

FuelCell Energy is completing design, engineering, procurement, assembly, integration, and demonstration of a solid oxide steam electrolysis system integrated with a simulated nuclear plant at INL. Although newly under way, the project has acquired all materials and the tooling for stack assembly and has initiated stack assembly and factory acceptance testing.

Frontier Energy is determining how hydrogen production costs can be minimized by using multiple generation sources, including steam methane reforming units that use renewable natural gas and electrolysis that uses wind and solar power. Over the course of the last year, Frontier Energy completed the site plans and engineering, began site installation of utilities, and procured major equipment and systems. In support of the plan for the Port of Houston, the team conducted workshops and developed a preliminary techno-economic model with supply and demand hubs.

Caterpillar Inc. is demonstrating hydrogen-fueled backup power for a Microsoft data center. A techno-economic analysis has been completed, and the system and component simulations showed a power capability similar to diesel gensets currently used for backup power.

Giner, Inc. is modeling and validating an integrated energy system designed to produce clean hydrogen using offshore wind power. The modeling performed over the past year predicts hydrogen can be produced at ~$2.20/kg from offshore wind. Researchers determined a tolerance of baseline Pt and Ir loading for common seawater ions, and the design process was initiated for the integrated 250 kW electrolyzer stack with the simulated wind turbine input.

Alchemr, Inc. is developing a low-cost anion exchange membrane water electrolyzer (AEMWE) that can operate using seawater as a feedstock, enabling direct coupling with offshore wind farms. The project has already demonstrated long-term performance of 5 cm^2 AEMWE cells with non-platinum-group-metal anode and cathode catalysts at 0.3 A/cm^2 at 60°C with membrane electrode assembly degradation of 400 µV/h over 1,000 hours.

Chemical and Industrial Processes

University of California, Irvine is showing the technical and economic feasibility of the thermal and process integration between an SOEC module and a DRI furnace, paving the way for production of green steel. Over the past year, the project has developed system models that indicate potential energy intensity of less than 8 GJ/ton (crude steel) compared to 19–20 GJ/ton for a traditional blast furnace and basic oxygen furnace. In addition, SOEC modeling predicts electric-to-hydrogen efficiency less than 35 kWh/kg.

Missouri University of Science and Technology leads the Grid-Interactive Steelmaking with Hydrogen (GISH) project, aiming to de-risk industrial investment in infrastructure for hydrogen-based direct reduction of iron and steelmaking in an electric arc furnace by closing critical knowledge gaps in the current RD&D landscape. Over the past year, the project completed preliminary techno-economic analysis of the GISH process; developed and verified a kinetic model for hydrogen, natural gas, and mixed gas reduction and a DRI melting model; completed the GISH pilot reactor design; and initiated construction.

National Renewable Energy Laboratory is creating a hydrogen scenario analysis tool by developing new models and integrations for the NREL Hybrid Optimization and Performance Platform (HOPP). Although recently launched, the project has already developed the H2OPP analysis tool, which shows potential for renewable hydrogen at less than $2.50/kg in both near- and long-term scenarios.

Transportation

Center for Transportation and the Environment, in partnership with UPS and others, is demonstrating fuel cell hybrid electric delivery vans with fuel cell range extenders. To date, ten delivery vans have been built, five more are currently in various stages of assembly, and a 169-mile max range test was completed. The UPS delivery vans are entering service at UPS service centers, including operation in disadvantaged communities in California.

Cummins has partnered with the U.S. Army Engineer Research and Development Center's Construction Engineering Research Laboratory to develop and demonstrate a hydrogen fuel cell hybrid emergency disaster Class 7 relief truck. The project has completed final vehicle design, and vehicle assembly is currently under way.

Argonne National Laboratory is analyzing the TCO for various transportation applications. Results thus far indicate that fuel cost dominates TCO for passenger rail and ferries. In one example, it was determined that achieving a fuel cell cost of $60/kW and liquid hydrogen bunkered cost of $4/kg H_2 would likely make hydrogen fuel cell ferries cost-competitive with incumbent technologies. In another example, ANL found that a fuel cell cost of $60/kW and liquid hydrogen cost of $3.50/kg H_2 would likely make hydrogen electric multiple-unit passenger rail cost-competitive.

National Renewable Energy Laboratory is collecting and evaluating fuel cell electric bus (FCEB) performance to validate performance and cost using real-world data. Of the 38 FCEBs tracked, 12 surpassed 25,000 hours of operation, while one FCEB demonstrated over 32,000 hours of durability. The average fuel economy of these FCEBs was found to be approximately 9 miles per diesel gallon equivalent (up to two times greater than fuel economy for compressed natural gas or diesel buses), surpassing the target of 8 miles per diesel gallon equivalent. A range of approximately 280 miles was achieved with the buses, documenting progress toward the 300-mile-range target.

Hornblower Energy, LLC is establishing 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. Within the project's first year, Hornblower has been collaborating with the Port of San Francisco, Sandia National Laboratories, and various industry stakeholders to evaluate the performance, efficiency, and feasibility of such a system, while developing related safety protocols. The project has completed evaluation of equipment required for marine environments and design of the hydrogen barge.

Electricore, Inc. is developing, testing, and demonstrating a hydrogen fuel dispenser and nozzle assembly capable of fueling heavy-duty vehicles. Over the last year, the project team has completed the design work and manufacturing of the prototype nozzle components, computational fluid dynamics analysis, and failure modes and effects analysis. External assembly parts were procured, and the setup for dispenser manufacturing was completed.

Electricore has completed design, assembly, and initial testing of an advanced mobile hydrogen refueler capable of fueling 20–40 vehicles per day. The refueler is currently undergoing an upgrade to enable medium- and heavy-duty fueling. It will soon to be available for a fueling demonstration at the Foothill Transit bus station in Pomona, California.

Enabling Activities

National Renewable Energy Laboratory is developing, validating, and transferring technology to support QC diagnostics of membrane electrode assembly manufacturing. Over the past year, this project completed the demonstration and validation of optical transmission imaging of the electrode (IrO_x and Pt/C) loading. Chromatic confocal detectors for electrode thickness measurement were also explored, and the development and hardware fabrication of spatial in situ diagnostic tools for low-temperature electrolyte membrane electrode assembly testing was continued. NREL's partner on this project, Lawrence Berkeley National Laboratory, continued predictive finite element model development on performance impacts of membrane compression and electrode variations.

National Renewable Energy Laboratory is addressing the unknown high-volume scaling costs associated with roll-to-roll processing technologies and the effects on cell and stack manufacturing cost estimates. Over the past year, the project team explored the relationship between applied shear and degree of agglomeration for the coated catalyst layer in gas diffusion electrodes. The team also researched and documented the impact of different support structure types and Pt weighting amounts on ink properties and coating thicknesses for Pt/C fuel cell catalysts.

New Project Selections

In FY 2022, the subprogram added projects through a funding opportunity announcement (FOA) and a CRADA call, as noted below. In addition, FY 2022 selections are pending from the Office of Nuclear Energy industry FOA, jointly funded by the Hydrogen and Fuel Cell Technologies Office (HFTO), and the FY 2022 HFTO Annual Appropriations FOA.

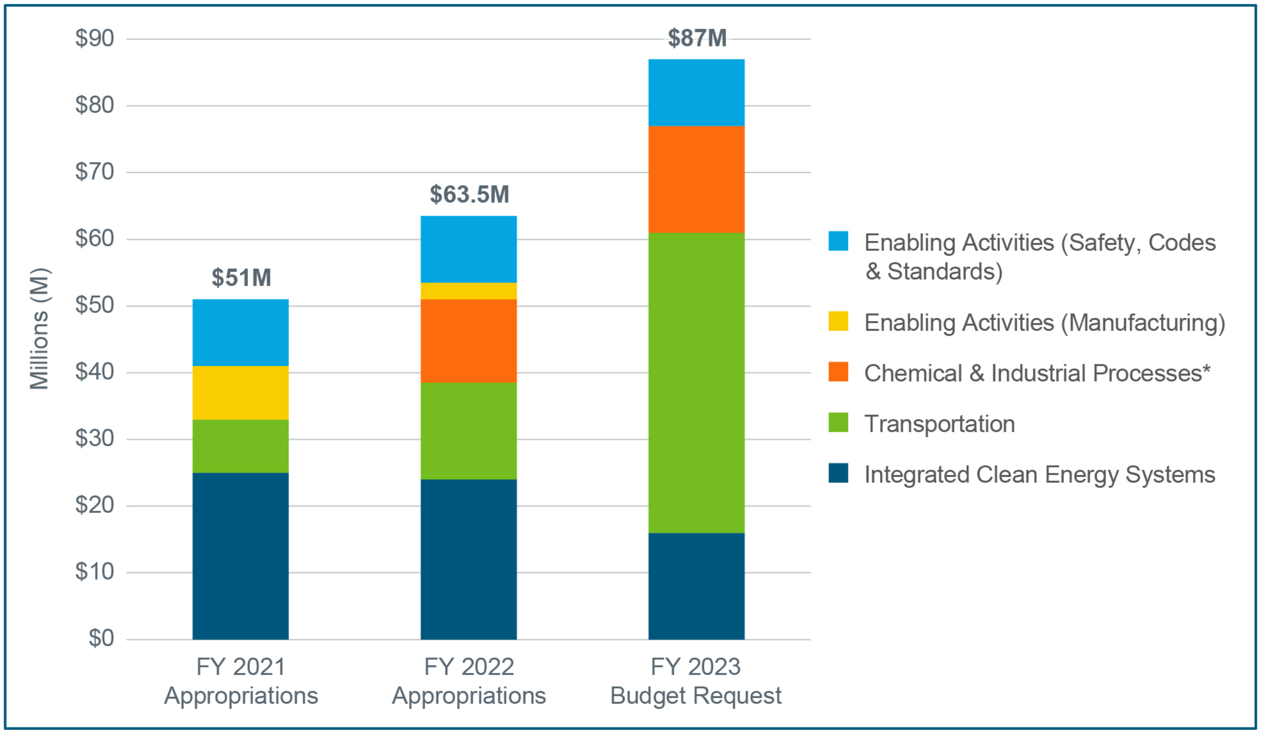
FY 2022 selections included the following:

- Projects selected under the H2@Scale CRADA call supporting ARIES:
  - NREL, GE Renewable Energy, Nel Hydrogen: Optimal Wind Turbine Design for Hydrogen Production (TA-061)
  - NREL, Southern California Gas Company (SoCalGas), University of California, Irvine: Validation of Interconnection and Interoperability of Grid-Forming Inverters Sourced by Hydrogen Technologies in View of 100% Renewable Microgrids (TA-062)

  - NREL, GKN Powder Metallurgy, SoCalGas: Metal Hydride Bulk (520 kg H_2) Storage System Coupled with Electrolysis and Fuel Cell Systems (TA-063)
  - NREL, EPRI**:** Optimize Hydrogen Production Via PEM Electrolysis with Grid Integration and Variable Renewables (TA-064)
- Projects selected under the SuperTruck 3 FOA:
  - Daimler Trucks North America: Ultra-Efficient Long-Haul Hydrogen Fuel Cell Tractor (TA-056)
  - General Motors: Freight Emissions Reduction via Medium-Duty Battery Electric and Hydrogen Fuel Cell Trucks with Green Hydrogen Production (TA-057)
  - Ford Motor Company: High-Efficiency Fuel Cell Application for Medium-Duty Truck Vocations (TA-058)

Budget

The budget for the Technology Acceleration subprogram increased from $51 million in FY 2021 to $63.5 million in FY 2022. The FY 2023 budget request of $87 million includes a significant increase of $23.5 million to continue accelerating efforts to demonstrate and validate low-cost hydrogen production integrated with various hydrogen end uses to enable decarbonization and support the H2@Scale vision. Additionally, $8 billion in funds over five years has been congressionally approved for Clean Hydrogen Hubs through the Office of Clean Energy Demonstrations, in collaboration with HFTO and the Hydrogen Program.



**Includes $7.5 million to fulfill congressional language requirement in coordination with Advanced Manufacturing Office*

Project Summaries

Below are brief Technology Acceleration project summaries of oral presentations given during the 2022 Annual Merit Review. The full list of projects, including oral and poster presentations, is provided in Appendix D.

Project #TA-001: Membrane Electrode Assembly Manufacturing Research and Development

Michael Ulsh, National Renewable Energy Laboratory

DOE Contract #	WBS 10.1.0.501	
Start and End Dates	7/1/2007	
Partners/Collaborators	• General Motors • Mainstream Engineering • Gore, 3M • Nel/Proton • Giner, Inc. • Plug Power	• AvCarb • Lawrence Berkeley National Laboratory • Colorado School of Mines • National Research Council–Canada • Fraunhofer-ISE

Project Goal and Brief Summary

The objectives of this project are to (1) understand QC needs from industry partners and forums, (2) develop diagnostics by using modeling to guide development and in situ testing to understand the effects of defects, (3) validate diagnostics in-line, and (4) transfer technology to industry partners.

Project #TA-018: High-Temperature Electrolysis Test Stand

Micah Casteel, Idaho National Laboratory

DOE Contract #	WBS 7.2.9.1
Start and End Dates	9/30/2020
Partners/Collaborators	• Idaho National Laboratory • Strategic Analysis, Inc. • Bloom Energy • FuelCell Energy • Nexceris, Energy • Xcel Energy • OxEon

Project Goal and Brief Summary

The project objective is to advance the state of the art of HTE technology by discovering, developing, improving, and testing thermal–electrical–control interfaces for highly responsive operations. The project will (1) develop an infrastructure to integrate support systems for 25–250 kW HTE testing units, (2) support HTE research and system integration studies, (3) measure cell stacks, performance, and materials health under transient and reversible operation, (4) characterize dynamic system behavior to validate transient process control models, (5) demonstrate integrated operation with co-located dynamic thermal energy distribution/storage systems, and (6) operate the system with co-located digital real-time simulators for dynamic performance evaluation and hardware-in-the-loop simulations.

Project #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	10/1/2019–4/1/2023
Partners/Collaborators	• Idaho National Laboratory • National Renewable Energy Laboratory • Argonne National Laboratory • Nel Hydrogen

Project Goal and Brief Summary

This project aims to demonstrate cost-effective supply of in-house hydrogen consumption at an Exelon nuclear power plant. A 1 MW PEM electrolyzer and supporting infrastructure will be installed at an Exelon plant, providing an in-house supply of hydrogen. Researchers will also simulate the scale-up of electrolyzer participation in power markets. The project will demonstrate the potential for hydrogen production to increase the value of nuclear power plants, both by supplying plants' onsite hydrogen needs and by providing hydrogen to regional markets.

Project #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	1/10/2019–1/31/2024
Partners/Collaborators	• Air Liquide • CenterPoint Energy • Chart Industries • Chevron • ConocoPhillips • GTI Energy • Low-Carbon Resources Initiative (LCRI) • McDermott • Mitsubishi Heavy Industries Americas • OneH2, Inc. • ONE Gas, Inc. • ONEOK, Inc. • Shell • Southern California Gas Company • Texas Council on Environmental Quality (TCEQ) • Toyota • University of Texas at Austin • Waste Management

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 units that use renewable natural gas and electrolysis that uses wind and solar power. The project will also demonstrate hydrogen end uses, including using a 100 kW fuel cell to power a computing center. Base-load stationary power generation will be co-located with hydrogen vehicle fueling. The project will also develop a five-year plan for the Port of Houston area that considers existing hydrogen generation, distribution, and infrastructure assets to enable deployment of stationary fuel cell power and hydrogen-fueled vehicles. The plan will identify key barriers and partners, as well as the economic and environmental benefits of hydrogen deployment for the region.

Project #TA-039: Solid Oxide Electrolysis System Demonstration

Hossein Ghezel-Ayagh, FuelCell Energy

DOE Contract #	DE-EE0009290
Start and End Dates	10/1/2020–8/31/2023
Partners/Collaborators	• Versa Power Systems • Idaho National Laboratory

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 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 #TA-043: Electrolyzer Stack Development and Manufacturing

Olga Marina, Pacific Northwest National Laboratory

DOE Contract #	WBS 7.2.9.2
Start and End Dates	10/1/2019
Partners/Collaborators	• Pacific Northwest National Laboratory • Idaho National Laboratory

Project Goal and Brief Summary

PNNL and INL are collaborating to address important electrolyzer manufacturing issues that adversely affect stack performance and durability. The project team assists U.S. manufacturers in identification of manufacturing and operational issues by performing post-mortem stack characterization work. In addition, the team is developing and demonstrating an in operando stack health monitoring system, employing advanced manufacturing approaches (e.g., thin film deposition, electroplating, and 3D printing) to reduce stack manufacturing costs, and identifying QA/QC manufacturing gaps for SOEC systems.

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	• Microsoft, Ballard • National Renewable Energy Laboratory

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 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 U.S. Department of Energy goal of reducing greenhouse gas emissions by heightening the viability and expanding the capabilities of a green fuel source, namely hydrogen.

Project #TA-045: San Francisco Waterfront Maritime Hydrogen Demonstration Project

Narendra Pal, Hornblower Energy LLC

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 • Nel Hydrogen US • IGX Group, Inc. • Glosten • Moffett Nichol

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 for refueling hydrogen vessels with renewable hydrogen and recharging 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 #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 Motor North America

Project Goal and Brief Summary

This project will design and commission a megawatt-scale electrolyzer, storage system, and fuel cell generator at the NREL Flatirons Campus. The system is designed with flexibility to demonstrate system 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 R&D to study the science of scaling for hydrogen energy systems.

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	10/1/2019–8/31/2022
Partners/Collaborators	• WEH Technologies Inc. • Bennett Pump Company • Quong & Associates Inc. • National Renewable Energy Laboratory

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 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 #TA-051: Lowering Total Cost of Hydrogen by Exploiting Offshore Wind and Polymer Electrolyte Membrane Electrolysis Synergies

Hui Xu, Giner, Inc.

DOE Contract #	DE-SC0020786
Start and End Dates	8/23/2021–8/22/2023
Partners/Collaborators	• National Renewable Energy Laboratory • GE Research • Hygro • Plug Power, Inc.

Project Goal and Brief Summary

This project aims to model and validate an integrated energy system designed to produce clean hydrogen using offshore wind power. A model will be developed to study offshore wind integrated with electrolyzers and its performance based on location (wind speed, intermittency, water depth, and distance to shore). The model will be used to calculate the levelized cost of hydrogen produced and how varying conditions affect that cost. Researchers will also determine the impact of seawater impurities on electrolyzer performance with the goal to optimize solutions for obtaining sufficiently pure water for electrolysis offshore. With modeling results in hand, the project will design and build a 250 kW PEM electrolyzer and integrate it with directly coupled emulated wind power at NREL. This stage entails determining system process and instrumentation needs for offshore wind with electrolyzers and designing power electronics and control systems for integration. These efforts will serve the Hydrogen Shot goals of reducing hydrogen production costs ($1 for 1 kilogram in 1 decade, or "1 1 1"), lowering greenhouse gas emissions, building clean energy infrastructure, and providing pathways to private-sector uptake.

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	3/10/2021–3/31/2024
Partners/Collaborators	• FuelCell Energy • Versa Power Systems • Hatch Associates Consultants, Inc. • Politecnico di Milano • Laboratorio Energia Ambiente Placenza • Southern California Gas Company

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 an SOEC module and a 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 #TA-053: Grid-Interactive Steelmaking with Hydrogen

Ronald J. 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, Voestalpine • Nucor • Steel Dynamics • Gerdau • Linde • Air Liquide

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 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 electric arc furnace operation with variable carbon-based and carbon-free feedstocks; and (4) conducting a techno-economic assessment 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 #TA-054: Anion Exchange Membrane Water Electrolyzer for Hydrogen Production from Offshore Wind

Gholamreza Mirshekari, Alchemr, Inc.

DOE Contract #	DE-SC0020712
Start and End Dates	8/23/2021–8/22/2023
Partners/Collaborators	• University of Connecticut

Project Goal and Brief Summary

The main goal of this project is to develop a low-cost AEMWE that can operate using seawater as a feedstock, enabling direct coupling with offshore wind farms. To improve cell performance and durability in a marine environment, researchers will develop high-performance oxygen evolution reaction selective electrodes and modify the anode flowfield/current collector. Based on the architecture of the small single cell, the project team will construct a three-cell single stack to increase hydrogen production. In addition to developing an improved marine-based system, the project will reduce capital costs associated with hydrogen storage and transmission as well as the power electronics required for grid integration.

Project #TA-060: U.S. Wind-to-Hydrogen Modeling, Analysis, Testing, and Collaboration

Aaron Barker and Sam Spirik, National Renewable Energy Laboratory

DOE Contract #	7.2.9.15
Start and End Dates	8/1/2021–6/30/2022
Partners/Collaborators	• Netherlands Organization for Applied Scientific Research • Giner, Inc. • GE Research

Project Goal and Brief Summary

A key barrier to industry adoption of hydrogen production using renewable energy sources is certainty that the approach is economically viable. This project aims to create a hydrogen scenario analysis tool by developing new models and integrations for the NREL HOPP. The tool provides rapid, high-resolution insights into optimized green hydrogen pathways and alternatives. The tool will be equipped with modeling capabilities for on- and off-grid systems, electrolyzer configurations and operation, compatibility with renewables, and design and sizing optimization. The tool can be used to reveal pathways to achieving the Hydrogen Shot goal ("1 1 1"). The project will provide visualization sets, with accompanying data files, for hydrogen production across the United States, using land-based wind (under on- and off-grid scenarios) and offshore wind. Cost data will span 2020–2035.

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 #	9.3.0.6
Start and End Dates	10/1/2020–9/30/2022
Partners/Collaborators	• Argonne National Laboratory

Project Goal and Brief Summary

Construction, mining, and agriculture equipment are the largest contributors to off-road greenhouse gas 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 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.

Annual Merit Review of the Technology Acceleration Subprogram

Summary of Technology Acceleration Subprogram Reviewer Comments

This section provides a summary of the reviewers' remarks. The content reflects those inputs only and not the views of Program management. The complete set of review comments received is provided as Appendix A.

Goals, Strategy, Targets, and Metrics

The Technology Acceleration subprogram recognizes—and acts on—the importance of demonstrating and de-risking integrated hydrogen systems, fostering community engagement, developing technology deployment strategies, developing regional markets and supply chains, and advancing domestic manufacturing to accelerate the commercialization of both current and future hydrogen and fuel cell technologies at large scales. The Technology Acceleration subprogram has a clearly articulated mission and strategy and appropriate goals, milestones, and quantitative metrics. However, it could be argued that there are differences between the stated materials and performance goals of industry and national laboratories, as different manufacturers use different approaches and national laboratory experts are not sufficiently engaged with industry. Other suggestions for improvement are having the subprograms add goals to ensure their technologies are manufactured in the United States, having the subprograms ensure alignment of the metrics down to the individual project level, and developing metrics and equity program principals that translate into improved outcomes for communities and the workforce.

The Program might build on the Technology Acceleration subprogram's achievements by conducting a study to identify the most successful projects and the critical elements and technical goals that led to their success.

Technology Acceleration Subprogram Portfolio

The Technology Acceleration subprogram's portfolio of projects is appropriately balanced across research areas to help achieve its mission and goals. There is also an appropriate balance between near-, mid-, and long-term R&D. The subprogram has increased funding for demonstration projects of high-technology-readiness-level technologies, especially the funding that will be available through the Bipartisan Infrastructure Law, to help move hydrogen and fuel cell technologies from R&D to commercial markets. Although this funding increase is appropriate, mid- and long-term research should remain in the future portfolio. Projects of particular note are the hydrogen and fuel cell systems at NREL's ARIES facility in Boulder, Colorado, and recent demonstration projects within H2@Scale. Technology Acceleration is an important stepping stone to higher technology readiness levels that will lead to manufacturing; however, there is some concern as to the extent to which data generated from pilot- and demonstration-scale activities is shared with domestic and international industry stakeholders.

Reviewer comments and recommendations relating to the Technology Acceleration subprogram's portfolio of projects were offered in the following four areas: transportation, manufacturing, grid integration, and industrial hydrogen use. In the transportation area, a thorough assessment is needed of hydrogen and hydrogen-derived non-fossil liquid fuels for long-haul trucks, as hydrogen may not succeed as a direct-use fuel in freight and maritime applications. Additionally, there is a need for work on how to maintain reliable supply of fuel and electricity during the transition to alternative fuels and longer-term dependence on fewer sources of energy (e.g., common mode failure).

In the manufacturing area, funding of manufacturing R&D must be increased to lower technology cost and address a gap in high-speed, low-cost manufacturing technologies in the United States. The use of domestic materials should be prioritized in projects funded by the subprogram, and the projects' impacts on the domestic supply chain should be considered. In addition, more attention should be paid to ensure safe, secure, economical, and reliable sources of materials within industry.

In the grid integration area, the subprogram could increase the number of neighborhood-level microgrid demonstrations and minimize hydrogen cost for grid energy storage through multiple generation sources. One possibility is to investigate opportunities to integrate renewable power, grid capacity, and hydrogen production at the point of use to minimize hydrogen transport.

Regarding industrial hydrogen use, training on the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model could be helpful in integrating non-carbon energy facilities or upgrades with facilities that use or produce fossil fuels.

Challenges

The Hydrogen Program's strategy has been formulated to meet the challenges of integrating hydrogen-based technologies into the overall renewable energy portfolio in a timely, cost-effective, and impactful way, in part thanks to the Program's strong collaboration with industry. The Program has not always had the budget to address all the important challenges, particularly for demonstration, deployment, education, and outreach. The Bipartisan Infrastructure Law will provide adequate funds to address the challenges, but DOE may not have sufficient staff to manage the increased efforts. The Program might consider increasing staff and identifying management tools and approaches to provide effective oversight of the hydrogen hubs and other projects.

The Program did not present a clear path to implementing its technologies in the market; the current frameworks will not ensure a smooth transition from lab-scale innovation to benchtop to prototype to pilot to large-scale manufacturing. Engagement with a wide variety of stakeholders, including demonstrated technology disruptors and innovators, is encouraged for rapid progress. International collaboration is also encouraged to leverage the knowledge and progress being made in other countries.

Hydrogen demand projections are needed for various applications, taking into account potential cost increases resulting from the transition to hydrogen-based processes. One reviewer's recommendations included (1) requiring technology validation projects to collect and supply data and (2) identifying or developing an inventory of existing facilities that could utilize hydrogen, including their ages and their replacement/upgrade costs, for use in developing demand projections and populating "e-learning" systems to train the workforce. In contrast, however, another reviewer recommended reducing the administrative burden of reporting and data collection requirements for projects funded under the Bipartisan Infrastructure Law.

Discussion was lacking in terms of quantifying/controlling greenhouse gas and air pollutant emissions from hydrogen projects; there is a need to identify the challenges in overcoming the extent of energy and greenhouse gases related to producing hydrogen at larger scales. Furthermore, there is a need for adequate materials, at reasonable prices and from reliable sources, to meet future alternative energy needs. One reviewer observed insufficient involvement and support for (1) the smooth transition of energy technologies without significant disruption and (2) economic and secure supply chains that benefit all stakeholders.

Collaborations/Stakeholder Engagement

While the Program has a well-organized structure for collaborating and gathering feedback from stakeholders, coordination with these stakeholders could be improved and increased. There is alignment between the Program and the hydrogen and fuel cell industry and energy stakeholders. The Program's engagement with American Indian Tribes, the Native Hawaiian community, and other underserved and disadvantaged communities is noteworthy and important. The Program is to be commended for its coordination and co-funding with DOE's Advanced Manufacturing Office, such as on the Roll-to-Roll Advanced Materials Manufacturing DOE Laboratory Collaboration. However, there should be more direct engagement with local officials/municipalities, state agencies, community groups, leaders of distressed communities, workforce development organizations, environmental justice organizations, manufacturing and supply chain stakeholders, technology incubators and startups, non-governmental organizations, community-based organizations, non-profits, and education and outreach programs such as Clean Cities. Such alliances would enable effective technology deployment, community acceptance of the technologies, expansion of domestic manufacturing, workforce development, and timely market transformation.

Specific recommendations regarding collaborations and stakeholder engagement include the following:

- Assess the validity of concerns of environmental non-governmental organization stakeholders before basing decisions on these concerns.

- Provide guidance to community leaders, municipalities, and workforce development organizations on siting and deployment of hydrogen and fuel cells in stationary, transportation, and utility markets, including combined heat and power, mission-critical facilities, microgrids, reversible fuel cells, light- and heavy-duty vehicle fleets, materials-handling, aircraft, decarbonization of electric and natural gas infrastructure, and refueling.
- Provide guidance for hydrogen production to identify and coordinate with renewable feedstock producers, including offshore wind and solar developers.
- Provide guidance to facilitate community siting and investment to help identify and address concerns of distressed communities, underserved cities, and opportunity zones consistent with state policies and goals, goals for community investment, and the requirements of the Bipartisan Infrastructure Law.
- Provide guidance to encourage alliance-building with local industry, supply chain, and community resources.
- Provide guidance to local community stakeholders on environmental performance (to identify carbon offsets, greenhouse gas equivalent reductions, air quality improvements, community siting impacts, and potential impacts from hydrogen production and leakage), safety, and economic projection of the impact to consumer energy costs and the utility rate base.
- Coordinate with non-hydrogen stakeholders on overall integration with other technologies, including battery storage, battery electric vehicles, gas blending and decarbonization, production of hydrogen with renewable energy project developers (biomass, wind, and solar energy), utility-based energy storage and dispatch, and direct consumer use.

Safety, Codes and Standards – 2022

Activity Overview

Introduction

The Safety, Codes and Standards (SCS) activity area, part of the Technology Acceleration portfolio, 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 Fiscal Year (FY) 2022, SCS focused on:

- Validating liquid hydrogen release models to inform and update setback distances for bulk liquid hydrogen storage.
- Developing sensor use guidance and wide-area-monitoring technologies and addressing component failure data needs by analyzing component failure modes and quantifying leak size.
- Developing hydrogen-specific quantitative risk assessment tools, data, and methods for supporting, harmonizing, and revising hydrogen codes and standards.
- Providing hydrogen safety expertise and recommendations to funded projects through the Hydrogen Safety Panel, including sharing best practices and lessons learned to the hydrogen community.
- Developing professional training courses and university curriculum content to support workforce development for the hydrogen industry.

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 industry, etc.).

Goals

The overarching goal of the SCS activity area is to enable the safe deployment and use of hydrogen and fuel cell technologies and ensure that key stakeholders have confidence in that safety. This goal is pursued by:

- Facilitating the creation, adoption, and harmonization of regulations, codes, and standards (RCS) for hydrogen and fuel cell technologies.
- Conducting research to generate the valid scientific bases needed to define requirements in developing RCS.
- Performing RD&D to inform deployment and enable compliance with RCS.
- Developing and enabling widespread dissemination of safety-related information resources and lessons learned.
- Ensuring that best safety practices are followed in activities sponsored by the Hydrogen Program; to that end, soliciting and reviewing project safety plans and directing project teams to safety-related resources.

Key Milestones

- Identify ways to reduce the siting burdens that prohibit expansion of hydrogen fueling stations by using hydrogen research and development (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.

Fiscal Year 2022 Technology Status and Accomplishments

The SCS activity area continues to perform RD&D to provide the scientific basis for codes and standards development with projects in a wide range of areas, including hydrogen behavior, hazard analysis, material and component compatibility, and hydrogen sensor technologies. Using the results from these RD&D activities, the subprogram continues to actively participate in discussions with standards development organizations such as the National Fire Protection Association (NFPA), the International Code Council, SAE International, the CSA Group, and the International Organization for Standardization (ISO) to promote domestic and international collaboration and harmonization of RCS.[1]

A number of codes and standards relevant to the hydrogen industry were published or revised during FY 2022. A database of these codes and standards is maintained on the Hydrogen Safety Panel's H2Tools website.[2]

The H2Tools website provides up-to-date information relevant to the status of SCS activities and enables dissemination of key safety knowledge resources, including several that were updated in FY 2022:

- Hydrogen Incident Examples
- Hydrogen Incident Recovery Guide
- Simplified Safety Planning for Low-Volume Hydrogen and Fuel Cell Projects.

While significant progress has been made in establishing needed RCS and in developing and disseminating safety information, several barriers remain in developing adequate codes and standards and supporting safe deployment of hydrogen technologies. Near-term barriers include:

- Few science-based requirements on hydrogen–natural gas blends
- Incomplete data for liquid hydrogen system component failures and leaks
- Lack of standoff detection technologies for wide-area monitoring of hydrogen leaks
- Insufficient workforce for the emerging hydrogen economy.

Longer-term barriers to both safe deployment and scale-up include:

- Lack of standards for high-throughput fueling for heavy-duty applications, including trucks, marine, and rail
- Incomplete codes and standards for bulk storage of hydrogen
- Unknown regulatory processes for emerging applications, such as those for bulk transport of hydrogen as cargo
- Inconsistent RCS needed to support national and international markets
- Lack of capability of sensors and detection technologies to quantify or monitor hydrogen releases at levels needed for environmental monitoring.

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[1] The full text of relevant RCS can be found at their respective codes and standards development organization websites: NFPA (https://www.nfpa.org/), International Electrochemical Commission (https://www.iec.ch/), SAE International (https://www.sae.org/), American National Standards Institute (https://www.ansi.org/), and ISO (https://www.iso.org/home.html).

[2] Hydrogen Safety Panel, "H2Tools," accessed August 2022, https://h2tools.org/.

In FY 2022, the SCS activity area has continued to make progress in the areas of hydrogen behavior, risk assessment, materials compatibility, hydrogen fuel quality assurance, and codes and standards harmonization. Notably, along with the European Commission, the Hydrogen and Fuel Cell Technologies Office hosted the Clean Hydrogen JU [Joint Undertaking] Expert Workshop on Environmental Impacts of Hydrogen[3] to identify technical needs and next steps for monitoring and mitigating hydrogen releases into the atmosphere.

Of particular significance is NFPA 2, the NFPA's Hydrogen Technologies Code. NFPA 2 is a critical element of the framework for deploying hydrogen technologies in the United States. Enabling the revision of the separation distances laid out in the code document is a major element of the SCS RD&D portfolio. Significant progress was made this year, as SCS met the milestone for 40% reduction in station footprint by enabling updated tables and language for NFPA 2 (2023 edition).

Hydrogen Behavior and Risk R&D

- Utilized bulk cryogenic hydrogen behavior validation data to enable 40% reduction in hydrogen station footprint based on NFPA 2 (Sandia National Laboratories).
- Performed SCS gap assessments for large-scale hydrogen applications, including bulk storage and rail (Sandia National Laboratories).
- Updated HyRAM+ (Hydrogen Plus Other Alternative Fuels Risk Assessment Models) with capability to simulate unconfined overpressure, as well as alternative fuel releases (Sandia National Laboratories).
- Published a literature review of hydrogen–natural gas blend releases (Sandia National Laboratories).

Safety Resources and Support

- Through Hydrogen Education for a Decarbonized Global Economy (H2EDGE), launched five professional workforce development courses, covering basic hydrogen science as well as production, storage, end use, and safety (Electric Power Research Institute [EPRI]).
- Published "Simplified Safety Planning for Low-Volume Hydrogen and Fuel Cell Projects" (Pacific Northwest National Laboratory).

Component R&D

- Developed computational fluid dynamics models of hydrogen dispersion in small enclosures, validated by HyWAM (Hydrogen Wide Area Monitoring) (National Renewable Energy Laboratory).
- Demonstrated the use of ultrasonic leak detection to characterize signatures for leaks with orifices down to approximately 0.02 mm (National Renewable Energy Laboratory).

Materials Compatibility R&D

- Published a U.S. Department of Energy (DOE) Program Record titled "Increased design life for high-pressure stationary hydrogen storage vessels through development of empirically based design curves" (Sandia National Laboratories).

New Project Selections

- Sandia National Laboratories and Wabtec: Risk Assessments of Design and Refueling for Hydrogen Locomotive and Tender (cooperative research and development agreement [CRADA])
- National Renewable Energy Laboratory, National Energy Technology Laboratory, Paulsson, Element One, Renewable Innovations, and others: Assessment of Heavy-Duty Fueling Methods and Components (CRADA)

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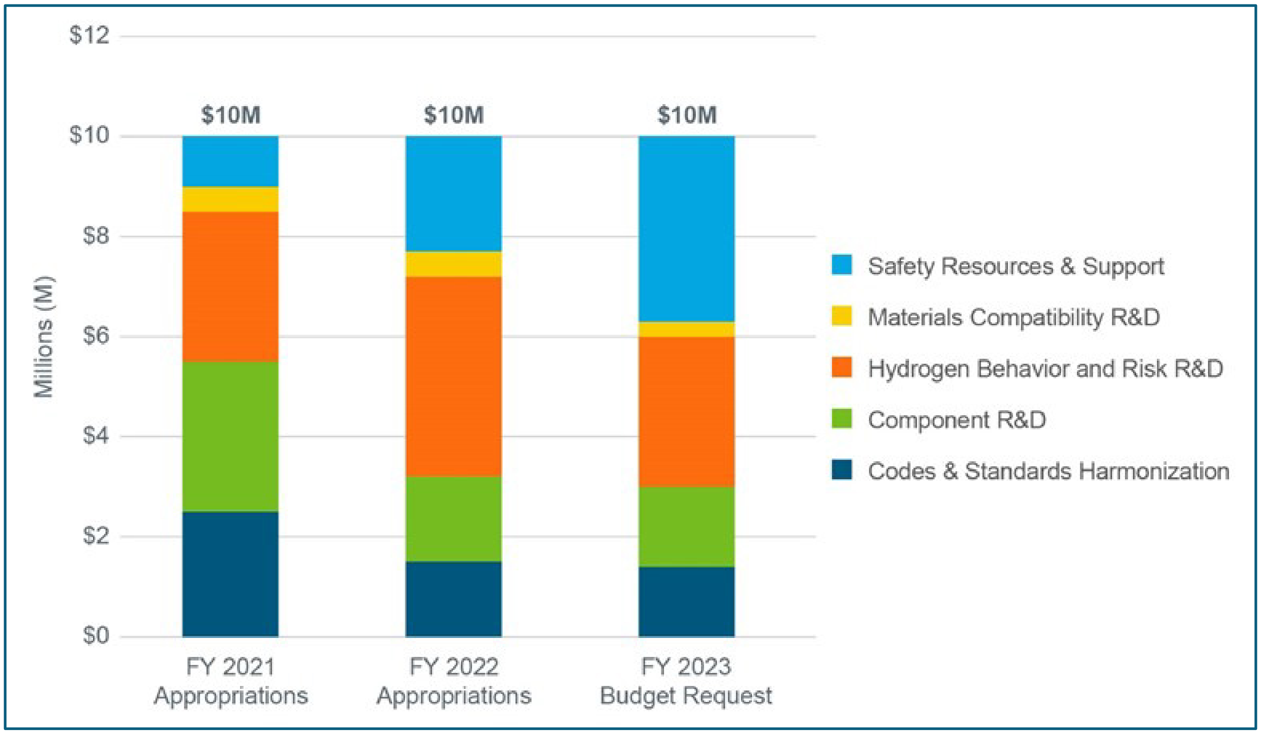
[3] A. Arrigoni and L. Bravo Diaz, Hydrogen emissions from a hydrogen economy and their potential global warming impact, EUR 31188 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-55848-4, doi:10.2760/065589, JRC130362, https://publications.jrc.ec.europa.eu/repository/handle/JRC130362.

- National Renewable Energy Laboratory and Frontier Energy: MC Formula Protocol for H35HF Fueling[4]

Budget

The FY 2021 appropriation for the SCS activity totaled $10 million, as did the FY 2022 appropriation. Funding in FY 2022 showed an increased focus on applied risk assessment and additional funding support for safety resources and workforce development, balanced funding for codes and standards harmonization and component RD&D, and lower levels of funding for materials compatibility RD&D. Future work in the SCS activity is expected to focus on continued applied risk assessments, expanding sensor and detection work to include quantification and monitoring of hydrogen for environmental impact studies, development of new codes and standards tools, and continued emphasis on safety training and workforce development.



[4] MC refers to total heat capacity. H35HF refers to refueling hydrogen at a high flow (HF) rate to an onboard pressure of 35 MPa (H35).

Project Summaries

Below are brief SCS project summaries of oral presentations given during the 2022 Annual Merit Review. The full list of projects, including oral and poster presentations, is provided in Appendix D.

Project #SCS-010: Research and Development for Safety, Codes and Standards: Hydrogen Behavior

Ethan Hecht, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	• Air Liquide (via H2@Scale CRADA) • Lawrence Livermore National Laboratory • National Renewable Energy Laboratory • Compressed Gas Association 5.5 testing task force • Fuel Cells and Hydrogen Joint Undertaking • National Fire Protection Association 2 • Massachusetts Institute of Technology • BKi (via previous CRADA, which included the California Fuel Cell Partnership, an auto original equipment manufacturer group, Linde, Shell)

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 SCS by (1) providing a science and engineering basis for understanding the release, ignition, and combustion behavior of hydrogen across its range of use (i.e., high-pressure and cryogenic applications), (2) generating data to address targeted gaps in the understanding of hydrogen behavior physics (and modeling), and (3) developing and validating scientific models to facilitate quantitative risk assessment of hydrogen systems and enable revision of RCS to accelerate permitting of hydrogen installations. The project began in 2003.

Project #SCS-011: Hydrogen Quantitative Risk Assessment

Brian Ehrhart, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	• FirstElement Fuel • Air Liquide • Quong & Associates • Pacific Northwest National Laboratory • National Renewable Energy Laboratory • Argonne National Laboratory • Network of Excellence for Hydrogen Safety (HySafe) • organizations using the Hydrogen Risk Assessment Model (HyRAM) • National Fire Protection Agency 2/55 • U.S. Department of Transportation Federal Highway Administration • California Fuel Cell Partnership • International Partnership for the Hydrogen Economy • International Electrotechnical Commission

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 RCS and permitting stations. Sandia National Laboratories will develop and validate hydrogen behavior physics models to address targeted gaps in knowledge, build tools to enable industry-led codes and standards revision and safety analyses, and develop hydrogen-specific quantitative risk assessment tools and methods to support RCS decisions and to enable a performance-based design code compliance option.

Project #SCS-019: Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources

Nick Barilo, Pacific Northwest National Laboratory

DOE Contract #	6.2.0.502
Start and End Dates	3/1/2003
Partners/Collaborators	• California Energy Commission • American Institute of Chemical Engineers • Center for Hydrogen Safety

Project Goal and Brief Summary

This project provides expertise and recommendations through the Hydrogen Safety Panel and through the Hydrogen Tools Portal, H2Tools.org (H2Tools), to identify safety-related technical data gaps, best practices, and lessons learned, as well as help integrate safety planning into funded projects. Data from hydrogen incidents and near misses are captured and added to the growing knowledge base of hydrogen experience to share with the hydrogen community, with the goal of preventing safety events from occurring in the future. The project also aims to implement a national hydrogen emergency response training resource program with adaptable, downloadable materials for first responders and training organizations.

Project #SCS-021: Hydrogen Sensor Testing Laboratory

William Buttner, National Renewable Energy Laboratory

DOE Contract #	WBS 6.2.0.502
Start and End Dates	10/1/2010
Partners/Collaborators	• Shell North America • Amphenol Thermometrics • AVT and Associates • Element One • KWJ Engineering Inc. • First Element, Emerson • Health and Safety Executive's Health and Safety Laboratory • Transport Canada • Environment and Climate Change Canada

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's Sensor Testing Laboratory tests and verifies sensor performance for manufacturers, developers, end users, and standards developing organizations. The project also helps develop guidelines and protocols for the deployment of hydrogen safety sensors under a variety of conditions and applications.

Project #SCS-028: Hydrogen Education for a Decarbonized Economy

Tom Reddoch, Electric Power Research Institute

DOE Contract #	DE-EE0009253
Start and End Dates	10/01/2020–03/31/2025
Partners/Collaborators	• Gas Technology Institute • Oregon State University • University of Delaware • Embedded Assessments • Hydrogen Industry Partners

Project Goal and Brief Summary

As an emerging field, the hydrogen industry faces the challenge of mobilizing an experienced workforce—a critical need where safety must be emphasized. This project establishes the H2EDGE initiative to enhance 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.

Annual Merit Review of the Safety, Codes and Standards Activity

Summary of Safety, Codes and Standards Activity Reviewer Comments

This section provides a summary of the reviewers' remarks. The content reflects those inputs only and not the views of Program management. The complete set of review comments received is provided as Appendix A.

Inconsistent standards are beginning to be established across the globe, which will cause confusion in the market if not addressed, especially as companies and governments work toward implementing low-carbon energy solutions. More support for codes and standards development is suggested, particularly regarding new and emerging applications for hydrogen. Widespread commercialization will require regulatory changes at the national, state, and regional levels, and with so many emerging applications, it may be time to establish a specific mission, strategy, and goals for the SCS subprogram. To facilitate the regulatory frameworks for deployment of technologies across a range of new applications (e.g., grid resilience, heavy-duty trucks, maritime, aviation, and railway), related R&D needs should be identified.

The Hydrogen Safety Panel is a great resource that can help drive consistency and learnings. The Hydrogen Program should clearly communicate and push to resolve obstacles in existing codes and standards that are hindering implementation. There is a need to achieve alignment and standardization of clean hydrogen production and distribution evaluation methods, metrics, targets, and implementation. There should also be a focus on codes and standards for local/lower-pressure hydrogen distribution networks, and it would be helpful to accelerate both SCS work and materials testing work to support easier and less costly deployment of hydrogen pipelines. Technology validation efforts related to light-duty vehicle and forklift fueling are providing a large enough body of data to inform practical, statistics-based standards going forward. Moreover, the larger industrial uses of hydrogen will need to be addressed, as existing codes and standards generally do not cover such processes and are handled independently through risk analysis by producers and users.

International collaboration is an area where there should be many opportunities for projects that support global harmonization of hydrogen standards. The Hydrogen Program could develop a strategy to ensure that international partnerships and related agreements are reflected in the myriad of regulatory frameworks in the United States. It is very encouraging to see international collaborations; perhaps these collaborations could be further enhanced in terms of SCS development. Design and parts standardization would also be a good focus for international collaboration. Such collaboration could be used to encourage original equipment manufacturers to communicate and standardize certain parts and designs, which would be very beneficial to supply chain development.

Systems Analysis – 2022

Subprogram Overview

Introduction

The Systems Analysis subprogram 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, and 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 Manufacturing Office, and others
- State and local government organizations
- Other federal agencies (e.g., the U.S. Environmental Protection Agency)
- Private sector companies
- International organizations.

The subprogram leverages external activities, coordinates efforts, and works with these partners to build opportunities for new technology applications and deployment.

Goals

The subprogram supports HFTO's decision-making and prioritization process by evaluating technologies and energy pathways, identifying gaps and synergies, and providing insights into future benefits, impacts, and risks.

Key Milestones

Near-Term (2022–2027)

- Develop models and analyses to support the implementation of the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA).
- Conduct state-of-the-art assessments of technology cost, performance, and value proposition to help guide the research, development, demonstration, and deployment (RDD&D) portfolio.

Mid-Term (2027–2035)

- Validate and refine models and tools to enable large-scale market growth, inform multisector coupling, and realize emissions reductions and jobs potential.
- Characterize market barriers and opportunities for supply chain expansion and high-volume manufacturing.

Long-Term (2035–2050)

- Assess RDD&D and market transformation processes, policies, and progress across applications and sectors to enable system resilience, emissions reduction, and sustainability; assess job potential, including impacts on disadvantaged communities.

Fiscal Year 2022 Technology Status and Accomplishments

Activities Supporting the Bipartisan Infrastructure Law and the Inflation Reduction Act

HFTO has continued funding analyses of the cost and emissions benefits of hydrogen use in industry and transportation relative to other decarbonization solutions, in collaboration with offices across DOE and the federal government. These analyses informed the draft DOE National Clean Hydrogen Strategy and Roadmap[1] and the Clean Hydrogen Production Standard Draft Guidance,[2] both of which were released in September 2022 in support of the BIL. The draft roadmap identified sectors in which hydrogen could have a strong potential role in decarbonization: long-haul heavy-duty trucks, production of clean biofuels for aviation, chemicals production and iron ore refining in industry, high-temperature heat generation for industry, and long-duration energy storage for a clean grid. DOE is currently also supporting the U.S. Department of the Treasury's implementation of the IRA provisions, including Section 45V Credit for Production of Clean Hydrogen, which relies on Argonne National Laboratory's (ANL's) Greenhouse Gas Regulated Emissions, and Energy Use in Technologies (GREET) model.

Market Segmentation in Medium- and Heavy-Duty Transportation

The transportation offices within DOE (HFTO, Vehicle Technologies Office, and Bioenergy Technologies Office) collaboratively completed an analysis project, led by the National Renewable Energy Laboratory, that evaluates market adoption of medium- and heavy-duty vehicles, with varying ranges and operating conditions. The analysis leveraged a newly developed vehicle choice model at the National Renewable Energy Laboratory (NREL), Transportation Energy and Mobility Pathway Options (TEMPO), which estimates how segments of the trucking sector could transition to new powertrains as a function of fuel cost, vehicle cost, and assumptions around driving behavior, such as annual vehicle miles traveled within each segment of the market.[3] If DOE targets for the cost of hydrogen fuel, fuel cells, and storage are achieved, modeling shows that the trucking sector would start to adopt fuel cells over the next several decades and that 10%–14% of trucks could be using hydrogen fuel cells in 2050.

User-Friendly Model Development

HFTO routinely funds the development of tools that characterize the cost, emissions, and performance of hydrogen and fuel cell technologies. In 2022, HFTO and other DOE offices provided ANL with funding to complete an annual update to the GREET model, which is already used by 50,000 stakeholders worldwide to characterize emissions of hundreds of fuel pathways, including hydrogen. As part of this update, ANL developed a user-friendly interface to characterize the well-to-gate emissions of hydrogen production from diverse feedstocks.[4] Additionally, NREL developed the Hydrogen Analysis (H2A) Lite Production tool (H2A-Lite), which characterizes the levelized cost of hydrogen production from systems with user-defined assumptions (e.g., cost of electricity, efficiency, cost of fuel). H2A-Lite is pre-populated with configurations of key hydrogen production technologies, including electrolyzers, steam methane reforming with and without carbon capture and sequestration (CCS), and coal gasification with CCS.[5]

In addition, HFTO led DOE's first Hydrogen Business Case Prize competition in 2021, inviting teams to develop models that quantify the value proposition of hydrogen deployments in specific regions of the country. During this nine-month challenge, competing teams were asked to develop user-friendly Excel-based tools and supplemental final reports characterizing business cases for hydrogen. Team members received access to mentors across industry

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[1] DOE, *DOE National Clean Hydrogen Strategy and Roadmap* (draft), September 22, 2022, https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf.

[2] DOE, U.S. Department of Energy Clean Hydrogen Production Standard (CHPS) Draft Guidance, September 22, 2022, https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-production-standard.pdf.

[3] NREL, "TEMPO: Transportation Energy & Mobility Pathway Options Model," accessed 2022, https://www.nrel.gov/transportation/tempo-model.html.

[4] ANL, "GREET with H2 User Interface," accessed 2022, https://greet.es.anl.gov/greet_hydrogen.

[5] For more information on H2A-Lite, see NREL, "H2A-Lite: Hydrogen Analysis Lite Production Model," accessed 2022, https://www.nrel.gov/hydrogen/h2a-lite.html.

and national laboratories. Four winning teams received cash prizes of $20,000–$50,000, and the top two teams also received offers for paid internships at companies and the national labs.[6]

International Collaborations

HFTO's Systems Analysis team led U.S. engagement in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) Hydrogen Production Analysis (H2PA) task force. Members of H2PA include representatives from 10 countries, working to develop methods of life cycle analysis of hydrogen production and distribution; application of the mutually agreed upon methodology will help to inform global trade. Last year, HFTO supported the H2PA in completion of guidance around emissions analysis of electrolysis, steam methane reforming, and coal gasification, led by representatives from France and Australia.[7] In 2021–2022, HFTO led the H2PA in completing additional guidance on emissions analysis of hydrogen carriers and liquefaction, and contributed to guidance on hydrogen production from biomass and autothermal reforming.

Assessing Decarbonization Potential of Hydrogen Across Sectors

HFTO is currently funding updates to Pacific Northwest National Laboratory's Global Change Analysis Model (GCAM)[8] and the National Energy Modeling System (NEMS)[9] to represent the cost and emissions of hydrogen production from diverse resources, for use in industry, transportation, and the grid. These updated tools can then be used to characterize market potential of hydrogen in various sectors, relative to other decarbonization tools, such as electrification and CCS.

New Project Selections

- ANL is developing GREET+, a version of the GREET tool including pathways and assumptions of interest worldwide, in collaboration with the International Energy Agency.
- NREL, in collaboration with Mission Innovation, is developing guidance on how to characterize the sustainability of hydrogen deployments.
- DOE's Strategic Analysis team is launching several projects involving multiple entities across the Office of Energy Efficiency and Renewable Energy. These initiatives aim to characterize the decarbonization potential of a range of technology options, including clean fuels such as hydrogen, energy efficiency, electrification, and CCS. ANL and NREL are leading sprint studies, and longer-term projects are currently under development.

Budget

The Fiscal Year 2022 appropriation for Systems Analysis was $3 million. The program's budget was focused largely on scenario analyses evaluating priority sectors for hydrogen and key market drivers, techno-economic and life cycle analysis evaluating cost and benefits of hydrogen production from different pathways and hydrogen use, and the development of user-friendly platforms to characterize the cost and benefits of hydrogen technologies.

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[6] American-Made Challenges, "Hydrogen Business Case Prize," accessed 2022, https://www.herox.com/h2businesscase/teams.

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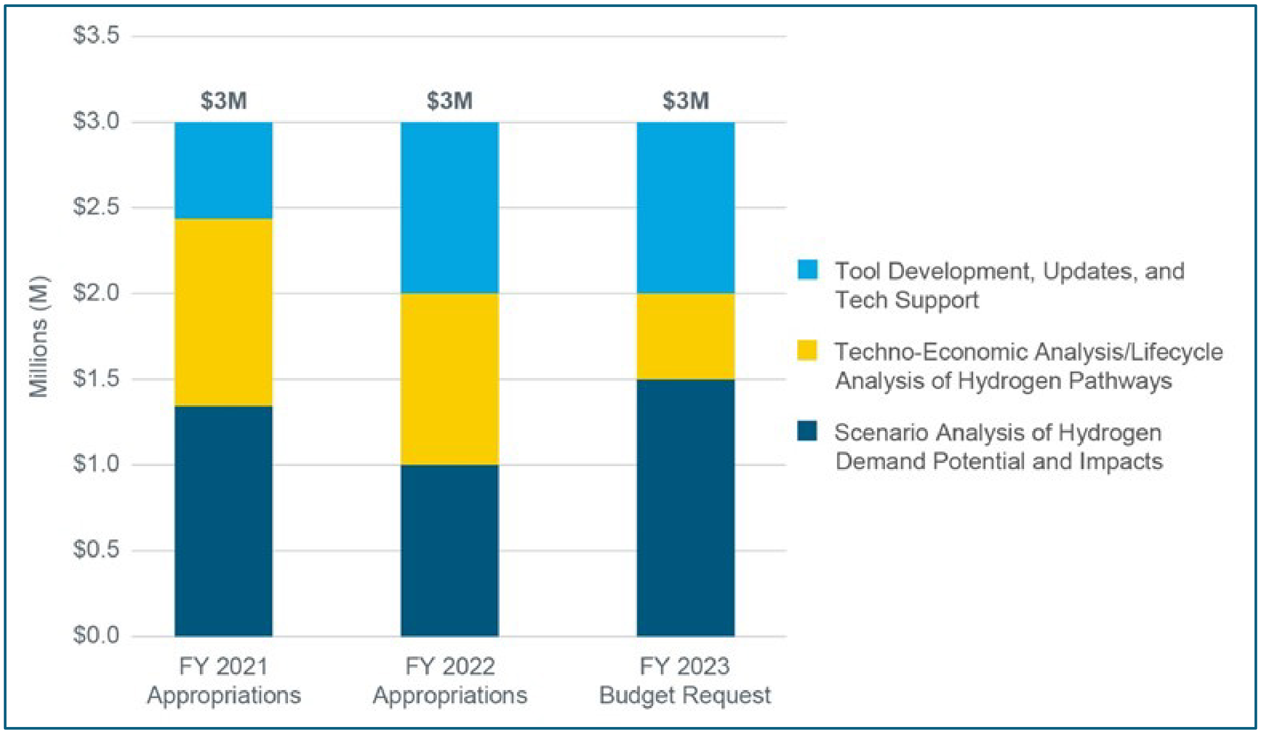

Project Summaries

Below are brief Systems Analysis project summaries of oral presentations given during the 2022 Annual Merit Review (AMR). The full list of projects, including oral and poster presentations, is provided in Appendix D.

Project #SA-174: Life Cycle Analysis of Hydrogen Pathways

Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	5.1.0.6
Start and End Dates	10/1/2019
Partners/Collaborators	• National Renewable Energy Laboratory • Lawrence Berkeley National Laboratory • University of California, Irvine

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 techno-economics and environmental implications of hydrogen use in these applications, providing estimates of associated costs and greenhouse gas emissions. Argonne National Laboratory is collaborating on this project with DOE's Strategic Analysis Office, DOE's Advanced Manufacturing Office, NREL, Lawrence Berkeley National Laboratory, and the University of California, Irvine.

Project #SA-175: Regional Hybrid Energy Systems Technoeconomic Analysis

Mark Ruth, National Renewable Energy Laboratory

DOE Contract #	5.3.0.502
Start and End Dates	8/22/2019
Partners/Collaborators	• Idaho National Laboratory • Argonne National Laboratory • Xcel Energy Inc. • Electric Power Research Institute (EPRI)

Project Goal and Brief Summary

This project aims to quantify the potential financial impact of hybridizing Xcel Energy's Prairie Island and Monticello nuclear power plants to produce hydrogen. This project will provide investment-grade information to support Xcel Energy's greenhouse gas reduction efforts, improve understanding of the potential for hybridized nuclear power plants to produce hydrogen at $2/kg or less, and develop tools and capabilities to better characterize hybridized hydrogen production on the grid so that new opportunities can be analyzed.

Project #SA-181: Global Change Analysis Model Expansion – Hydrogen Pathways

Page Kyle, Pacific Northwest National Laboratory

DOE Contract #	5.2.0.107
Start and End Dates	05/1/2021–10/31/2022
Partners/Collaborators	• Argonne National Laboratory • National Renewable Energy Laboratory

Project Goal and Brief Summary

This project seeks to add a hydrogen module to a configuration of 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 that 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 #SA-182: Biomass Gasification Optimal Business Case Analysis Tool

Bridger Cook, Oregon State University

DOE Contract #	5.3.0.502
Start and End Dates	10/5/2021–5/20/2022
Partners/Collaborators	• U.S. Department of Agriculture • Sun Grant Program (Western Region)

Project Goal and Brief Summary

Wildfire mitigation efforts create large amounts of potential biomass feedstock. Woody biomass gasification could potentially take advantage of this waste product to provide low-carbon hydrogen and enable the co-location of hydrogen supply and demand. However, the capital costs are high, and stakeholders considering these systems lack the proper analytical tools to make informed decisions. This project will develop an Excel tool to evaluate the economic, social, and environmental potential of a woody biomass-based hydrogen production facility. In addition to optimizing plant scale and production levels to maximize net present value, the tool will provide environmental and social impact metrics, offering further insight into the overall impact of a business venture, with cost and performance data being sourced from the H2A and GREET models. Access to such a business case analysis tool will decrease investment risk while promoting environmental and social justice, as well as supporting DOE's goal of supporting private-sector uptake of hydrogen production.

Project #SA-183: H2X Tool: Technoeconomic Modeling for Utilizing Curtailed Solar Power in California for Green Hydrogen Generation

Sharun Kumar and Amanda Wonnell, Pure Hydrogen

DOE Contract #	5.3.0.502
Start and End Dates	10/5/2021–5/20/2022
Partners/Collaborators	N/A

Project Goal and Brief Summary

By creating a techno-economic modeling tool, this project aims to enable the utilization of curtailed solar power for green hydrogen generation in California. The H2X model will evaluate end uses for green hydrogen generated from curtailed electricity. Hydrogen can be used to power manufacturing, transportation, and residences, and excess electricity can be sold back to the grid during peak demand. Tool users will input the following site-specific information: facility (plant capacity, depreciation, and hydrogen transport), technology (electrolyzer and fuel cell type, storage method), costs (electricity, water, and KOH), and end users (allocation of hydrogen sales to different industries). Once inputs are processed, the model will output the following: income statement information (including cost breakdown over the lifetime of the plant), carbon dioxide savings (per industry as a result of green hydrogen usage), and socioeconomic justice factors (i.e., jobs created).

Project #SA-185: Hydrogen Business Appraisal Tool

Nicolas Alfonso Vargas, University of Southern California

DOE Contract #	5.3.0.502
Start and End Dates	10/5/2021–5/20/2022
Partners/Collaborators	• Pacific Northwest National Laboratory • Los Alamos National Laboratory • National Renewable Energy Laboratory • Carnegie Institution for Science, Plug Power, Inc.

Project Goal and Brief Summary

This project aims to develop a user-friendly computational tool for DOE's Hydrogen Business Case Prize Competition. The tool will characterize business cases for hydrogen in user-defined scenarios and will also model four sectors of the hydrogen supply chain (production, storage, transportation, and end use) to produce comparable financial, environmental, and societal reports. This model was designed not only to provide assessments of hydrogen business cases but also to serve as an exploratory tool, exposing users to emerging methods of hydrogen production, storage, and transportation for various end uses to optimize parameter and technology selection.

Annual Merit Review of the Systems Analysis Subprogram

Summary of Systems Analysis Subprogram Reviewer Comments

This section provides a summary of the reviewers' remarks. The content reflects those inputs only and not the views of Program management. The complete set of review comments received is provided as Appendix A.

The Systems Analysis subprogram is managed well, with clearly articulated goals, milestones, and quantitative metrics. Suggested next steps included systems analysis efforts aimed at accelerating the transition of research to commercialization, while also engaging the community and advancing domestic manufacturing to meet demand. The Hydrogen Program (the Program) could more clearly define and communicate the research and development pathways to reduce costs, including the remaining risks or barriers along each pathway and the probability of achieving the goals. In addition, there could be more Program efforts to support transition to a hydrogen-based infrastructure, including analysis of the workforce needed, more training on the GREET model, and macroeconomic and system-wide economic studies. While Systems Analysis cannot easily foster innovation, analyses provide value by showing how the innovations might fare if they do in fact succeed.

Hydrogen Shot Goal

Specific pathways to achieving the Hydrogen Shot goal were not sufficiently articulated. The Program would be better served with more analysis to relate the goal to what is achievable in different timeframes. Technology innovations could be explained as part of a total cost of ownership model, helping stakeholders to better understand the impacts of these innovations on the Hydrogen Shot goal.

Analysis Needs

The subprogram has appropriately kept its focus on overall energy efficiency and environmental protection. This emphasis should continue so that hydrogen and fuel cell technologies can have meaningful impacts in transportation electrification and the broader energy transition to cleaner and more sustainable options. More specifically, while maintaining the strong focus on greenhouse gas emissions is important, local air pollutants also need further evaluation, as they are a key factor in addressing communities' environmental and health concerns. Hydrogen is considered a powerful avenue for global decarbonization, and the hydrogen community must ensure the credibility and transparency of environmental impact analysis. Investigating details of all the environmental impacts of hydrogen pathways on a life cycle basis—such as carbon footprint, land use, and materials needs—could contribute to building that trust.

Quantifying the projected demand for hydrogen is important, and continued analysis in this area is encouraged. Related activities could include developing an inventory of existing facilities, with their replacement/upgrade cost potential.

While Program cost status and goals were clearly articulated during the AMR, more analysis is needed to go deeper on a systems level, into the entire value chain, and to go beyond viability analysis. For electricity cost, the value of 3 cents/kWh used in some of the analyses and modeling seems questionable, since this does not include costs for transmission and distribution, and the lowest industrial electricity prices in the United States are now near 6 cents/kWh.

Analyses should incorporate some additional factors, such as the impacts of the war in Ukraine and the recent drought conditions. Technology comparative analyses could be beneficial in evaluating whether funding levels in each area are appropriate.

Given the plans for regional hydrogen hubs, the Program could perform more state- and region-specific analyses to assist states and regions in planning hydrogen and fuel cell demonstrations and deployments.

Regarding diversity and inclusion-related issues, discussions usually were more qualitative, as compared to the quantitative and clear metrics laid out for technology. Perhaps the Program could support development of a model (like the H2A and GREET models) that could provide more quantitative insights.

Appendix A: 2022 Hydrogen Program Review Summary

This appendix shows the results of the Hydrogen Program (the Program)-level peer review for the 2022 Annual Merit Review (AMR). A total of 71 Program-level reviewers were invited to provide feedback, and 38 reviewers responded. 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	Nel Hydrogen US
ACS Industries Inc.	New Energy and Industrial Technology Development Organization, Japan
Air Products and Chemicals, Inc.	New Jersey Fuel Cell Coalition
Ballard Power Systems	Pajarito Powder LLC
Bar-Ilan University	Patturns
Boston University	Plug Power Inc.
California Air Resources Board	SLR Consulting
California Fuel Cell Partnership	Stottler Development LLC
French Alternative Energies and Atomic Energy Commission (CEA)	Strategic Analysis, Inc.
Connecticut Center for Advanced Technology	Toyota Motor Corporation
DJW Technology, LLC	University of California San Diego
Fuel Cell and Hydrogen Energy Association	University of Connecticut
General Motors Company	University of Maryland
Hyrax Intercontinental	University of South Carolina
KeyLogic	U.S. Department of Energy
NASA	U.S. Nuclear Regulatory Commission
NASA, White Sands Test Facility	West Virginia University

1a. The Hydrogen Program and strategy was clearly articulated and well-aligned with mission and goals of the National Clean Hydrogen Strategy 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.

Average Score	**9.0**
Number of Responses	38

Comments:

- The U.S. Department of Energy (DOE) Program and strategy were easy to understand and are indeed very well-aligned with the goals of the National Clean Hydrogen Strategy and the Hydrogen Shot. You can see a clear connectivity and logic in the Program's many parts and a consistent focus on $1/kg hydrogen and development of markets to use it. The goals are supported all the way from fairly early technology readiness level (TRL) research and development (R&D) seeking big changes in cost and efficiency to market de-risking of technologies just entering the marketplace. Safety and diversity and environmental justice were clearly part of the plan for reaching these ambitious goals.

- The Program is well-aligned with the mission and goals of the National Clean Hydrogen Strategy and Hydrogen Shot. Moreover, the strategy was clearly articulated and well-aligned with U.S. energy policy through work that includes extensive research, modeling, analysis, and assessment of energy alternatives. The work is of very high caliber and recognized worldwide for leadership with development of clean energy technology.
- A comprehensive strategy that includes R&D, demonstration, deployment, education, and outreach—on a national scale—is required to achieve the ambitious Hydrogen Shot goals. The Program has done an excellent job developing that comprehensive strategy. To date, the Program has executed the R&D strategy extremely well and designed an ambitious pathway for the other elements, which are critical to demonstrating and deploying hydrogen at scale and reducing the cost of hydrogen infrastructure.
- Goals are exceptionally well-aligned. The increased integration across multiple projects over the past few years is really impressive. Also, the nearer-term goals in the strategy ($2/kg by 2026, for example) make the longer-term "shot" feel more manageable.
- Overall, this is a really well-organized and well-run program—great on vision, strategy, and execution.
- Goals were well-defined. The reviewer particularly liked the balanced portfolio of companies, consortia, direct projects with the laboratories, and Small Business Innovation Research (SBIR) projects.
- The goal is clear ("1 1 1"), and the focus on scale-up is appropriate.
- The presentation made it clear that there is a well-coordinated national effort.
- The hydrogen plan does an excellent job of covering the entire gamut of hydrogen management from production to consumption.
- The Hydrogen and Fuel Cell Technologies Office (HFTO) has done a nice job in 2021–2022 to quickly develop the Program's strategies and plans toward realizing the big Hydrogen Shot challenge. When the Hydrogen Shot vision was announced at last year's AMR meeting, this reviewer was honestly concerned that it might be just a slogan without a possible action plan. However, with the strong funding support from the infrastructure bill and quick actions from the Office of Efficiency and Renewable Energy (EERE), we will have a chance to fight. Thanks for the great effort.
- The Program and strategy were clearly articulated and well-aligned with the mission and goals of the National Clean Hydrogen Strategy and the Hydrogen Shot. The focus supports the mission, and the goals of using clean hydrogen to decarbonize industry, fuel heavy-duty (HD) transportation applications, and enable energy storage are unambiguous. Thank you for providing an explanation of the sector-based CO_2 emissions. People need this reference. The snapshot of "where we are presently" is important, i.e., hydrogen production, pipeline, polymer electrolyte membrane (PEM) electrolysis, fuel cell buses, retail stations, and light-duty (LD) passenger cars. The only "adds" would be that the production is in many cases "already spoken for" by paying customers and the primary feedstock is natural gas.
- The strategy supports the Hydrogen Shot goals, and the existing program has done as well as it can to address these goals with the very small amount of funding allocated versus the investment made to date in fuel cells and batteries. The Program will take some time to catch up based on the new funding; there was no funding for new low-temperature electrolyzer projects last year, other than within the national laboratories. It is extremely important to "catch up" to the strategy through industry engagement with Hydrogen from Next-generation Electrolyzers of Water (H2NEW) and the HydroGEN Advanced Water Splitting Materials Consortium (HydroGEN) and use of the new funding through the Infrastructure Investment and Jobs Act/Bipartisan Infrastructure Law (BIL), to kick-start new, applied R&D projects in key electrolyzer components and system concepts.
- It is strongly agreed that the Program and strategy are clearly articulated and well-aligned.
- The Program has done a very good job of communicating overall goals and targets and how each of the subprograms fits into the larger picture.
- The U.S. policy of leading the world was clearly stated and easy for participants to understand.
- The vision articulated was uniformly delivered by all speakers during the plenary.
- It was clear that coordination had occurred among the presenters.
- The Program is addressing the daunting challenges and obstacles facing full implementation and consumer acceptance of hydrogen infrastructure and fuel cell technologies in a comprehensive and impressive way. A well-coordinated research, development, demonstration, and deployment (RDD&D) strategy comprising input from multiple national laboratories, private companies, and DOE offices is ensuring that critical issues are being thoroughly evaluated and addressed. Successful and complete integration of hydrogen-based technologies into our overall renewable energy portfolio is clearly challenging. The Program strategy

has been formulated to meet those challenges in a timely, cost-effective, and impactful way. The Hydrogen Shot initiative is an aspirational "reach" that provides well-formulated, concise, and challenging goals and focus for the Program. Achieving those goals is imperative for the Program to be established as a major element of the renewable energy portfolio. Minor note: One issue that would have been helpful in the AMR Program strategy discussion is a candid and honest comparison with incumbent and other emerging technologies (especially batteries). Such a comparison would provide a useful context for reviewers to fully appreciate and assess the future impact and advantages/disadvantages of the Program in relation to all other renewable energy options.

- This question is a bit difficult to gauge, as the final National Clean Hydrogen Strategy has not been published yet. The reviewer evaluated this based more on the general concepts and draft thoughts presented during the plenary and with respect to the known information about the Hydrogen Shot.
- The reviewer requested more on a metric-driven, investment-inspiring national strategy.
- There is good overall Program strategy targeting high-impact end uses and bringing in other DOE offices like the Bioenergy Technologies Office and Office of Fossil Energy and Carbon Management (FECM). The only overarching concern is that five years of BIL funding may not be enough to move the cost curves sufficiently. One would hope there are milestones and gates built into the funding allocation that can apply the brakes if necessary. Scaling up expensive technologies too early would be a costly mistake, given the unique nature of this opportunity.
- The presentation provided a clear and comprehensive document identifying the group of hydrogen projects and their objectives, with high-level discussion of how to meet those objectives. This included the identification of H2@Scale, H2NEW, Electrocatalysis Consortium (ElectroCat), Million Mile Fuel Cell Truck (M2FCT), Hydrogen Shot, hydrogen demonstrations, etc. The 92 charts identifying these activities was somewhat overwhelming. With the expansion of the Program, it may be necessary to modify the structure of the AMR to address the large number of project recipients and subrecipients, consortia, etc. With over 400 projects spanning from basic research to demonstrations and deployment, the audience for the Program overview has many diverse interests, and there are areas where the audience has little interest.
- The three charts that discussed the Justice40 Initiative did not provide a clear pathway to execute the objectives. A definition of the acronym DEI (diversity, equity, and inclusion) was not found.
  The Hydrogen Education for a Decarbonized Global Economy (H2EDGE) discussion did not identify "industry-led" activities but discussed academic accomplishment; it was unclear what the industry did. Chart 76 necessitated going to Google to find out what IPHE was (International Partnership for Hydrogen and Fuel Cells in the Economy). It was unclear if technical transitions were planned and why they were being reported, as they appear to be getting only 0.024% of the budget. Budgets were clearly identified for the HFTO.
- Chart 23 identifies a minimum of four hydrogen hubs, while chart 46 suggests there could be tens of hydrogen hubs; it was unclear how the number of hydrogen hubs would be resolved.
  It was not clear if "National Clean Hydrogen Strategy" and "National Hydrogen Strategy and Roadmap" were the same thing.
- Yes, the Program was well-articulated. What was not clear was whether there would be expenditure issues with the present pace of the Program rollout. In other parts of the government, the funds would be swept up. With other pressures on the government (pandemic, inflation, war in Ukraine), it was not clear if DOE would be able to protect the funds or if they would be targeted for changing priorities.
- There are numerous positive aspects to the overall Program. However, it appears that politics have started to overcome the technical aspects of the Program. This is a longer-term risk to the Program, as has been seen in the past.

1b. Were the important challenges to meeting goals identified, and were plans to address the challenges articulated?

Comments:

- From 3 respondents: Yes.
- Important challenges, including cost reduction, durability improvement, and technology provision to meet market demands for clean energy production, were well-articulated. These challenges have been heightened

and may continue to grow with the recent global cost increases for energy. Plans to accelerate progress, given these global changes in energy pricing, may be welcomed.

- The goals were listed at both a high level and in specific within subprograms, and the goals are very aggressive. Each speaker was clearly aware of the challenge that lay before them. Indeed, without this level of funding, it is unlikely the goals could be met.
- The Program is well-structured, with precise objectives (through clear key performance indicators) identifying the important challenges.
- The meeting's goals were well-identified, and the plans, to a large extent, were well-articulated.
- Yes, they were, along with opportunities to engage to help overcome the challenges.
- Yes. The goals and objectives were clearly stated, with plenty of references to the plans to achieve them.
- Yes, the plan and approach seem fairly comprehensive.
- In most cases, yes.
- The Program did an excellent job outlining the goals and their alignment with the challenges. Hydrogen production cost was clearly identified as a key challenge, and some time was spent outlining the pathways at a high level. Current projects are a good balance between high and low TRLs. Transport is also a key area and significant source of cost. There seemed to be fewer projects in this space overall.
- Yes, they were, to the extent that they can be in a public meeting. The proof of plans to address the challenges will be in the upcoming funding opportunity announcements (FOAs) and awarded projects, which DOE obviously cannot comment on before projects are actually selected.
- Yes, the BIL provisions seem to have given DOE much-needed tools to develop a more holistic strategy than ever before, one that addresses the needs of scaling up, market development, analysis and evaluation, and basic and applied research. There seems to be a good mix of research into the production, conversion, and end uses of hydrogen fuel. There is appropriate focus in the technical areas of the Program to address ways that costs (one of the most prevalent hurdles now) can be reduced over time. The Program also continues to keep its focus on overall energy efficiency and environmental protection. This needs to continue to be emphasized in order for hydrogen and fuel cell technologies to actually have a meaningful impact in transportation electrification and the broader energy transition to cleaner and more sustainable options. Within the environmental impact, there is a strong focus on greenhouse gases (GHGs); it would be good to see this GHG effort maintained while also diving deeper into air pollutants. The GHG effort is well-justified and aligned with today's challenges across the globe. But the local air pollutants are also an important factor in addressing individual communities' concerns about environmental health hazards. Extending this to other hazards, like the emission of air toxics species, would also help fill a large gap in data, science, and understanding. DOE should consider adding this to the scope of analysis for evaluating hydrogen's environmental impacts. This will require basic science analysis, as well as engineering and modeling work. Finally, the reviewer deeply encourages DOE to bring back some of the overall focus on the light-duty vehicle (LDV) sector. It is well understood why medium-duty (MD) and HD sectors are receiving significant focus, and those sectors do need more effort to get them ready for broad deployment. However, the work on LDVs is not yet finished, and that market is currently at a more advanced stage. In spite of that advancement, improvements are still desperately needed in durability and cost. It does not yet seem like scaling up manufacture will be the solution. It would be highly unfortunate if that market were to falter now after so much work has been put into it simply because the focus shifted at the wrong time.
- Oral presentations were focused on the reduction of carbon fiber, which is critical for reaching near-term goals for hydrogen storage. In addition, more focus has been shifted to HD applications, which has become much of the focus of industry. The Hydrogen Materials Advanced Research Consortium (HyMARC) continues to focus on material evaluation to meet long-term goals for low-cost, high-volumetric, and high-gravimetric efficiencies.
- Coordinating across DOE is an important challenge. Sharing information from the recipients of grants and contracts, the work of the consortia, national laboratories, and small businesses is also an important challenge. More information is needed as to the practicality of how the efforts will be coordinated and how the shared information will be provided to the public. Real-time information is needed, from all of the parts of DOE, including for the failed projects and go/no-go decisions for projects that border on failure. The presenters brought up, in general terms, the need for a trained workforce, but they did not provide quantitative or qualitative analyses about the jobs that are needed, nor did they provide information as to how the jobs will be created. It is advisable to include the potential for incremental changes and course correction if the goals for projects and workforce development are missed.

- Cost status and goals were clearly articulated, but more analysis is needed to dig into the entire value chain. For example, it would be good to know what the buffering costs are when hydrogen is made from intermittent wind/solar power yet downstream users require an uninterrupted feed for continuous operation. In the ammonia space, it would be good to know what discount is required to move urea users to neat ammonia. A good start has been made on the viability analysis—it just needs to continue and go one or two layers deeper.
- Although the goals have been clarified, the detailed issues to achieve them are a subject for future study.
- There was a lot of strategy and activity to address the strategies outlined, but the presentations could have been more upfront about the challenges and barriers in the plenary sessions (as was done in the detailed technical presentations). For example, it would be interesting to show the predictions in these presentations over the past 5 to 10 years, what has actually played out, and what was learned from that in terms of what the biggest challenges are and how to tackle them. Learning from missteps can be very instructive.
- Yes, because of its strong collaboration with industry, the Program has always had a good grasp of the important challenges. Plans to address those challenges have also been developed in collaboration with industry. However, the Program has not always had the budget to address all of the important challenges, particularly for demonstration, deployment, education, and outreach. Now DOE has ample budget through the BIL funds. Also, the regional-hydrogen-hub approach will provide DOE with increased opportunity to engage with states, which was not well-supported in the Program in the past. However, with the significantly increased budget and opportunities will come the challenge of managing many more projects to ensure optimal results. Currently, it appears that DOE does not have the staff to manage the increased effort effectively. It is critical that DOE increase staff and identify management tools and approaches to provide effective oversight of the hydrogen hubs, mitigate risk, and achieve steady progress toward goals.
- Overall, yes. However, the staffing challenge to administer and manage/provide oversight was not addressed on the timeline(s) laid out, while simultaneously there is an initiative under way to grow DOE staff with several hundreds of positions.
- The key challenges around hydrogen cost, scale, and timeline are clearly articulated and hard to miss. However, other equally important technical challenges in achieving the "clean" or "net-zero" goals are less obvious and ought to be more visible in the Program, especially in the early TRL projects. Given that hydrogen is an energy carrier and not a primary energy source, the challenges in overcoming the inherent but significant energies/GHGs involved in producing large-scale hydrogen should be highlighted and addressed sooner rather than later.
- The technical goals and solutions were clearly articulated. However, what is not clear is how technologies at different TRLs will be treated in the Program. For instance, integration with nuclear plants may take 5 to 10 years for permitting, testing, and training. It was not clear whether there would be different rating systems for high-TRL technologies (such as alkaline with solar) versus low-TRL/manufacturing-readiness-level (MRL) technologies (such as solid oxide electrolysis cell [SOEC] with nuclear).
- There were not always clearly defined R&D pathways to reduce the costs of various components or approaches, for example. It would be more useful to present some idea as to what the R&D pathways might be, as well as a probability of achieving the goals, or the remaining risks or barriers involved in meeting the various goals (be they cost, durability, etc.).
- The DOE targets were clearly identified on chart 16 for clean hydrogen, electrolysis, and fuel cells for HD trucks. There was a clear statement of guiding principles for DOE's National Clean Hydrogen Strategy development, and targets were clearly defined. The reviewer did not find a discussion or details about the establishment of a roadmap and its goals, unless this was included in the National Clean Hydrogen Strategy development. It was unclear what the deliverable is, who is doing the roadmap, and whether this was the existing U.S. hydrogen industry roadmap. Further, it was not apparent whether the clean hydrogen use scenarios suggest industry (ammonia and refineries) will change its hydrogen production processes to a new and cleaner hydrogen production process or whether this includes an evaluation of potential cost increases.
- The important challenges have been clearly identified. However, connecting the challenges to meeting the goals could use some work. It has been discussed that the Program will focus on decreasing the stack cost by 80% and determining which components it will be necessary to improve to meet this goal; however, it has not been articulated how much cost reduction is really possible with each component.
- Generally, yes. Discussion of the ability of the electric grid to move clean power to the point of hydrogen production was lacking and needs consideration.

- To the extent that hydrogen is an energy carrier, its cost will be heavily dependent upon the input energy. As events over this past year show, there is not a clear pathway to unsubsidized renewable energy to produce hydrogen at the indicated $1/kg, even if there are large-scale breakthroughs in technology. There is virtually no mention of the significant materials-related infrastructure that is needed to support these goals.
- Goals were clearly identified; however, they are aggressive, and the plans to mitigate challenges as they are now presented may not be enough to meet the goals outlined.
- The important challenges need to be prioritized and better articulated.

2. The Hydrogen Program is aligned well with industry and stakeholder needs and is appropriate given complementary private-sector, state, and other non-DOE investments.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion.

Average Score	**8.1**
Number of Responses	38

Comments:

Please describe any areas that you feel are not well aligned with industry needs or that require more (or less) federal funding support.

- Clearly, there has been a massive effort to obtain industry and community input in many locations. There were multiple instances in which the work was integrated with state and local efforts and, in some cases, international programs like IPHE. The private sector is a bit harder to be sure of because much of that work is secret, but obtaining input from industry technical teams is probably as good a strategy as one can imagine for avoiding duplication with industry work. Of course, much funded work is with industry partners and recipients, and in this case, proper collaboration is assured. While not a part of this question specifically, there is clear cooperation and avoidance of duplication between offices in DOE and with non-DOE U.S. government programs in other departments.
- The Program appears to be tackling all sectors at once, so industry needs are likely being met. Making these programs self-sustaining (eventually with less federal support) will be the proof. The many public–private partnerships, hubs, etc. are impressive.
- The Program is well-aligned. There is very little "clean" hydrogen produced today, and the Program is well-designed to address that gap.
- The Program is well-structured, with strong involvement of the industry. There is no specific missed area, keeping in mind the TRL range covered.
- For the budget it has had, the Program is as aligned as it can be with stakeholder needs. Additional testing infrastructure and increased investment in component development will be critical in the next two to four years.
- The active and pending activities address the non-DOE needs as well as a government agency can.
- The Program works very well with industry.
- The AMR rightly focused primarily on DOE investments. There was not much information on private-sector, state, and other non-DOE investments. Perhaps it would have been helpful to have a roundtable of state officials or investors to explain their views regarding hydrogen. Input from Europe's point of view could also be helpful. However, it is not clear that non-DOE input was appropriate for this Program review. Perhaps it would be appropriate for another venue.
- The stated aspiration and scope of the Program are well-aligned with what is needed to move related initiatives by the private sector and other non-DOE stakeholders. The proposed significant investment in hydrogen hubs is especially meaningful and, if successful, could build confidence in private-sector and other investments and propel the envisioned hydrogen economy. Overall, the Program has a much broader scope that intersects with multiple hydrogen stakeholders. Two notable examples this year are as follows:

  - The introduction of hydrogen activities in FECM. This is important since almost all current domestic and global hydrogen supplies come from fossil fuel sources, and it may stay that way beyond the next decade. For the goals of the Hydrogen Shot to be realized, significant advances in large-scale, low-carbon hydrogen production from fossil fuel will be necessary. As such, higher federal funding will be needed for FECM to demonstrate technical feasibility and meet the ambitious cost and timeline.
  - The proposed material recycle and end-of-life effort. This is also necessary and significant progress toward achieving the big goal. One area of activity that could use more funding and expertise is the development of a robust standard of life cycle analyses around GHGs and other environmental impacts (air quality, water, energy, land use, etc.) across all hydrogen production and delivery systems. That way, researchers and stakeholders could use this as an additional screening tool beyond just cost and scale.
- The appropriations for Fiscal Year (FY) 2022 and the request for FY 2023 appropriations are "heavy" in the areas of workforce development; validation of one-of-a-kind technologies; de-risking technologies; and safety, codes and standards. Perhaps the data and information gained from the work in one-of-a-kind and de-risking of technologies could be fed into the workforce training systems. That way, the infrastructure and the people who will build it have a better chance of progressing together. E-learning systems, based on artificial intelligence and machine learning, can be used to train the workforce and document the infrastructure. Eventually, e-learning systems will reside in the metaverse, and they will facilitate three-dimensional (3D) virtual learning—i.e., site visits and testing. Funding support is needed to integrate these e-learning systems with hydrogen and fuel cells and allow "learning for all," including for individuals living in rural areas and disadvantaged communities (DACs). This would differ from and be more effective than providing static, non-interactive pages. Funding is needed to capture and mine the project information, in situ. This "natural fit" of materials for the future workforce should be addressed immediately.
- The Program is well-aligned with industry and stakeholder needs. Extensive collaborations and industry engagement are evident. Multiple consortia (HydroGEN, HyBlend, H2NEW, ElectroCat, M2FCT, HyMARC, Hydrogen Materials Compatibility Consortium [H-Mat], etc.) that address critical Program challenges have been established. Although those consortia seem to be functioning well, the Program Office must be cognizant of the potential difficulties with coordinating those activities in closely related areas and avoiding redundancies across so many parallel efforts. Particularly confusing is the perceived overlap of technical efforts within the H2NEW and HydroGEN consortia. It would possibly be helpful in future reviews to clarify the differences in related consortia objectives and directions. In addition, it seemed that no mention was made concerning the role of "Tech Teams" in future reviews and planning going forward, and it was unclear if those relationships with industry stakeholders were continuing.
- The Program is well-aligned with the hydrogen and fuel cell industry and energy stakeholders. However, additional efforts to provide education for local officials, state agencies, and community groups would be welcomed to enhance opportunities for effective technology deployment, community acceptance, and market transformation.
- The large number of industrial participants confirms the Program is well-aligned with industry. It was not clear how large the contributions from the states were.
- State-level investments and policy support were not as visible in the previous Program projects. It would be great if the hydrogen hubs could motivate more support from regional governments. One important aspect that DOE may need to consider is how to provide stability and continuity assurance for these hubs. Basically, developing a sustainability plan/strategy beyond the five-year period would be very important and helpful to ensure that these hubs will continue to serve their local communities, not just be short-term experimental trials.
- Although the BIL calls for continued work on fossil fuel implementation for hydrogen production, this is one area where the work that is called for may not be in line with stakeholder needs. It is not immediately clear what fossil-fuel-production pathways will have to offer in the future that other, renewable-based pathways will not be able to provide. Especially when we are looking significantly into the future, between the resources available from solar, wind, biomass, and other renewable feedstocks, it is unclear how much fossil production will still be necessary. DOE should work to clarify this and very carefully consider how much fossil fuel production will really be necessary, for how long, at what cost, and for what benefit. Absent a more thorough evaluation, it seems that continued development (if any is even really needed) of fossil-fuel-based pathways is simply too at odds with the worldwide movement away from these limited resources and the desires of stakeholders at large for a clean energy transition.

- One area that might need different focus is the area of reducing the cost of carbon fiber for fiber-reinforced tanks. Much of the DOE effort is focused on polyacrylonitrile (PAN) precursors; presumably, the industry is well-invested in processes for PAN to try to reduce costs. Perhaps DOE efforts should focus on wholly new approaches. Perhaps there are biopolymers that could be investigated, conversion chemistries and mechanisms detailed, and wholly new processes discovered for the production and upscaling of aerospace-grade carbon fiber.
- While the industry needs for a hydrogen society are still unclear, the reviewer liked that the policies necessary to actually use hydrogen were clearly outlined.
- Although there was discussion of codes and standards, that is an area where more support is needed—particularly in new and emerging applications for hydrogen.
- Emissions from hydrogen combustion (turbines) will be a continued area of discussion, and clarification is needed regarding the methods for reducing nitrogen oxide (NO_x) emissions.
- In the area of freight trucks and maritime, it should not be assumed that hydrogen will succeed as a direct-use fuel. Zero-emission vehicles (ZEVs) may not be required in trucking freight long distances in certain parts of the country, so a thorough assessment of hydrogen versus hydrogen-derived, non-fossil liquid fuels is in order. On the electrolyzer front, there did not seem to be any mention of Chinese competitors. Major Chinese players should at the very least be thoroughly benchmarked. The solar industry is in an awkward position at present with respect to supply from China (wanting domestic but needing Chinese supplies). Policymakers need to be informed to avoid this same situation with electrolyzers. Reports out of China (per BloombergNEF) suggest a cost level of $300–$500/kW already with alkaline units.
- This year saw a substantial reduction in the emphasis of solid oxide fuel cells (SOFCs) compared to polymer electrolyte fuel cells. The industry appears to be still focused on commercializing the technology, and yet DOE seems to be de-emphasizing this area. The reasons for this were not clearly spelled out, and it would have been helpful to hear a little more about why this is so. High-temperature fuel cells have a vital role to play in stationary power generation applications and do not require the use of precious metals. These fuel cells have to be part of the mix of our energy future going forward. There are many important basic and industry challenges that need to be solved, and more federal funding is necessary to address these continuing challenges. There ideally could have been more emphasis on the current state of SOFC technology and its remaining challenges.
- It is unclear to what extent hydrogen end-user/demand-market stakeholders are engaged in assessing the needs and whether these needs are being addressed.
- The decrease in the Program's 2023 fuel cell budget request, when the overall Program budget is increasing, is a concern. Though the Program has made outstanding progress in improving fuel cell performance and reducing cost, the shift in focus from LDVs to MD vehicles and HD vehicles (HDVs) has increased durability requirements, which also makes cost goals more challenging to achieve. The fuel cell budget should be increased to achieve these goals, not decreased. The apparent move away from LDVs is also a concern. LD fuel cell electric vehicles (FCEVs) should remain a ZEV option for fleets and for drivers whose vehicle range and refueling needs are not met by battery electric vehicles.
- There is a difference between cost and price. Private suppliers will require a return on investment and operating costs, which will drive the price of hydrogen to a higher level. It is not clear that this is addressed in the targets. Adequate materials, at a reasonable price and from reliable sources, are required to meet future alternative energy needs. There is a lack of involvement and support for a smooth transition of energy technologies without significant disruption (note today's energy prices and supply chain challenges), as well as for economic and secure supply chains that benefit all stakeholders.
- One of the challenges in this Program is aligning existing national laboratory resources and expertise with industrial needs, including the industrial need for secrecy. Unfortunately, it is unclear how this can be addressed. Yes, there are agreements that can be signed in place; however, the tendency of national laboratories to then publicize similar work makes reliability challenging.
- The alignment is not very clear from the Program presentations.

3. The Hydrogen Program is collaborating with and gathering feedback from appropriate groups of stakeholders, including those with a focus on workforce development and justice, equity, diversity, and inclusion.

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.

Average Score	8.1
Number of Responses	33

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.

- Multiple speakers, both at the high-level plenaries and discussing specific projects, pointed to progress in environmental justice (EJ), creating opportunities for minorities and traditionally disadvantaged groups, and the inclusion of community/Tribal concerns and knowledge. It is indeed quite remarkable and commendable to see this level of response to these issues so quickly, by far the most this reviewer has ever seen in 35 years of watching and doing cooperative and industry–government research.
- The Program has done a solid job of engaging external stakeholders and enabling collaborations. No additional participation or involvement appears to be needed. A solid plan (based largely on DOE's Justice40 Initiative) is in place to address DOE policy priorities for underserved and disadvantaged communities. An impressive array of DEI- and EJ-related activities are in place. Although the impact of those activities remains to be seen, they provide an excellent framework for addressing critical issues associated with workforce development in DACs and collaboration with minority-serving institutions (MSIs). The engagement with Tribal communities is especially noteworthy and important.
- The Program is collaborating with a very broad variety of stakeholders, both at the Program level and within the different projects. Inclusion of justice, equity, diversity, and inclusion has been particularly stressed during the whole AMR.
- DEI is included in the guiding principles for DOE's National Clean Hydrogen Strategy and Roadmap development. There is emphasis on benefits in underserved and disadvantaged communities, as well as emphasis on engaging the American Indian Tribes, Native Hawaiian communities, and others. Funding opportunities have been established for Historically Black Colleges and Universities (HBCUs) and MSIs. The funding for HBCUs/MSIs is very important for developing the next generation of engineers and scientists.
- Overall, the Program has good external engagements on these points.
- DOE has done a good job of gathering feedback through requests for information (RFIs).
- There does appear to be a clear direction or intent to incorporate DEI, but it seems a bit too early to fully judge DOE's effectiveness. It has only recently become such an explicit part of the strategy. It does seem well-structured and similar to other efforts around the United States, but whether the strategy works well at the national level is not yet discernable. It was also not clear what stakeholders have been invited into DOE's efforts to address workforce concerns. There would likely need to be significant outreach to non-governmental organizations (NGOs), community-based organizations, nonprofit organizations, and/or their representatives, and not much discussion has been seen in terms of the groups that have been engaged in that regard. So far, it seems this is part of the planning for future work. That is, their importance is recognized in things like the planned requirements for the hydrogen hub solicitation, but then that means it is left up to funding applicants, instead of direct work by DOE, to research this area. In-depth discussion was not seen regarding the metrics and expectations when this effort is relegated to funded parties instead of DOE. This may be an area that could provide fertile ground for research from an organization with such a high-level view and extensive reach as DOE. Understanding the strategies, approaches, analyses, and metrics that actually effect community change and are successful at meeting workforce and community

member needs could help inform state and local governments across the country about how to better implement their programs toward equity goals. DOE is encouraged to take a more active role in helping to establish equity program principles that translate into improved community and workforce outcomes.

- The advances in EJ and outreach to DACs and Tribes is really admirable and a big step forward for the Program. The discussion of Tribal views took up one slide out of 92 in Sunita Satyapal's presentation. This could be expanded, especially if hydrogen could benefit these remote communities.
- This has been a relatively new focus, and it is therefore difficult to quantify whether the engagement has been sufficient or has made an impact. However, the "listening sessions" and engagement with distressed communities are a good first step and are highlighting needs such as hydrogen education and dispelling myths about clean energy.
- It was apparent that the Program team made significant efforts in collaborating with and gathering feedback from a variety of stakeholders. A little more transparency or communication about how these collaborations and feedback might have affected the Program's strategy would be helpful in future AMRs.
- DOE has done an excellent job stating the importance and the goal of justice/DEI, and it is commendable. It is important to determine clear goals and actionable pathways.
- It is strongly agreed that the Program is very good at gathering feedback from and responding to stakeholders across the portfolio of efforts. The reviewer was not able to speak directly to whether these stakeholders have a focus on diversity, inclusion, etc.
- The structure to collaborate and gather stakeholder feedback is well-organized and well-intended. However, direct feedback from community groups, distressed-community leaders, municipalities, workforce development organizations, and EJ organizations may be of value for effective technology deployment, community acceptance, and timely market transformation.
- H2EDGE is a great start. While this effort is focused on training for electric power engineers, and the Center for Hydrogen Safety offers courses in general hydrogen safety, progress is needed in existing workforce development to include repair and maintenance of FCEVs and other hydrogen equipment. Collaboration with original equipment manufacturers (OEMs) and institutions providing auto mechanic training is needed.
- It seems that most people understand the needs and importance of diversity and inclusion. Ms. Shalanda Baker talked about the toxic legacy of fossil fuels and how the Program was supposed to help fix that problem. As most of the people involved in hydrogen research are not involved with the fossil fuel industry, it would have been helpful if DOE could have provided quantitative illustrations of the toxic legacy that she was talking about and perhaps map out a more desirable outcome. As described, this discussion was very qualitative relative to the other clear technical metrics laid out by DOE. DOE could also provide some clear references, and perhaps a model (like the National Renewable Energy Laboratory's [NREL's] Hydrogen Analysis model or Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies [GREET] model).
- The IPHE Early Career Network is important. It is recommended that the participants provide input to e-learning systems. Perhaps business partnerships could be established for education and outreach, as is done by the Center on Hydrogen Safety to reach future experts who work in hydrogen and fuel cells and/or live in rural areas and DACs. Business groups could potentially be set up to collect and curate the data and information from DOE projects for training in DACs. ("All tools in the toolbox.") Also, perhaps individuals in DACs with expertise in the extraction and management of fossil fuels could be helped so they can understand how to transfer their skills to non-fossil industries. It is recommended that business partnerships coach those individuals on new uses for fossil fuel expertise and that training systems augmenting formal education be developed to accelerate the workforce development.
- The Program should be more engaged with states and with education and outreach organizations, such as Clean Cities and other coalitions. However, the Program has had insufficient budget and staff to pursue those engagements adequately in the past. The regional hydrogen hubs should enable the Program to increase those engagements.
- Manufacturing and supply chain stakeholders should be engaged more—it is unclear what challenges are ahead for this sector's capability to ramp up production or transition from manufacturing other products. The supply chain for hydrogen-related technologies is challenged as is with increased demand and geopolitical changes. Environmental–NGO–stakeholder concerns should be assessed on validity and "apples-to-apples" comparisons before adopted/confirmed as an actual concern affecting decision-making.

- It is important to interact with small businesses, labor unions, and technical training schools regarding workforce development in order to reduce job loss fears caused by the transition to clean energy from fossil fuel. It was not necessarily clear how jobs would be plentiful and cleaner, safer, etc., nor what the impact on pay would be for employees who have to learn new skills. It is worth considering how the geographic dislocation of employees could be minimized.
- It is agreed that the current Program is collaborating and gathering feedback. However, it was not clear if this has been identified as an issue with previous DOE technology efforts. Decisions should be based on technical and economic merit and, as always, appropriately within the existing law. Otherwise, this runs the risk of being a distraction from the core goals.
- It is recognized that an effort is being made, but diversity seems to be lacking.

4. 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 R&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.

Average Score	8.2
Number of Responses	37

Comments:

Please describe any over- or under-represented areas, including any gaps in the portfolio or any comments you may have on whether funding levels in each area are appropriate.

- The new budget planning and breadth of the Program, with the addition of the BIL funds and goals, is definitely enabling DOE to accelerate some research areas that previously needed more attention for a major hydrogen transition in the United States. The overall structure looks to really be attempting to accelerate technology potential and is appropriately focused on identifying R&D needs that were possibly languishing or simply not being advanced quickly enough with private enterprise alone. The current Program plan has the potential to address many areas of need and really translate mid- and long-term issues into more near-term solutions. Given the urgency, scale of the desired eventual hydrogen industry, and desire for solutions to come quicker than ever before, this is entirely appropriate.
- Program research, without question, has been of very high caliber, directed to achieving mission goals, and well-balanced between near-, mid-, and long-term goals. Next steps may be directed to focus on the transition of research to commercialization and then to widespread deployment through community engagement, technology deployment strategies, and advancement of domestic manufacturing (balanced with demand).
- The Program's portfolio covers all of the hydrogen value chain. Budgets allocated for the different projects reflect the prioritization to be given to achieve the near-, mid-, and long-term objectives. Early-stage (low-TRL) research aiming at preparing the mid- to long-term solutions is very well considered. It can be seen as a general strength of the Program.
- The way national laboratory research expertise is made available for state and regional projects, as well as industry, is particularly impressive.
- The reviewer has advocated the importance of scale-up projects and demonstrations for many years and, as such, is happy to see things like the Advanced Research on Integrated Energy Systems facility in Boulder being included in the portfolio.
- The portfolio seems to be appropriately balanced across RDD&D areas. DOE consortia and related seedling projects have become important technology incubators and especially useful for organizing disparate activities in a collaborative and effective way.

- The portfolio is well-balanced. In particular, the incorporation of difficult issues such as alkaline-type PEM water electrolysis as a long-term issue is commendable.
- It is good to see low-NO_x hydrogen turbines as a priority. This seems like a good opportunity to utilize existing assets as part of the transition.
- Clearly, the portfolio of projects in electrolysis will be expanding greatly over the next few years. DOE currently does a good job of supporting U.S.-based electrolyzer manufacturers. In the future, there will need to be a significant focus on supply chain development.
- It is impossible to know what the "appropriate" balance of short-, mid-, and long-term R&D should be; there are too many unknowns, and even if we did know right now, it would change rapidly. Rather, there is a significant effort at all TRL levels appropriate for this office and its peers to fund. There are more early projects and more money in higher-TRL projects, as there should be. Effort and funding are appropriately distributed, but we will not know until the results are in if this was the best distribution of projects possible given the challenge.
- This is well-designed overall. Arguably, there is a critical need to do large projects, and this is something that the Loan Programs Office is starting to support now.
- It is not possible to comment on funding appropriateness, but the strategy clearly addresses near- and long-term challenges across many sectors.
- The funding levels in each area appear appropriate.
- There is definitely a mix of near-, mid-, and long-term projects, although sometimes it is not explicitly stated in those terms.
- The Program has generally been doing a good job in balancing near-, mid-, and long-term R&D. With the infrastructure bill and ambitious Hydrogen Shot goal, it is recommended that the Program management team consider "breaking" such a balance for the next three to five years, concentrating manpower and resources on addressing critical barriers on hydrogen production, storage, transportation, and refueling infrastructure. As this is a once-in-a-lifetime opportunity for the hydrogen community, a typical balanced approach that covers everything may not serve the best purpose under such a situation. Time is limited to achieve the significant milestone by 2026.
- As shown, the funding level in each area is appropriate to reach the planned cost reduction thresholds for hydrogen to be cost-competitive across markets: today, $7/kg for forklift applications, and the long-term goals of $1/kg for chemical industries, seasonal storage, synthetic fuels, industrial heat—and then, the longer-term export markets. This, however, is for today's known conditions. There are some gaps—namely, contingencies. Perhaps contingencies could be developed and the funding plans modified to include encumbrance and liquidation dates. For example, if electrolysis optimization falls, ever so slightly, out of sync with deadlines because of a parts shortage or supply chain difficulties, it is possible the encumbrance and liquidation dates become important, such that those projects would have to undergo course correction. The plenary presentations, which include the portfolio, could become public dashboards to show the progress in meeting the thresholds: $7/kg today, $6.50/kg in two years, etc. A dashboard could remain stationary such that comparisons can be made from year to year, and go/no-go decisions about continued funding could be made publicly available. It was unclear if funding has encumbrance requirements such that it could be reallocated if a project were to fail.
- Overall, the Program has a broader scope and well-balanced portfolio of research, development, and demonstration (RD&D) projects that aim to address the long-term goals. It is understandable that the near- and mid-term targets/objectives would vary by R&D areas, with some more challenging than others. Most near- and mid-term expectations involve incremental improvements to the hydrogen process. And often these incremental improvements result in performance trade-offs that may not be readily recognized or recorded. For example, a hydrogen production system may achieve some improvement in $/kg hydrogen cost but at the expense of increased emissions per kilogram of hydrogen, which may not be a line item in the near- or mid-term performance goals. Therefore, it is recommended that near- and mid-term improvements also identify and, if possible, quantify any performance trade-offs caused by the improvement that may have an impact on the ultimate long-term goals.
- In a relative sense, it appears that production overall is appropriately represented in the portfolio because of its importance to meeting Hydrogen Shot goals. Distribution seems to be relatively under-represented, and fuel cells are somewhat over-represented since they are not critical to achieving low-cost hydrogen. Platinum-group-metal-free (PGM-free) catalysts for water electrolyzers and fuel cells are perhaps over-represented, considering the very large durability challenges that remain. Notably, the above are assessed

on a relative scale, based on current funding levels. It is likely that with the BIL funding, projects in all areas will be raised. One key gap that may have a strong impact on the ability to achieve near- and long-term goals is that the size of the technical R&D workforce in the United States may not be sufficient. That is how it seems. It is based on a wide-scale departure and shrinking of the field in the mid-2010s as automotive fuel cells were diminishing in relative importance and hydrogen/water electrolyzers were not yet gaining steam. The talent pipeline partly depends, of course, on the number of graduate programs in the hydrogen economy. This should be assessed, and if truly insufficient, some efforts may be needed there.

- As previously stated, the decrease in fuel cell R&D funding for FY 2023 is a concern, especially when the overall Program budget is increasing. There are still many technical challenges to overcome to improve fuel cell performance and lower costs. In fact, the Program's focus on HDVs has made the durability target much more stringent, and although the cost target is higher than it was for LDVs, higher durability is difficult to achieve at low-precious-metal loadings. Developing non-PGM catalysts is a significant challenge, as will be developing alternatives to fluorinated membranes, which the industry will likely have to move away from because of environmental concerns. On the positive side, it is good to see an increase in the Basic Energy Sciences (BES) program's hydrogen R&D budget request. Given the plans for regional hydrogen hubs, the Program should consider increasing the Systems Analysis budget to increase analysis efforts for specific states and regions. For example, updating the Northeast Electrochemical Energy Storage Cluster's techno-economic analyses that were conducted in 2017–2018 for the Northeast states and expanding to other states could be useful. Finally, the Program should continue to apply sufficient resources to manufacturing R&D to lower technology costs.
- Yes, the 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 R&D. A major challenge with hydrogen fuel cell technology is that it is "bottom-heavy," with many researchers and has few opportunities for profitable successes. As set up now (by U.S. law), the universities and national laboratories develop intellectual property that then needs to be licensed by a company to be put into practice. However, the hydrogen company is presently unlikely to have enough profits or resources to be licensing technology. Perhaps this will change as new companies try to get into the hydrogen field. DOE should track how business practices and licensing progress over the next few years, and DOE hopefully helps businesses to be profitable with a robust hydrogen economy.
- The current portfolio is under-represented in near-term R&D, especially TRL 7 and above. The recent demonstration projects within H2@Scale are very good additions to the portfolio, and the plan as described to use BIL funds to expand more in these higher-TRL/nearer-term technologies will help correct this imbalance. This should not be at the expense of mid- and long-term research, which is also critical to maintain technical leadership in the United States.
- From a deployed-system-capital-expenditure perspective, some of the sub-cell- and cell-level electrolysis and fuel cell research should reassess the trade-offs between near-term high performance and long-term stability. The techniques that achieve highly performing electrochemical cells often do not persist and may require replacing the expensive electrochemical hardware more frequently.
- The reviewer hopes DOE continues to provide strong support for early-stage R&D work in the areas that may take a long time to mature, such as proton-conducting SOECs.
- The impact on industry if the Hydrogen Shot is achieved should be analyzed. It is unclear how Hydrogen Shot success would impact the agricultural community (ammonia cost).
- It appears that the time horizon for several of the R&D areas seen during this AMR has shortened significantly. This is appropriate for some (where the technology is at or on the cusp of being handed off to industrial concerns), but there are other areas where there is still much need for out-of-the-box thinking—storage, liquid carriers, and materials for high-pressure tanks, to name a few.
- The near- and mid-term goals are well-represented. Longer-term goals appear somewhat out of balance. SOFCs seem to have been largely de-emphasized. Also, the rationale for the 75%/25% funding split between low- and high-temperature electrolysis was not made clear. Clearly, high-temperature electrolysis has many thermodynamic advantages, even if it is behind on TRL levels relative to low-temperature systems, but the longer-term funding picture should recognize the advantages offered by high-temperature systems. Going forward, a more equitable distribution of funding between low- and high-temperature systems is more desirable.

- University support is lacking compared to national laboratories. There are still some fundamental issues to be solved for the PEM- and solid-oxide-based (SO-based) electrolyzers. In tackling these problems, universities have advantages.
- The projects seem to be more focused on the mid-term goals, whereas not enough emphasis is put on more basic science to allow the development of solutions for the long-term goals.
- Additional attention is needed regarding safe, secure, economical, and reliable sources of materials within the industry. More work is needed on how to maintain reliable energy supplies during the transition and the longer-term dependence on fewer sources of energy (e.g., common mode failure).
- Underrepresented topics include pipelines, small (up to 10,000 kg) engineered underground hydrogen storage (versus salt domes), liquid hydrogen storage, liquefaction technology R&D, fueling interfaces for liquid hydrogen, and off-road FCEVs.
- There are several interesting projects with industry that seem either not to have done any work or to not be well-developed and implemented for a domestic supply chain. If a domestic supply chain is supposed to be developed, it should be developed using domestic materials.

5a. The Subprograms of the Hydrogen and Fuel Cell Technologies Office (HFTO) have clearly articulated their mission and strategy and have appropriate goals, milestones, and quantitative metrics.

For the HFTO subprogram(s) you are evaluating, 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 Technologies Sub-Program Rating	Fuel Cell Technologies Sub-Program Rating	Technology Acceleration Sub-Program Rating	Safety, Codes and Standards Sub-Program Rating	Systems Analysis Sub-Program Rating
Average Score	**8.7**	**8.7**	**8.6**	**8.7**	**8.5**
Number of Responses	34	33	27	24	28

Comments:

- The subprograms indeed have clear and appropriate goals across all those that presented. Milestones along the way were provided, and goals/milestones were quantitative, time-bound, and generally very challenging.
- The subprogram organization is logical and effective. It provides a rational framework for coordinating complementary RDD&D activities. As currently configured, the framework is structured to mitigate unwanted "stovepiping" of priorities and reduce organizational redundancies.
- Technology Acceleration has been a particularly excellent addition to the subprograms.
- These subprograms are focused and based on metrics that are well-thought-out and well-modeled.
- The subprograms are considered to be very proactive in promoting the Program.
- The subprograms all have a clear mission and strategy. The level of detail in the metrics varies, and it is difficult to define these for some areas, such as Systems Analysis, where metrics may relate only to achieving certain dates for important analyses, for example. The Fuel Cell Technologies subprogram has by far the most detailed metrics, and it would help if the Hydrogen Technologies subprogram had similar metrics and targets. For example, the targets are defined by component (membrane, catalyst, bipolar plate, etc.) and through multiple parameters (conductivity, durability, activity, etc.), while Hydrogen Production is defined only by $/kg and $/kW. The latter, while easy to compare, should really be changed since $/kW is better for lower-efficiency electrolyzers but actually increases $/kg.
- The Fuel Cell Technologies plan is well-articulated, with specific achievement metrics for each subcomponent. The Hydrogen Technologies plan needs to be developed further to this level of subcomponent analysis.
- All of these subprograms appeared to be extremely well-managed and well-articulated to achieve goals, milestones, and quantitative metrics. The next steps may be to emphasize Systems Analysis and Technology Acceleration to hasten the transition of research to commercialization, with community engagement and advanced domestic manufacturing to meet demand.

- The subprogram presentations (specifically the Program/subprogram plenary and Hydrogen Technologies oral presentations) were uniformly solid in describing the pathways and goals with appropriate metrics needed to “move the R&D needle.” If an improvement could be made, a more semi-quantitative assessment of the risks remaining to overcome barriers could be useful.
- HFTO clearly conveyed the current mission with appropriate goals, milestones, and metrics. It appears to be challenging to incorporate the rapidly evolving commercial space and Congressional directives.
- The Hydrogen Technologies and Technology Acceleration goals make sense for the current level of technology—it is time to get this technology commercialized. Not a lot of new goals/projects were seen for the Safety, Codes and Standards (SCS) subprogram, and it was not clear if any new projects have begun or are envisioned. It seems that new or ongoing data from a “technology validation” project on fueling (both LDV and forklift) is a large enough body of data at this point that it can inform practical, statistics-based standards going forward.
- There was no SCS subprogram overview presentation. The SCS presentations from Tuesday morning have appropriate goals, milestones, and metrics. It may be time to establish the current SCS mission, strategy, and goals. The 2020 Program Plan also lists no specific SCS goals. With so many emerging applications, consideration should be given to determining goals, milestones, and metrics.
- Regarding the mission and strategy, it is suggested that MD/HD targets, goals, and research should be in addition to, and not in place of, parallel LD efforts. This is especially the case in the Fuel Cell Technologies subprogram where, as presented, all the LD targets and evaluation were not mentioned and were replaced with their MD/HD counterparts. The Program is asked to maintain the focus on LD and communicate clearly where the advances in one application may or may not be transferrable to the other. This will be especially important to keep stakeholders properly informed as these industries and technologies develop. For instance, as cost targets may be achieved for MD and HD, they might depend on technology advances that are particular to or only really achievable in that application. If so, it will be important to clearly communicate that so stakeholders have properly set expectations and an understanding of the overall market and the technology interactions between end uses.
- For Hydrogen Technologies, more information is needed on how the cost of electricity will be reduced. It was not apparent if natural gas would be a primary fuel for electrical power production, nor how the issues of spinning reserve would be addressed to reduce the cost of electrical power. For Fuel Cell Technologies, it would be good to know what cost breakthroughs are needed to achieve a cost-effective HDV fuel cell system, and if the cost-reduction program for fuel cells depends only on the benefits of high-rate production. It was not clear how projects that would reduce the cost of fuel cell systems are chosen, nor where manufacturing comes into the Fuel Cell Technologies, Hydrogen Technologies, and Technology Acceleration subprograms. It is possible that we would develop technology and manufacturing processes, only to have the products of this technology manufactured outside of the United States; “manufactured in America” should be a goal included in all of these subprograms.
- More work is needed on the demand and quantity of the projected use of hydrogen for various applications. It seems we are past the point of “Can we make hydrogen?” and are now at the point of asking who is out there to use hydrogen and at what quantity. An inventory of the age of existing facilities, along with their replacement/upgrade cost potentials (i.e., quantitative metrics), is needed. It is unclear what is out there, what can actually be transitioned into decarbonized approaches, and whether the industry is willing to go along with it. It is recommended that metrics be added to explain go/no-go decisions made at certain milestones that include the encumbrance and liquidation dates.
- There is an unfortunate mismatch between industrial- and national-laboratory-stated materials and performance goals. This is an ongoing issue that is partially caused by different manufacturers using different approaches with differentiators. It is also partially due to reliance on a set of experts who do not choose to engage with the difficult task of monitoring industrial goals and instead base their analyses on academic models and goals.
- Metrics could have been emphasized more in individual subprogram presentations—they are clear at the high level, but alignment down to the individual project level is important.
- It is difficult to apply quantitative measures to several of the subprograms. Systems Analysis needs to look at macro-economic and system-wide economics and reliability during transition.
- Systems Analysis needs to look deeper into the entire cost chain.

5b. Were the important challenges to meeting these goals identified, and were plans to address the challenges articulated?

Comments:

- From four respondents: Yes.
- Yes, the subprogram challenges are well-identified, and the plans to overcome those challenges have been well-communicated. In addition to the AMR, the subprograms' topic-focused webinars and workshops are an excellent approach to providing more detailed information on challenges, activities, and plans, as well as getting input from industry and other stakeholders. The goals, milestones, and quantitative metrics are ambitious, and appropriately so.
- Yes, for the Program goals, end uses, and applications as presented, the major challenges were properly identified, and DOE clearly has a strategy for addressing them.
- The ground that needed to be covered and the barriers to meeting the goals were correctly identified, along with plans (typically multi-path plans) to surmount the barriers. In general, there was an overarching plan to fund several approaches and then subsequently focus funding on those that work, helping those approaches progress up the TRL chain.
- Yes, well done.
- Mostly yes.
- Largely yes.
- Yes, in general. Please continue to update the understanding of challenges and revise plans accordingly at future AMRs.
- The communicated challenges include end-user cost, insufficient existing infrastructure, poor public awareness, limited business cases, poorly aligned annual demand of hydrogen relative to existing production capability, required technical innovations, and a limited skilled labor pool. Discussed solutions focus on outreach with academic and commercial partners to improve situational awareness and education while funding training/educational opportunities and research to close technology gaps.
- For each subprogram, and in particular Hydrogen Technologies and Fuel Cell Technologies, there is a clear and well-defined description of the qualitative and quantitative objectives, the articulation between the topics, and the timeframes. The Program is mainly focused on technology and economic aspects. Hydrogen is considered a powerful pathway for global decarbonization, as required by our society. This means the hydrogen community has to ensure that society can trust in the positive environmental impact of the hydrogen developed. Investigating in more detail all the environmental impacts (carbon footprint, land use, materials needs, etc.) could contribute to building that trust.
- Some challenges were clearly articulated—e.g., the case for integrating hydrogen production with nuclear. A near-term opportunity that was not covered is capturing the status and information from Technology Acceleration projects for training systems. For example, with the integration of hydrogen production with nuclear energy (again, this was well-presented), the learnings could be placed into training systems as they occur. It is recommended that future grants and contracts stipulate this data collection and reuse of the data.
- Mostly, yes. It would be good to see efforts to identify and address the challenges that will remain even after the technology and cost goals are achieved. Deploying the technologies will require acceptance by regulators, industry, and the public.
- While cost and technology performance may be a substantial challenge, community acceptance for market transition may be the greatest challenge to increasing market pull for a clean hydrogen economy.
- Challenges were well-identified; general plans were articulated, but this will take some time, given the large task ahead of HFTO. The FOAs would be expected to have more detailed information on how to address these challenges.
- Challenges were well-articulated and plans to address the barriers were also thoroughly discussed. One area of improvement might be to address the specifics of the R&D steps to achieving the goals, or at least there was little discussion as to the risks involved in how successful the R&D pathways might be. This comment comes from the impression that, for example, when waterfall charts are shown for reductions in cost, specifics were often absent as to how the reduction would be achieved and how much risk it would entail.
- For the most part, the challenges and obstacles were articulated satisfactorily, and plans to address the barriers were adequately formulated. In the 2022 AMR overview of the Hydrogen Technologies subprogram, there was a significant emphasis placed on approaches for efficient and cost-effective

hydrogen production. It is assumed that was done to set the stage for hydrogen production R&D that will be devoted to addressing the challenging goals of the Hydrogen Shot initiative. That said, it was surprising that hydrogen storage technologies were relegated to second- or third-tier importance in the presentation. An approach that meets the volumetric and gravimetric capacity targets as well as reversible thermodynamic and kinetics targets has not yet been developed. This seems to remain a critical issue, and it should be highlighted in a more direct and active way. For example, work within the HyMARC advanced storage material consortium received very limited attention. It begs the question about the R&D directions in this important technology area. The HyMARC activity should have at least been granted an oral presentation slot in the review; it seems like that work is being marginalized.

- If one searches the Hydrogen Technologies subprogram for "challenges," nothing shows up. However, targets are identified and extensively discussed. Importantly, "focus areas" are identified. The planned progression through the TRLs is discussed, but no detailed pathway for achieving the progression was identified, and breakthrough technology needs were also not clearly identified.
    - The Fuel Cell Technologies subprogram identified four challenges: cost, efficiency, durability, and power density. Each of these challenges had approaches identified. Cost is a critical driving force for the HDV market. RD&D cost reduction areas identified for HDVs with high-level goals were presented (e.g., increased power density, although what would be done to increase the power density was not directly stated). (Perhaps Pt-to-Pt spacing would be modified to improve oxygen reduction catalysis, or ternary alloys of PGM would be considered to increase durability.) When considering plans to address challenges, discussion was at a high level—not what one would consider a "plan." The Los Alamos National Laboratory and Brookhaven National Laboratory catalysts look promising; however, it was not clear that the data after 90,000-hour-equivalent accelerated stress test (AST) cycles, as shown for these catalysts, are in the baseline. It is assumed they are, but a better label on the chart would help. The discussions of General Motors (chart 18) and Carnegie Mellon University (chart 19) provide greater insights into how the challenges would be addressed. The importance of a 25,000-hour-equivalent AST is a good addition to the Program. It may be difficult to separate out the different degradations if they interact; catalysts degrade, and there is higher current density at constant power, which may affect supports and vice versa. Migration of degraded catalyst into the membrane may suggest membrane weakness. There were a number of unclear points: whether there was the capability to sort out the potential mixing of degradative effects; whether the decrease in performance of a PGM-free catalyst compared to a PGM catalyst suggests a larger fuel cell stack, more bipolar plates, and more membrane; and how these are rationalized in the design for the fuel cell system.
    - Diversity, inclusion, equity, and accountability efforts would benefit from industry internships since RD&D drivers may be different in industry compared to national laboratories or universities.
    - Technology Acceleration is an important stepping stone to higher TRLs that will lead to manufacturing. It was not clear how HFTO rationalizes doing some of industry's important development activities. SCS programs by national laboratories are very important aspects of the Program and benefit all industry. For demonstrating hydrogen and fuel cell integration, it was not clear if a pilot facility needs to be developed and if this effort involves national laboratories/universities, nor what industries' participation is. It would be helpful to know whether industry results (patents/trade secrets) are shared with other industry on a non-competitive basis and whether the results of Technology Acceleration are only for U.S. industry. Ammonia production is a well-defined and mature industry. Further questions include what level of improvement (as a percentage of current cost) is needed for the ammonia industry to expend new capital based on Technology Acceleration results, if there is a study that states what cost improvement is necessary to undertake capital expenditures, and whether H2@Scale cooperative research and development agreement (CRADA) results from General Electric (GE) and Nel Hydrogen would be available to manufacturers not selected for the CRADA. There are similar questions for GKN Powder Metallurgy hydride storage.
    - Regarding grid energy storage and minimizing hydrogen cost through multiple generation sources, it was not clear why multiple generations were not just made using the lowest-cost system. The nuclear hydrogen production should be emphasized. It was not clear why there was more wind-to-hydrogen-electrolyzer modeling (this has been repeatedly done for the last 10+ years), whether transportation results would be available for all U.S. companies, and how the support of non-U.S. companies (e.g., Daimler) is justified. Hydrogen dispenser nozzles are currently in use, and it is unclear why new designs, etc. are needed and whether this is a cost or safety issue. Total cost of ownership analysis is

very beneficial and should be done in close cooperation with industry. It would be helpful to know how many hydrogen hubs there would be.

- The goals are clear; however, all subprograms and accomplishments are treated as equal. It would be helpful for DOE to illustrate the relative TRL and MRL of accomplishments. That is, if the current density of a small SOEC is increased, it is unclear how this will directly feed into the Program goals—for instance, whether it will increase the TRL at all, or just help toward the "1 1 1" goal if it could somehow be commercialized.
- The individual subprogram presentations included slightly more detail, but the challenges and past experiences were emphasized less than the future.
- DOE will need to address the larger industrial uses of hydrogen, which to date are generally handled by independent producers and users. For example, existing codes and standards generally do not cover larger industrial hydrogen processes and are handled independently through risk analysis by producers and users (e.g., not within the scale of such documents as NFPA [National Fire Protection Agency] 2).
- Real emissions from hydrogen projects (carbon emissions, constituent emissions like NO_x, and hydrogen in the atmosphere) were alluded to, but detailed discussion or projects directly related to quantifying/ controlling emissions were not seen.
- The challenges to meet the HFTO subprogram goals need to be prioritized and better articulated.
- HyMARC has been in process now for seven years; it is difficult to see if we have a clear path to a material that will meet the goals and is practical for the automotive environment.

6. HFTO Subprograms are effectively fostering innovation and advancing the state of technology for hydrogen and fuel cell technologies to be competitive and achieve widespread commercialization and adoption by industry.

For the HFTO subprogram(s) you are evaluating, 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 Technologies Sub-Program Rating	Fuel Cell Technologies Sub-Program Rating	Technology Acceleration Sub-Program Rating	Safety, Codes and Standards Sub-Program Rating	Systems Analysis Sub-Program Rating
Average Score	**8.4**	**8.4**	**8.4**	**8.5**	**8.3**
Number of Responses	34	33	27	24	28

Comments:

Please include recommendations on any novel or innovative ways to address the challenges and achieve the Program goals, including the challenge to meet the Hydrogen Shot production cost goal of $1 per kg of hydrogen in 1 decade.

- There are small projects to support scientific concepts, SBIRs to support nascent industrial innovations, and a variety of efforts with many players to progress the best ideas and work them toward commercialization. As they approach that point, there are then the hubs and Technology Acceleration to help bring up regional markets and supply chains, helping industry accept initial risks so that a demand-pull market results. Of course, this is easier in some areas than others; Systems Analysis cannot as easily foster innovation, but it does allow one to see how the innovations might fare if they succeed—so there is value. Likewise, Technology Acceleration is more about fostering market insertion and supply chain development, so innovation is less that subprogram's responsibility. But it does create a place where innovations, once developed, can thrive.
- The subprograms cover the novel and innovative ways of which this reviewer is aware.
- It is recommended that the Program look at the integration of renewable power, grid capacity, and hydrogen production at the point of use to understand how we can minimize the need to transport hydrogen other than via pipeline by developing production infrastructure at/near the point of use. It would also be helpful to accelerate both SCS and materials testing work to support easier and less costly deployment of hydrogen pipelines.
- DOE has done a first-rate job of structuring the overall Hydrogen Technologies and Fuel Cell Technologies subprograms to nurture innovation and to foster advanced technology development. Collaborations with the

Office of Science and Advanced Research Projects Agency–Energy (ARPA-E) are important. However, a continuing challenge remains to show stakeholders how those linkages are leading to meaningful advancements and impact in the core Program. The goals of the high-profile Hydrogen Shot initiative are clearly challenging. A focused effort is planned and being executed. However, other critical areas (e.g., storage and carriers) must not be de-emphasized at the expense of progress on the Hydrogen Shot activity.

- To achieve the Hydrogen Shot production cost goal of $1 per 1 kilogram of hydrogen in 1 decade, the addition of alkaline and anion exchange membrane (AEM) electrolyzers into the Program was a very good decision. With the cost of PGMs continuing to increase, AEM water electrolyzers seem to be the most promising candidate to reach the target. Acceleration of AEM water electrolysis R&D would be critical for future success.
- Achieving the Hydrogen Shot production cost goal of $1/kg of hydrogen in a decade, and considering only “clean” hydrogen, will depend mainly on the electricity cost, which is outside the influence of the Program. The technology impact is well integrated in the current Program.
- The thermodynamic advantages of high-temperature systems offer a clear path to achieving lower cost.
- Thinking a bit outside of the box: perhaps there should be a competition for which the prize would be the award of a federal fleet (or other hydrogen offtake) contract for the first organization to demonstrate production at $1/kg while also selling the hydrogen for the contracted use at a competitive rate (at or below conventional fuel cost equivalent).
- The number of neighborhood-level microgrid demonstrations should be increased. This simultaneously reduces the load on the high-voltage power grid and illustrates integrating the multiple renewable and hydrogen-based power sources needed to reduce the carbon footprint at a local level. With a properly selected site, this can demonstrate a reduced electricity cost, thereby increasing the demand for hydrogen. This added demand could create a business case for the commercial sector to participate. Unfortunately, this would likely result in a near-term increase in hydrogen costs before industry could develop enough to satisfy the demand. If combined with an educational institution (such as high school, vocational school, or community college), this can incorporate outreach and educational elements while potentially serving a DAC.
- The subprograms are working very well on innovation and technology. The concern is with “be competitive.” It is very hard to compete with fossil fuels, especially in transportation, so shooting for cost parity within five years or a decade is probably setting the bar too high. It should be reasonable to assume that good progress and a line of sight on ultimate goals will be enough to spur policy support.
- The Program has been very effective at fostering innovation and advancing the technology through R&D. The regional hydrogen hubs should enable innovation in demonstrations, deployments, education and outreach, and approaches to working with states. However, it is not clear that the HDV market alone will generate the demand needed in the transportation sector to reduce the cost of hydrogen to the Hydrogen Shot goal or enable widespread commercialization. The Program should do more to support LD FCEVs in applications where they make sense. In the Systems Analysis area, the Program should consider doing more state- and region-specific analysis to assist states/regions in planning hydrogen and fuel cell demonstrations and deployments.
- The $1/kg target is indeed very aggressive and aspirational. That is good, and a “failure” of achieving only $1.25/kg or $1.5/kg hydrogen would still be a major win. However, there is still a deficiency of specific articulated pathways to achieve the $1/kg goal. DOE would be better served with more analysis discussing what it will take to achieve the targets so as to relate the goal to what is achievable in the timeframe.
- HFTO has traditionally fostered significant innovation in electrolysis and fuel cells. However, the electrolysis area has had much less investment and very little funding past TRL 6–7, which leaves a lot of investment for small companies to actually transition R&D advancements to process development and scale-up. With the upcoming FOAs, hydrogen/electrolysis should start to catch up to fuel cells on being world-leading at the commercial level. On safety, the Center for Hydrogen Safety is a great resource and can help drive consistency and learnings. The one area where HFTO could play a stronger role is in clearly communicating and pushing to resolve obstacles in existing codes and standards that are hindering implementation. Similarly, NREL in particular is very strong on systems analysis, but some deeper dives across the community on what can be done to improve cost at the systems level would be a good next step with the added resources in hydrogen.
- A goal of $1/kg production cost by 2030 is a tremendous challenge. DOE should take a somewhat balanced approach. Higher-TRL technologies (PEM, alkaline) for production must be emphasized overall, as they

are the most likely to achieve the substantial improvements needed. While the operating efficiency can only be increased somewhat, capital costs can be dramatically improved through scale-up, but this can get us only part of the way down the cost curve. Balance of plant efficiencies needs to be improved as well, but it is unclear how much is possible. The remaining path is a reduced stack capital cost at the material level, meaning increased operating rate while maintaining/improving efficiency. For alkaline, thinner separators are critical. For polymer electrolyte membrane water electrolysis (PEMWE), thinner PEMs with lower hydrogen crossover and mechanical strength are needed—research is needed to define targets and measurement methods to know what is truly needed from a materials property perspective in the PEMWE environment. For PEMWE catalysts, it seems that only Ir-based catalysts will be impactful by 2030. Significant materials development is needed to develop truly stable Ir-based catalysts at the low loadings needed for PEMWE at the multiple-gigawatt-per-year scales needed to achieve the vision. In-depth understanding of degradation mechanisms are needed, and new materials science is needed to stabilize—i.e., through optimization of Ir structure and composition (oxide level, grain/particle size), support–catalyst interactions, and surface modification. This needs to be done with both strong computational theory guidance, as well as advanced fabrication and characterization methods. Toward the reduced capital cost, DOE should consider projects that directly address higher-current-density operation in the near term—5 A/cm^2 or higher. The key barriers (material stability, reaction uniformity, heat and mass transfer) should be determined through advanced characterization, modeling, and baselining, and then focused materials development efforts should be initiated to address these barriers. Along with the high-TRL emphasis, DOE should also fund lower-TRL efforts at appropriate levels. AEM technologies have incredible promise but are still far away from the goals—no supporting electrolyte, durable ionomers for membranes and electrodes, and PGM-free catalysts. Focus needs to be on developing truly durable ionomers. HFTO should also have seed programs for innovative high-risk–high-reward-type projects, akin to the ARPA-E model.

- To foster innovation and advance the state of the technology for competitive applications and widespread commercialization, an inventory of the expended life and life expectancy of carbon-based energy systems is needed. This may not be novel. The data and information in the inventory "review" can be imported into e-learning systems that use artificial intelligence and machine learning to train the workforce. These can be served as free-of-charge apps that provide a dynamic learning environment. These systems help the workforce and instructors realize their progress and also design personal pathways to broaden and strengthen their knowledge. Project developers also need assurance that training systems meet their needs and that these systems will help attract and retain a skilled workforce, so the developers must be included as partners. The developers will gain confidence as they experience how the e-learning systems expand with use and interaction. Somehow, the impact of the war in Ukraine and the drought conditions and precious nature of water should be added to analyses.
- The HFTO programs are clearly technically sound and advancing technology. However, the innovations as described were not explained as part of a total cost of ownership/techno-economic analysis model, so it was hard to understand how they have an impact on DOE's "1 1 1" goals. Quantifying progress toward "1 1 1" goals should be included in all future programs if DOE can provide a model for reference. It probably makes the most sense for the DOE laboratories to model the projected impact of the university/corporate innovations, as the labs can be impartial. There are so many issues related to "adoption by industry" that it seems like an unrealistic metric. Perhaps it is better to think about "accelerating the hydrogen industry."
- The Program should not penalize lower-cost "gray" sources of hydrogen waiting for more cost-effective green hydrogen. Inexpensive gray hydrogen can help nascent hydrogen applications gain traction earlier and still result in emissions reduction. With a lower barrier to hydrogen use, efficiency increases and long-term carbon goals will be obtained as a natural optimization process. Too high of a hurdle upfront will slow the technology. "The perfect should not be the enemy of the good."
- Unfortunately, it is unclear how there is going to be a clear path to implementing the necessary groundbreaking technology in the market. This requires both refinement of existing technologies and significant breakthroughs. While the refinement is likely and can likely achieve $4/kg or even less, $1/kg really does seem to require significant technological breakthroughs. And the current frameworks do not seem to encourage a smooth transition from laboratory-scale innovation to benchtop to prototype to pilot to mass production. Encouraging national laboratory scientists to become innovators and entrepreneurs will not achieve this in the timeframe desired. It is critical that DOE actively engage with demonstrated technology disruptors and innovators at the incubator level, and the A- through C-round start-up.
- Unfortunately, it is difficult to believe $1/kg of hydrogen will be achieved in a decade. HFTO and FECM and their predecessors have been working at this for over 10 years. Improvements have been evolutionary,

not breakthrough. This does not suggest that the subprograms should be eliminated; they are definitely of value. Recognizing that progress would be evolutionary and setting goals with that approach in mind for some of the subprograms and establishing breakthrough projects (the reviewer avoided using ARPA-E) with recognized high risk would be beneficial.

- The Hydrogen Shot production cost goal of $1/kg of hydrogen in 1 decade is ambitious, as it should be, but the work being done is less ambitious and relies solely on U.S. progress, whereas—in contrast to the development of fuel cell technologies, where the United States kept the lead for several decades—hydrogen production using electrolyzers is much more developed in the European Union (EU). More international collaboration is required to leverage the knowledge and progress outside this country. As it seems, the work done in the United States is still at a very early stage compared to many other countries.
- Increased education to local communities may be an effective pathway to gain market acceptance, commercialization, and transformation. Direct communications with community leaders may be needed and welcomed to create an effective pathway for market transformation. Generally speaking, DOE needs to move the research to community markets for commercialization, domestic manufacturing, and workforce development.
- There was no SCS subprogram overview presentation. It may be time to establish the current SCS mission, strategy, and goals. Widespread commercialization will require regulatory changes at the national, state, and regional level.
- From the reviewer's experience, work on porous transport layers is necessary for PEM electrolysis. It will also be valuable to expand the portfolio in alkaline electrolyzers.
- The challenges to meet the Hydrogen Shot goals need to be more clearly defined.

7. The HFTO Subprogram'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 R&D.

For the HFTO subprogram(s) you are evaluating, 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 Technologies Sub-Program Rating	Fuel Cell Technologies Sub-Program Rating	Technology Acceleration Sub-Program Rating	Safety, Codes and Standards Sub-Program Rating	Systems Analysis Sub-Program Rating
Average Score	**8.4**	**8.4**	**8.5**	**8.5**	**8.4**
Number of Responses	34	32	26	23	29

Comments:

Please describe any over- or under-represented areas, including any gaps in the portfolio or any comments you may have on whether funding levels in each area are appropriate.

- As with the overall Program, each of the subprograms has early- and mid-term R&D and some near-term projects. The only exception is Technology Acceleration, which is designed to be focused on helping high-TRL products make it through the valley of death to a functioning capitalist market. But even Technology Acceleration has commitments at different timescales befitting the goal of demonstration, de-risking, or transition to demand-pull.
- Given all the moving pieces, the staff has done an excellent job overall in balancing priorities and investments.
- No particular area seems inappropriate.
- GREET training is needed for integrating non-carbon energy facilities or upgrades with those facilities that use or produce fossil fuels. This would support a gradual and reasonable transition. Additionally, an analysis of the workforce is needed to support the transition. The analysis needs to be specific, determining who works now, what training is needed for the future workforce, where they live so that we can reach them, and whether those who live and work in rural areas have high-speed internet access (broadband) so that announcements and training in energy systems can be sent to them. The distribution of information

about new energy systems or modifications of existing energy systems can assist with the permitting process and public acceptance.

- Other than Hydrogen Technologies, the reviewer's scores/comments are from the Program/subprogram plenary presentations. One impression received over the years is how extremely important it is to transportation applications to obtain high-strength materials for high-pressure tanks. Toray has been in the carbon fiber R&D business for roughly four or five decades, and carbon fiber is still far short of its theoretical properties, with just incremental progress still occurring. Perhaps a joint BES–EERE program in materials discovery is in order to make a big leap forward in properties, which would hopefully go to tackling the cost barriers that have been identified.
- With the focus on "1 1 1" and hydrogen hubs, several of the legacy programs are somewhat orphaned and not related to new DOE goals. The long-term research is inappropriate for the "1 1 1" programs but, overall, is important to hydrogen research. For instance, the HydroGEN programs seem somewhat unrelated to "1 1 1," but they do important research and should not be cut. Solid-state hydrogen storage does not work despite ample investment, but the payoff of a success would warrant the investment. The Technology Acceleration projects seem very successful. DOE might study which projects were most successful and which were their most critical elements, and consider what mix of high and low technical/industry goals have led to commercialization.
- For Hydrogen Technologies, it does seem that while the biomass/waste pathways are included in the scope of the goals, they are certainly taking a back seat in focus and funding in that subprogram. This should perhaps be reconsidered or adjusted, especially as waste and waste emissions will continue to be an issue that needs to be addressed in the future and could be a positive opportunity for hydrogen to abate these emissions. In addition, LD fuel cell development should not be left behind in favor of MD/HD; rather, development for these end uses should be pursued side by side.
- The Fuel Cell Technologies work has been changing its focus over the past couple of years and to some extent putting aside previous achievements related to AEM fuel cells, SOFCs, and PGM-free catalyst development. The subprogram has completely removed the development of PGM catalysts, losing capabilities that could benefit both PEM fuel cells and PEM electrolysis. It is important to maintain these projects in order to avoid the loss of capabilities after such a long and costly investment.
- Overall, the subprograms' R&D seems to be geared toward the long-term goals, but the mid-term R&D activities seem to be lacking. It is a long road to achieving certain goals, and working toward intermediate steps will provide important milestones and opportunities to re-evaluate whether the goal previously set is still the right one.
- R&D needs must be determined to facilitate the regulatory frameworks necessary for deployment of technologies across a range of new applications, such as grid resilience, heavy-duty trucks, maritime, aviation, and railway.
- Near-term R&D for hydrogen production has been under-represented because of funding availability, other than some H2@Scale demonstrations, which are very valuable in showing real-world integration. This can be re-balanced as BIL funds start to be allocated.
- As a skilled workforce may become the main barrier of hydrogen deployment, increased investments on this topic are recommended to ensure inclusion of hydrogen specifications in general courses starting at undergraduate levels. Training activities for teachers and trainers might also be more strongly considered.
- As an evolutionary process, more emphasis on balance of plant is recommended. For breakthrough projects, more industry participation is suggested, with industry accepting some financial risk but receiving greater rewards (with exclusive patent awards).
- With pre-BIL funding levels, non-PGM catalysts for fuel cells and water electrolyzers seem over-represented. While they hold great long-term promise for addressing cost, they remain far from commercial viability.
- A balance of short-term ways to ease the economic transition to cleaner fuels with longer-term benefits is needed. A realistic self-evaluation of the scales of effort and timeline will pay off with a more achievable approach.
- SCS seems under-represented this year, with only five projects reviewed. There needs to be a focus on codes and standards for local/lower-pressure hydrogen distribution networks.
- It is premature to reduce funding for fuel cell R&D when significant performance and cost challenges remain for HDV applications.

- The split between low-temperature systems seen to have a higher TRL and high-temperature systems with a lower TRL seems out of balance. Future funding should be more balanced.
- Direct communications with community leaders, workforce development organizations, municipalities, and EJ groups should be a priority for market transformation.
- While a longer-term issue, recycling fuel cell stacks, systems, and vehicles could use additional support.
- Technology comparative analysis should be conducted to evaluate whether funding levels in each area are appropriate.
- Alkaline electrolysis is under-represented.

8. 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:

- International partnerships appear to be of high quality, balanced, well-organized, and effective for international cooperation and global progress.
- The international collaborations that developed over the last two years are very impressive, and an increase in acceleration of these collaborations is highly encouraged. This is especially relevant in ally nations in Europe, the United Kingdom, Japan, and Korea, who are well-integrated into our economic system, educational system, and market.
- There is significant coordination between DOE and other government and policy groups internationally, including joint activities, workshops, webinars, etc.
- Numerous global and bilateral collaborative partnerships are in place. They are contributing to solid progress, as well as international awareness of the Program. Well done.
- One of the most important issues will be to achieve alignment and standardization of clean hydrogen production and distribution evaluation methods, metrics, targets, and implementation. Right now, there are inconsistent standards across the globe that are beginning to be established. This will likely cause confusion in the market if not addressed, especially as companies and governments work toward implementing low-carbon and low-emission energy solutions. Verifiable, trusted, certified, and consistent hydrogen life cycle performance is required to make sure this is not a speedbump that is later an impediment. There should also be an international alignment of strategies and use cases for support of or preference for certain hydrogen distribution and use life cycles, especially as concerns the method of transport, distribution, and delivery of hydrogen. There simply does not appear to be common understanding of the multiple options, their requirements, and the potential impacts. The reviewer has been witness to this lack of consistency being a cause of confusion and at times even being exploited by organizations to mischaracterize their product offerings. It seems that more standard methods and terminology is sorely needed when it comes to the environmental performance and the engineering and technology language used. One thing DOE should be commended for in this regard is the focus on terminology of "clean" hydrogen rather than "green" hydrogen. The use of the term "green" is rapidly being tightly associated with only renewable-powered electrolysis and risks leaving out other production methods than can still be carbon-neutral or -negative while producing low or no emissions.
- Clearly, monitoring what is happening around the world in hydrogen technologies is a benefit to DOE and to U.S. industry. Partnering, collaborating, and meeting with international peers has always been an excellent window into ascertaining progress, and sometimes an early window into important developments can accelerate progress.
- It is very encouraging to see the international collaborations. Although global hydrogen communities have witnessed significant growth in recent years, they are still weak and in the early stages overall. DOE may further enhance collaboration with internal organizations on safety, codes and standards development, which is going to be very helpful. Another aspect is related to design and parts standardization. Currently, each company has its own design, which increases the cost of suppliers. If DOE can collaborate with

organizations from other countries to encourage OEMs to communicate and somehow standardize certain parts and design, it will be very beneficial to supply chain development.

- The new BIL-driven effort will be much greater than most countries can contemplate, and it is appropriate that U.S. taxes pay for work in the United States. Nonetheless, these goals are sufficiently aggressive that coordinating work with existing foreign efforts would make the odds of timely success greater. Such an outcome would help other countries as well, as a robust supply chain serves all. Thus, as projects are considered, it would be good for proposers to both (1) show that they are aware of international efforts in their area while demonstrating that they are not duplicating work, and (2) preferably, wherever possible, show international partnership with accompanying international funding (wherein there is one goal and the tasks are allocated between teams, allowing the overall team to accomplish more than either could alone).
- These partnerships help establish agreements that can then be deployed in participating countries. Perhaps there is a strategy or roadmap for ensuring the agreements are reflected in the myriad U.S. regulatory frameworks. There is the Global Technical Regulation for FCEVs and the U.S. Department of Transportation engagement. Aside from those and other environmental goals, this reviewer would like to better understand how these international partnerships can effectively accelerate U.S. adoption and deployment of hydrogen and fuel cell technologies.
- DOE is engaged in extensive collaboration. Co-funding of joint research projects would further accelerate U.S. progress through increasing leverage of global activities.
- Collaborations and exchanges with international partnerships/efforts are very welcome and should be continued. Opening calls to non-U.S. partners (as partner but not as subcontractor)—as it is, for instance, at the EU levels for non-EU partners—may contribute to supporting international collaborations.
- The United States has the potential to be an exporter of hydrogen-based energy and materials to other regions. International partnerships, and the connections formed therein, are a good opportunity to explore this potential.
- This is another area where there should be many SCS opportunities for projects that support harmonization of hydrogen standards globally.
- International coordination and collaboration should be encouraged and facilitated.
- The definition of renewable hydrogen, globally, needs technical development. For example, the Asia-Pacific Economic Cooperation (APEC) is reviewing the existing standards that are relevant to low-carbon hydrogen, the value of developing a low-carbon hydrogen international standard that reflects the APEC region's views, and ways that a low-carbon hydrogen international standard could be implemented, particularly from the perspective of certification, accreditation, and assurance. It is recommended that U.S. experts participate through the IPHE. Another potential study topic is how to accelerate the deployment of renewable hydrogen in the United States and Europe to decrease dependence on fossil fuels.
- Coordination of these efforts usually involves senior researchers and program managers going to many meetings. Perhaps DOE could consider another model, such as international postdoctoral fellow exchanges or rotations/details to the different committees. This is a long-term process, but it is worth the investment to keep DOE involved. DOE might look at successful programs from the U.S. Department of Defense—for instance, the U.S. Navy has science advisors through the U.S. Office of Naval Research Global. This is a very successful and long-term program.
- DOE should establish a team of experts whose only responsibility is to evaluate the results of other countries and international partnerships, with the goal of identifying the technology innovations that will accelerate U.S. progress. This team of experts should report back to senior management of DOE (HFTO, Office of Science, FECM, etc.) on a quarterly basis. To avoid bias and dilution of a researcher's RD&D focus, the team of experts should not have their own RD&D responsibility.
- These associations are nice to maintain the dialogue with the rest of the world, but they are not enough. The global effort in realizing the full potential of the hydrogen economy is much larger than just the U.S. effort, and DOE should leverage the work being done elsewhere. It needs to extend its international collaboration significantly in order to maintain its leadership. To do this, it needs to facilitate joint international research programs.
- Advertising DOE's activities in this area through Electrochemical Society meetings on fuel cells and hydrogen generation symposia is recommended. The Program managers can seek to participate more actively in symposia organized by the Electrochemical Society.
- In order to promote R&D, it may be worth considering, for example, a program that would require applicants to collaborate with overseas research institutions.

- This is not the reviewer's area of expertise. IPHE's focus is very practical and most likely to lead to sustained change across the international space. Perhaps regional hubs at the Canadian and Mexican borders could be considered, especially given the large amount of trucking across these borders.
- Market and techno-economic analyses are important.
- It would be helpful if the Program shared lessons learned from its international engagements or what it considers best practices from overseas efforts.
- How international collaboration can effectively accelerate the Program is not clearly articulated.

9. Do you have any comments or recommendations on the Hydrogen Program's research consortia approach for conducting laboratory-supported research (e.g., H2NEW, M2FCT, HydroGEN, HyMARC, ElectroCat, and H-Mat)? Please state what is working effectively and areas that may benefit from further improvement.

Comments:

- The Program's research consortia approach has been working very efficiently for many years. This approach enables focusing on specific items with a highly skilled core team. Giving the possibility to add further complementary "classical" projects emphasizes this positive effect and should ensure a smooth transition to the industry. This approach should be spread in other countries with the creation of bridges between them.
- The consortia approach has been shown time and time again to be a valuable catalyst to innovation and progress. DOE should stay the course. Bringing multiple laboratories together with appropriate industrial and academic participation supercharges the ideation and knowledge creation that is necessary to support the applications at hand.
- The research consortia approach appears to be very well organized for the production of high-quality research directed toward specific technology development for safe and effective operations.
- The consortia model has been very successful. It allows for a sustained effort with national laboratory experts focusing on key issues.
- Support of the FOA projects through laboratory facilities and other research support is an effective way to accelerate learning in those projects and therefore accelerate the progress overall.
- These consortia are vitally important, and DOE has done a good job of advertising them to university researchers and participants. The work should continue.
- The laboratory consortia model has worked very well.
- The extensive collaboration is admirable.
- This reviewer is involved in infrastructure projects at commercial scale and so did not sit in on many research presentations. Conceptually, it seems like an effective approach, and it is apparent many capable people/organizations are involved.
- It has been especially impressive how "seedling" and "push" projects have been fully and effectively integrated into subprogram consortia (led primarily by national laboratories). The seedling and push projects have energized and expanded the technology purview of the consortia, and they are leading to important new technology developments. The Program administrators are commended for creating such an effective model for integrating those activities into the larger consortium framework. It would be useful to know whether any lessons learned concerning organizational approaches and consortium logistics have been shared across consortia. There are undoubtedly some approaches to addressing common concerns and issues that could be important to share. It is unclear from the 2022 AMR whether changes (perhaps due to mid-course corrections) in the priorities and DOE recommendations for the HyMARC hydrogen storage consortium are occurring or being planned. It is understandable that the compressed gas (incumbent) storage approach is being adopted for the near term. It was not apparent if decisions have been made concerning continuing work on advanced technologies (metal–organic frameworks, covalent organic frameworks, complex metal hydrides, advanced carrier systems, etc.). Specifically, it would be good to know whether there are plans in place to "sunset" any technology areas in which insufficient progress might warrant diminishing support and, if so, how those decisions are being made.
- HydroGEN in particular was an extremely effective consortia model, at least for research groups that were familiar with the laboratories' capabilities and collaborative project structures. Having an FOA model where winning teams could then work with the laboratories worked very well. H2NEW should get to that

point as the electrolyzer FOAs are released, and the current capabilities being developed within H2NEW should set up the laboratories well for this effort.

- The consortia are working well to distill and collate the disparate ranges of information. A mechanism needs to be found to better advertise these consortia to academic entities and U.S. businesses (particularly SBIRs), which would increase the rate of innovations progressing from ideation to commercial implementation. The consortia links could be posted to the SBIR sites.
- The consortia approach seems to be working well. The laboratories appear to be collaborating more, and that increased collaboration should lead to accelerated progress. It would be interesting to know whether the Program surveyed the laboratories and other participants to get their feedback on how well the model is working. An anonymous survey of laboratory personnel, along with industry and university partners, would likely identify best practices and areas for improvement.
- Areas of improvement may not be in the scope of work of these groups but rather in information sharing in the metaverse (3D and virtual learning). This will save time and open up the work to all stakeholders. It is recommended that the learnings from these groups be continually posted for public review and input and that the future workforce shadow these groups to learn from them. Mentoring from these groups to members of the future workforce is also recommended.
- These projects appear to be doing well. There are some management challenges for projects involving more than five or so key principal investigators.
- The emphasis in these larger subprograms has to be more than simply funding the projects that comprise them. Some consortia have been more successful than others at spurring new ideas, shifting resources to help one or another project when it needs them, and building together—as a portfolio of independent research funding and a complex project integrate several work streams differently. Simply holding a seminar where everyone presents their work is not enough, and just having monthly or weekly manager meetings is not enough; the best of these start with an integrated plan and manage it. The best of these have managers who *actively* look for opportunities for projects that support each other and amplify outcomes. Likewise, when teams come together and every person is looking to advance to a goal (and not get their idea or work the most funding), these consortia do wonders. When they are funding mechanisms for academics to publish papers and industrial researchers to augment funding, then they serve no purpose other than to help DOE spread the load of project review.
- As direct water splitting is unlikely to contribute to the 2030 Hydrogen Shot goal, it is suggested that HydroGEN reconsider its position and research focuses. For ElectroCat, switching direction toward developing PGM-free catalysts for AEM electrolyzers would be a good strategy for the next three to five years. For HyMARC, with many new applications beyond passenger vehicles, the consortium may consider developing specific hydrogen storage materials that can be less challenging to some applications, including one-way storage materials for hydrogen cartridges.
- Although all of these subprograms try to accommodate the needs of industrial stakeholders, they must keep one foot in basic research to allow development on groundbreaking technologies. It seems the steps these subprograms are making are more low-risk–low-gain, which is good for meeting the near- and mid-term goals, but they must also have some high-risk–high-gain projects to allow for meeting the long-term goals.
- The emphasis on meeting performance goals for the Program is useful as a general guideline; however, there are many examples in which the targets have shifted over the lifetime of a specific funded project while the state of the art has shifted. For example, PGM loadings have gone both higher and lower than expected, but the subprograms do not adjust the targets. Similarly, other projects have continued even though fundamental flaws in applicability of the material set have been identified.
- Based on the presentations, the Program's research consortia approach should be beneficial. However, it is not clear whether RD&D participants participate in multiple consortia; if they do, whether this dilutes their RD&D focus; and whether the lead researchers spend too much time at meetings and not on RD&D.
- The consortia involve many meetings and are typically organized by top scientists. Perhaps DOE headquarters might use technical program managers to handle the administrative burdens for the scientists so that they can focus on work.
- The laboratory nodes program in HydroGEN needs a clear set of metrics for evaluation and feedback from the performing teams. Some of the laboratory node collaborations are not very effective.
- It is recommended that the Program's research consortia be reviewed periodically by "outside review committees" to assess operation and effectiveness.

10. Is the Hydrogen Program sufficiently incorporating a diversity of approaches for improving justice, equity, diversity, and inclusion in the execution and impacts of its RDD&D activities (e.g., multi-disciplinary approaches to project/research design, demographic diversity in project input and execution, diversity in geographic applications/impact of research efforts)? Please provide any recommendations for additional approaches or strategies the Program can employ.

Comments:

- From two respondents: Yes.
- There has been a drastically improved approach to this in the last year. The reviewer works for a small company with internal resources devoted to equity, and they have been very impressed in what is becoming available and will continue to support and try to address this greatly. This respondent happens to be based in one of the poorest states and one of the few states with a predominant majority of underrepresented groups. Company staff strongly believe that energy independence and security are critical for all groups and that, in this particular instance, the modularity have clean energy and availability of clean energy to underrepresented groups as a very well-aligned goal. As a small company, they would welcome any resources developed by DOE to augment their own internal resources and efforts.
- A broad-based, inclusive approach has been formulated. There are no suggestions for additional programs or strategies. Collaborations and engagement with the Tribes are especially compelling. Outreach to Tribal colleges is a useful way to increase engagement and to recruit participants into the Program.
- A diverse group of participants are conducting research. In addition, they are able to exchange opinions at places like the AMR provided by DOE.
- HFTO has done an excellent job highlighting the importance of justice/DEI and has made very good efforts to address these issues. It will be important to have key measurable indicators to determine the success of the effort and to determine a means for making these efforts sustainable through changes in administration.
- The goal of 40% in EJ communities, as well as the increased outreach to these communities, is notable and a big change. Continued outreach to understand (not assume) the needs of these communities is important. Current issues with gas prices may make these conversations easier to start. To the extent that demographic diversity can be increased in projects and employment, that would also be great to ensure the views of all groups are well-represented. Increasing Tribal engagement and direct participation would be very helpful, especially given negative Tribal experience with other forms of energy production.
- While the structure for improving EJ and DEI is well-designed, direct communications with community groups, municipalities, workforce development organizations, and EJ groups could be prioritized for effective Program execution and market transformation.
- There is a good focus on diversity and a good start with some diversity supported. Increasing the trajectory of some of the efforts initiated (e.g., scholarships, fellowships, and projects with appropriate institutions) will be beneficial.
- Participation and collaboration must be more diverse. Reaching out to underprivileged communities and providing knowledge and sparking interest in hydrogen would be greatly beneficial.
- The increased focus on EJ and DEI is encouraging. It would be helpful to hear more from local officials and residents who live in DACs about their needs related to energy, the environment, and education and outreach.
- The efforts from the Program to address diversity have been very visible at the AMR. The Program is encouraged to continue. However, the Program should not compromise technical purpose and goals for apparent diversity.
- It is not clear that the diversity of the presenters in the AMR is really representative of that of the general population. However, some of the education/internship initiatives are promising in regard to more diversity in the future of science and engineering. There was a map of underserved communities across the United States, suggesting that DOE is tracking/aligning projects and spending, so that is a positive sign.
- This has historically not been a major emphasis, but it is clearly an increasing priority, and the activities are appropriate.
- Yes. The reviewer did not see internships in industry, which would be beneficial, but may have missed it.
- As part of the Justice40 Initiative, an interactive strategy could be deployed. The approach could use computer software that is based on artificial intelligence. The software can support instructors and serve information to individuals in DACs who are interested in learning. There is great potential in serving 3D

imagery of energy systems so that the individuals who live or live/work in DACs become familiar with the technologies and the benefits of using them prior to the permit application. The systems can serve to inform previous detractors so that they better understand the benefits and the creation of good jobs. The systems can also address past opposition to the installation of new energy systems as part of the determination of how to educate. Perhaps it would help if universities in poverty-stricken cities (e.g., Rochester [New York], Detroit [Michigan], and Buffalo [New York]) were included in the introduction of apprentice programs for energy systems. It is not clear whether the universities themselves understand the potential for cleaner air, more sustainable energy systems, and the development potential for new jobs. The Program should establish business partnerships to conduct outreach to determine the degree to which the installations will be embraced by the communities. Perhaps local jobs can be created to operate energy systems ("learn while earn") and partnerships can be established to create the training for in-demand skills in the "real world" to meet the needs of jobs (e.g., safety crews, construction, manufacturing, surveying and land use, and supply chain logistics). The Program might consider requiring "community benefits plans" and readiness plans. The principles of "good jobs" should be required of the recipients of DOE funding: benefits, diversity–equity–accessibility, the right to organize (representation), job security/working conditions, pay (prevailing wage), "proof" that the funded organization exemplifies leadership and respects employees, fair recruitment and hiring skills, and career advancement (to the next career).

- One of the major needs in the areas of justice, equity, diversity, and inclusion is developing best practices and methodologies for sound evaluation of investment benefits to advance the goals. For example, there is still much uncertainty about how to measure and evaluate the benefits of ZEV infrastructure built in or near DACs. So far, the most common metric has simply been proximity of the infrastructure to these communities, but this is an incomplete picture. It does not address the actual use of the infrastructure by the community members or how the infrastructure use by those traveling from outside the community may or may not benefit the community where the infrastructure is located. There are a number of questions: whether there is actually an air quality improvement that can be tracked/measured/estimated; whether there are additional secondary considerations, such as traffic and congestion, that can actually work counter to advancing equity, justice, etc.; and whether these are additional impacts (e.g., jobs and the local labor market) that can be quantified. An organization like DOE is well-positioned to investigate, test, and validate different thoughts on appropriate methodologies, bring together key stakeholders to develop consensus, and help refine the finalized methods.
- It seems that these goals are being considered at the early stages; of course, it remains to be seen what amount of progress will actually be enduring. It would help if DOE further encouraged projects (especially high-dollar projects) to make permanent hires from lesbian–gay–bisexual–transexual–queer-and/or-questioning (LGBTQ+) and minority communities rather than funding interns. It is also critical to see that the DACs targeted are indeed disadvantaged. The money going into Opportunity Zones is a cautionary tale; almost all of that money poured into a very small percentage of these zones, and of course, they were either not very distressed or were adjacent to wealthy communities—the money mostly went to make large firms wealthier, rather than to the people in those DACs. This must be avoided. Proposers must show they are not cherry-picking but actually helping the disadvantaged. Secondly, while it is true that hydrogen will reduce greenhouse and criteria pollutants and that this is preferentially good for DACs, it is also inherent in the concept, so it is not appropriate that proposers use reduction of diesel exhaust or reduction in potential warming as what they are doing to help DACs. It is DOE who is helping them by causing such work to occur; the proposer must show more.
- The Program should be consistent with applicable U.S. laws and regulations. Disproportional impacts on blue collar jobs (manufacturing, mining, transportation, etc.) are being insufficiently understood for this energy transition. This is true for both jobs and cost of living and will have an impact on lower-/middle-income groups more than higher-income groups. Effective programs are needed to ensure that long-term benefits of key technologies are not offshored for design, manufacturing, or production. The United States is effectively energy-sufficient today with fossil fuels, so the transition has to maintain that balance to remain neutral. This will require activities that might otherwise be considered "dirty" (metals production and refining, manufacturing, etc.) but are an important aspect of a stable blue collar workforce. This has to be more than political "window dressing". It is an interesting balance to provide benefits in certain areas without also being perceived as "dumping" less attractive aspects into those same areas.
- The listening sessions are a start but should be turned into actions. For example, it should be clear how teams should incorporate research impact and diversity into proposals to help improve equity and justice efforts across the hydrogen landscape.

- The goals for diversity and inclusion are very vague and should be better articulated by DOE. There is also confusion about diversity and inclusion versus EJ. The scientists and engineers do well when a technology roadmap is presented, and DOE might think of creating something similar for their social goals.
- This reviewer cannot speak to that. While it was a focus of the DOE Program directors' (and others') discussions, it may not yet have drifted down into the wide variety of R&D cultures represented in the technical portfolio.

11. Is the Hydrogen Program doing enough to advance goals for workforce development and science, technology, engineering, and mathematics (STEM) education? How can we build on and/or adjust our current portfolio to accomplish our goals in workforce development and STEM?

Comments:

- Yes. The work done at Los Alamos National Laboratory and the number of undergraduate students involved in the work are impressive. It is extremely important to engage more students to be able to meet the increasing need for qualified researchers in the field.
- The reviewer has limited knowledge about this area and no suggestions for improvement. However, based on the information presented at the AMR, there is confidence that Program administrators are well aware of the underlying issues and are crafting a program that is responsive to workforce development and STEM needs.
- The Program has done enough to advance the goals of workforce development and STEM education.
- Yes.
- The advanced research is of very high quality. However, additional emphasis for workforce development (with or without advanced educational research degrees) may be of value to increase domestic manufacturing, commercialization, and market transformation.
- This area needs support, and there are already a number of DOE activities researching this topic.
- University collaborations, particularly with MSIs, are welcome. Because of how many disciplines can be involved in the Program, it could be challenging to focus these efforts in a way that is accessible to high schools and colleges. "Train the trainer" methods, such as workshops for high school teachers, have been successful in other areas, even fields with historically low visibility (space weather, materials engineering, etc.). These efforts serve as a force multiplier rather than reaching individual students or programs.
- Generally yes, as the Program has played an important role in STEM education through funding projects at universities and national laboratories. As there will be many new projects under the incoming BIL funding, one way to further enhance STEM education would be to mandate cooperative education programs into the projects in which companies serve as the lead principal investigator.
- Developed resources that would seek to incorporate clean energy, and in particular hydrogen, into standard curricula would be greatly appreciated. For example, this reviewer was not made aware of the technology until university, whereas in current discussions with university and high school educators, multiple instances have been found in which these new technologies can be used instead of the traditional demonstrations coming from the petrochemical world. Developing resources to aid in education across kindergarten through 12th grade (K–12) and university, as well as perhaps outreach to state educational groups, might be helpful here. Any support possible in this effort would be very appreciated.
- The Program has good ideas about funding different universities for workforce development; it is not yet clear how much these universities are practically implementing these goals. They should be working with industry to make sure workforce development actually results in skills that are valued by industry.
- It seems as though the modules on the DOE website are mostly static pages and do not necessarily interact and change with the progress of the online learner/instructor communities. Nor do they help the users to develop their individual learning paths to advance throughout their careers. Some discuss career paths, but these should be updated through discussions with actual hiring managers. Some training on the DOE webpage is out of date when compared with recent (2020) publications from DOE laboratories and presentations at the AMR (2022). Others seem to require DOE employees to deliver the modules, which in some cases may be impracticable. Perhaps the workforce training could address energy efficiency, durability/lifetime of systems (20–30 years), capital expenditures evaluation that leads to lower capital expenditures, and ways to decrease the cost of electricity. Much of the training presently addresses

individual energy technologies—i.e., a page for each renewable, instead of energy systems integration, which can be addressed in STEM. Learners could benefit from training in how the energy systems work together with various renewables, rather than basic STEM (which is available from many sources).

- Consideration should also be given to workforce development for blue collar workers, such as maintenance personnel. Auto mechanics and utility workers will need some training to work with the hydrogen and fuel cell technologies those workers will see in their work.
- Projects at universities could include some funding dedicated to STEM instruction, either for university students or for K–12 students in summer or school year programs. Most universities already have a big infrastructure for this type of work.
- There are more opportunities in this area, particularly getting a diverse cross section of students interested in STEM at the middle school and high school levels. One opportunity is to figure out how to facilitate local companies providing shadowing/internships for students less than 18 years old.
- To promote STEM, it is important to develop an interest in science from a very young age. Therefore, it would be better if outreach activities introducing research could also target elementary school students before they decide on their future life plans.
- More workforce development efforts at the state/regional level are needed. It seems the hubs will enable that. More industry internships would be helpful as well.
- Establishment of two-year training courses focusing on hydrogen and fuel cell technology at community colleges is suggested to develop a large number of technicians and support personnel for industry and national laboratories.
- The most direct and important way to build the workforce seems to be through targeted grants/scholarships for undergraduate/graduate programs.
- There should be more funding for summer fellowships for graduate students at national laboratories.
- Additional activities on training teachers and trainers might be considered.
- There should be a larger focus on non-PhD-level technician development.
- Inclusion of STEM activities in the research proposals is encouraged.
- It is not clear that the researchers in the Program should be directly responsible for workforce development, and DOE might involve other agencies with specific expertise to help in this area. Scientists at national laboratories and companies are trained in science/technology and often do not have specific training in workforce development. Professors can also help, but (as if at a research university) professors will be limited to the pool of students that applied to the program years earlier. Given all the pressures of carrying out successful research (safety, equipment maintenance, professional society responsibilities), DOE might make available specific resources to help scientists with workforce development and STEM. At present, the workforce development is largely ad hoc and left to individual passions—much more could be done with professionals helping. The researchers are under a good deal of pressure to deliver on technical targets, and it would be great to give them some support for the social goals of DOE. Some ideas include assistance with job finding and linking community colleges to research universities. DOE should also rethink their definition of a path to success—it might not mean working at a national laboratory. Owning a company that supplies high-pressure equipment to the industry is equally, if not more, important.
- This did not seem to be particularly highlighted in this year's AMR proceedings, other than perhaps the Hydrogen Business Case prize. So perhaps some additional refocusing on this area in the future would be reasonable. One possibility for future DOE work that would be well-suited to the organizational structure is perhaps the development of a hydrogen parallel to the Electric Vehicle Infrastructure Training Program, which sits on top of standard electrician certification and provides additional training and certification for topics specifically important for electric vehicle infrastructure development. DOE could potentially help with outlining the types of additional training and education that would be beneficial in the promulgation of such a certification.
- To date, this has not been a well-rewarded activity for R&D staff (based on the reviewer's years at a national laboratory). Finding ways to recognize and reward such outreach efforts should continue to be a focus. As for the laboratories, ensuring that any recognition gets to senior management is perhaps something to work on. In this reviewer's experience, the recognition has only been fairly "local" in character—i.e., it has not reached the upper echelons of the laboratories.
- There was not much discussion on this point in relation to the technical and EJ areas. While there will be benefits caused by many graduate students and even undergraduates being pulled into the fields needed to support the eventual hydrogen economy—and at least the hope of more disadvantaged students being given

a chance at good jobs—there is not much specifically directed at improving curricula and ensuring it supports what is needed. Promoting the teaching of life cycle analysis and the enhancement of communication skills are two areas that academia does not handle well enough, and DOE might try to nudge them along the right path.
- It is not clear what is being done in this area. If this is desired, then an effective, honest, and balanced approach is needed that highlights both the advantages of cleaner fuels as well as the practical challenges that need to be overcome.

12. Please comment on the overall effectiveness, strengths, or weaknesses of the Hydrogen Program or the individual subprograms and provide any additional suggestions you may have for improvement. Do any of the projects, subprograms, or activities stand out as particularly strong or weak (and if so, why?)

Comments:

Please include comments or recommendations on how the Hydrogen Program can better coordinate RDD&D among DOE offices (Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy and Carbon Management, Office of Nuclear Energy, Office of Science, ARPA-E, Office of Electricity, Office of Clean Energy Demonstrations).

- The increased coordination across offices is a dramatic growth area for the Program and very impressive. Just about three years ago, the highest-profile collaboration was with the Office of Fossil Energy on solid-state fuel cells, and other collaborations were growing but not at the point to be showcased in the plenary sessions. The chart showing the huge investment across offices ($400 million total in the FY 2023 request) is very impressive. Continuing this collaboration to reduce duplication, break down barriers between groups, and find solutions that help all is very important. The growing Office of Nuclear Energy collaboration is a good example of this; although it is unfortunate Jason Marcinkoski moved from HFTO to the Office of Nuclear Energy, his position there almost ensures good integration will continue.
- For many years now, the Program has been structured and managed very well. Exchanges with other offices is more recent and very welcomed in order to ensure an energy systemic approach (hydrogen, gas, electricity, heat) and to favor technology couplings (e.g., hydrogen–nuclear).
- Overall, the Program is directly focused on addressing the key gaps that need to be overcome to achieve the “1 1 1” goals. H2NEW is excellent overall—the technical understanding and capabilities are unparalleled.
- The Program has traditionally been excellent in TRL 3–5 or 6. Continuing to expand to more TRL 6 and 7–8 activities will be essential in the near term to make the hydrogen hubs and the United States a success story in hydrogen production. Coordination and co-funding with the Advanced Manufacturing Office, such as on the Roll-to-Roll Advanced Materials Manufacturing consortium, is also a strength that should be continued.
- The Program is one of the best overall programs in DOE. It is managed, coordinated, and directed exceedingly well. It is an excellent model for all government agencies and offices.
- Overall, the Program is comprehensive and managed and coordinated well. It is producing an impressive response to the daunting challenges of fully integrating hydrogen production, delivery, storage, and fuel cell technology/manufacturing into the DOE renewable energy portfolio. The consortium model is innovative and is enabling important progress on challenging problems to be made in an efficient and timely way. The Hydrogen Shot initiative provides a meaningful focus going forward. However, it will be important not to marginalize or de-emphasize other notable challenges (especially high-capacity, reversible hydrogen storage and hydrogen carriers) in pursuit of focused progress on the Hydrogen Shot initiative. Minor note: in future reviews, it might be helpful to provide a succinct and candid comparison with incumbent and other emerging technologies (especially batteries). Such a comparison would provide a useful context for reviewers to fully appreciate and assess the future impact and advantages/disadvantages of the Program in relation to all other renewable energy options.
- A strong and broad Program was presented. No evidence was seen of a lack of cooperation between the DOE offices. It is suggested that a branch of the effort focus on breakthrough technologies and that this branch have the charter to explore any technology that would benefit hydrogen and fuel cell technologies, while a larger effort addresses the evolutionary development of hydrogen and fuel cell technologies (very similar to the ongoing efforts).

- The overall effectiveness of the Program is very good. However, DOE should remain flexible to accelerate development and to increase community engagement to meet the recent challenges for the production of technology and clean, cost-effective, and sustainable energy.
- The Fuel Cells subprogram has always been strong; the couple of technical presentations seen on the nuclear hydrogen side were good, but the project management seemed uninspired. Also, there was a bit of discussion as to how important grid modernization was going to be in order to maximize the impact roles hydrogen and/or electrolysis may play on the grid. It was not clear whether DOE had been engaged in this discussion; if this is a major barrier to implementation of hydrogen technologies, perhaps this is an area that could be highlighted in the future.
- The Program is well-planned and has been very effective in driving hydrogen and fuel cell technology performance and cost improvements through R&D. It is encouraging to see that the Program now has the funding, through the BIL, to move those technologies through the typical post-R&D valley of death and into the market, with increased focus on nationwide demonstration, deployment, education, and outreach. While the Program usually does an excellent job communicating to its stakeholders, the Program's communications on the multi-billion-dollar hydrogen hub FOA were not timely. Industry, academia, small businesses, and state/regional NGOs were scrambling to pull together agreements, plans, and proposals for a legislated May FOA release, only to learn in June that the FOA's release is now planned for August/ September or September/October. While stakeholders are relieved that they have more time to plan these very large regional projects—and the work they did for a May FOA release certainly is not wasted—the uncertainties and rumors around the FOA release created difficulties for many organizations. The Program should improve its communications relative to FOA release dates.
- The increasing collaboration and coordination between the offices is promising and helpful. One area that remains weak is a credible, commercial-scale carbon capture and storage (CCS) technology. Many approaches are predicated on this, but it is not clear that we have anything yet that really works and is cost-effective at scale. It is also concerning that if you use CO_2 obtained from CCS to make a liquid hydrocarbon and then you burn that, you are still releasing that CO_2 into the atmosphere—at best you get a 50% reduction.
- Overall, the communications between the offices appears to be effective, but the websites appear to be weak. What would be helpful is a collaborative system to collect information on how projects are shared and a dashboard on the status of the projects. Additionally, perhaps the Program could embark on an inventory assessment of the carbon-based energy installations in use today, their life expectancy, scalability, and upgradability. This information may be difficult to obtain, should it be proprietary. If the information is proprietary, maybe a condition of applying for funding could include disclosure of the life expectancy of systems (under a nondisclosure agreement) and their potential for upgrade or future-proofing.
- The technical programs are especially adept at identifying fundamental technological aspects—for example, materials degradation development of analytical techniques and accelerating standardized testing. Development of materials, modeling systems, and commercialization efforts have been less successful. While these are worthwhile efforts in the long term, the time needed to develop effective methods in these preclude them from being useful in the Hydrogen Shot timeframe. Therefore, it is recommended that efforts be focused on developing the tools both to support existing stakeholders and to enable industrial partners who are interested in becoming involved in this field to come up to speed more rapidly.
- Overall, the Program has handled promoting low-TRL efforts well. The conversion of these technical progresses to products or commercialization were not as fruitful. There is a big gap in high-speed–low-cost manufacturing technologies in the United States. DOE should not expect companies to be able to develop such on their own. The clean hydrogen manufacturing funding is too little to address the issue. If possible, the Program is asked to help carefully consider priorities and additional support in this area.
- The biggest strength of the Program is its institutional memory. To maintain it, the Program must keep the specialized workforce that was developed over decades. One good example is the PGM work, which could be leveraged now for electrolyzers but has been turned down significantly during the past five years, with risk of losing capabilities.
- The main strength of the Program is the various initiatives and consortia to address the complexity of hydrogen technology development. The main weakness is the lack of prioritization and the need for improvements in interaction and coordination between the different subprograms.

- The basic research programs at the Office of Science are always important because they develop students and take on high-risk initiatives. It is not clear that ARPA-E is contributing to, or even wants to contribute to, the Hydrogen Shot goals.
- It might be good to know whether any of these offices have stakeholders with safety, codes and standards or R&D needs for hydrogen and fuel cell technologies, and to include these needs in developing plans.
- The reviewer did not see a really strong or weak subprogram but does see a train wreck approaching. Everyone knows what it is. The Program budget increased by roughly two orders of magnitude. It is astonishingly hard to spend that much more wisely for several reasons. First, the intellectual and physical infrastructure is not there to accommodate a 100-fold increase in funding; there just are not enough good ideas and good people to do the work. By increasing high-TRL work and loan programs, you decrease the pressure because they require massive funding relative to laboratory projects, but it is still going to be an issue. That makes the second issue worse: namely, you cannot do a sufficient job of choosing, much less monitoring, a 100-fold increase in funds with roughly the same number of people. It is doubtful the program is at liberty to increase its staff by even a factor of three, much less the roughly tenfold increase needed to really monitor all the new work closely. The Program should strongly consider taking on proven program monitors as contractors with full authority to monitor and coach projects—and take them on very clearly only for the term of the BIL funding so no one feels cheated. Otherwise, these major programs will reach suboptimal performance.
- One question is the use of 3¢/kWh in some of the cost models. While a standalone solar facility may achieve a value like that, unless the hydrogen production was "behind the meter" (and therefore either accepted power whenever it was produced, with a capacity factor matching the solar, or also relied on storage, in which case 3¢/kWh is too low), 3¢/kWh is too low. There are also costs for transmission and distribution, which are typically several cents per kilowatt-hour. The lowest industrial electricity prices in the United States now are near 6¢/kWh; again, excluding transmission and distribution from the electricity cost requires behind-the-meter solar or wind.
- The consortia need more visibility. Many of the small businesses that are tangentially related to this industry are unaware of these consortia and the potential benefits of participating. These tangential businesses are more likely to change their business model to support the hydrogen economy if they can leverage the consortia to modify their products.
- There is very little focus on the stable transition to alternative fuels—for example, how to maintain a reliable supply of fuel and electricity when entire industries will be eliminated. The risk is that no one will invest in or be committed to older technologies before new technologies are ready. This should not be underestimated since it is already becoming an issue in the electricity, refining, and automotive industries.

13. Do you have any specific comments on the Program's plans for the funding provided under the Bipartisan Infrastructure Law for (1) Regional Clean Hydrogen Hubs, (2) Clean Hydrogen Electrolysis Program, or (3) Clean Hydrogen Manufacturing and Recycling?

Comments:

- Goals appear to be well-aligned with efforts already under way.
- It is going to be awesome.
- There are exciting times ahead.
- The plans are very promising. Continuity is key to success.
- The level of support has been positively impressive and is appreciated. As always, administering these types of efforts is challenging, and hopefully the need for improving a domestic supply chain is not overemphasized in these days of integrated economies with allies such as the EU, United Kingdom, Japan, and South Korea—which both manufacture systems and components in the United States and are great consumers of our products.
- The Clean Hydrogen Electrolysis Program was well-detailed; it is well-planned, but it might be worth favoring advanced concepts a bit more to increase the odds of making the "1 1 1" goal on time. The manufacture and recycling program is less well-defined but is also much broader, so this is not too concerning. There could be more emphasis on refurbishing fuel cells rather than recycling them, since much of the value is in the structure of the materials (other than the PGMs, obviously), especially advanced catalysts with no PGMs, which will be much more dependent on structure than metal value (likewise

bipolar plates, etc.). The hydrogen hub structure still seems notional; if there are specific administrative, technical, or regional goals, they probably need to be made clearer prior to floating the FOA. It may be clear to DOE what is wanted, but truth be told, the Hydrogen Shot structure and goals were substantially clearer than the hydrogen hubs expectations.

- The Program's plans for hubs, electrolysis, manufacturing, and recycling are well-placed, well-thought-out, and articulated. One more concern to those mentioned earlier is the planned 50% cost share required at a time when inflation is causing businesses to curb spending—and within a small industry that will be spread very thinly among the regional hubs. Additionally, not all states will be in a position to provide substantial cost share.
- The Regional Clean Hydrogen Hubs shows great program strategy to solicitate multiple seeds and select to fund in later phases. This would definitely help spread out the infrastructures into different regions. If possible, the Program is encouraged to consider the sustainability plan for those hubs after the BIL funding period. Regarding Clean Hydrogen Manufacturing and Recycling, the funding for clean manufacturing may be too little to address all the technical barriers. Prioritization to a few critical items would be more effective.
- Efforts for the Regional Clean Hydrogen Hubs focus on various aspects (commercial/product) of hydrogen technologies (including production, storage, delivery, and usage), technology infrastructure, impacts on regional workforce development/employment, climate, and regional economy. Efforts on the Clean Hydrogen Electrolysis Program and Clean Hydrogen Manufacturing and Recycling focus on technology demonstrations, innovations, and R&D activities (since the technologies are not fully mature) to reduce cost and improve efficiency and reliability to meet the "1 1 1" goal.
- Having notices of intent for the electrolysis and manufacturing and recycling efforts will be very helpful in understanding the Program plans for these areas and allowing teams to prepare.
- Specific areas that could be enhanced include direct communications with community leaders, municipalities, and workforce development organizations, with guidance for siting and deployment to enable integration into the community. Guidance could include education and coordination to identify market opportunities for market transition of the following:
    - Stationary markets including combined heat and power, mission-critical facilities, microgrids, and siting for reversible fuel cells.
    - Transportation motive markets for LDV fleets, HDVs, materials handling, and aircraft.
    - Utility natural gas and electric utility markets to help decarbonize electric and natural gas infrastructure.
    - Refueling markets with renewable (offshore wind and solar) feedstocks and fueling with volume and pressures to meet application and market demands.

  In addition, DOE may seek to accelerate transformation by providing the following:

    - Guidance for hydrogen production to identify and coordinate with renewable feedstock producers, including offshore wind and solar developers. The guidance could help coordinate natural gas and electric grids for decarbonization with new opportunities to produce hydrogen during off-peak surplus periods, connection with natural gas distribution companies for blending and separation, and connection with energy markets for the storage, transport, and dispatch of hydrogen.
    - Guidance to facilitate community siting and investment to help identify and address concerns of distressed communities, underserved cities, and opportunity zones consistent with state policies and goals, community investment goals, and BIL requirements.
    - Guidance to encourage alliance-building with local industry, supply chains, and community resources. Participants may include direct coordination of OEMs, supply chain companies, renewable energy developers, and utilities with municipalities and community organizations. Such guidance could encourage coordination for community investment, clean energy market expansion, coordination with the supply chain, workforce training and placement, STEM education, and advanced domestic manufacturing to meet market demand and community needs, and to deliver the investment in jobs and economic development back to the local economy.
    - Guidance to local community stakeholders on environmental performance to identify carbon offsets, greenhouse-gas-equivalent reductions, air quality improvements, community siting impacts, and potential impacts from hydrogen production and leakage; safety, including assessment of leakage and materials embrittlement for integrity management and safe operations; and economic projection of the

impact to consumer energy costs and the utility rate base. This engagement may be helpful to ensure non-technical community stakeholders that hydrogen can, with direct community input, provide a positive impact on the economy, environmental resources and climate, energy reliability, domestic production and manufacturing, EJ, and safety.
    - Coordination with non-hydrogen stakeholders on overall integration with other technologies, including battery storage, battery electric vehicles, gas blending and decarbonization, production of hydrogen with renewable energy project developers (biomass, wind, and solar energy), utility-based energy storage and dispatch, and direct consumer use. Results could provide confidence to local stakeholders that hydrogen can be part of an integrated and diverse clean energy ecology.
- Since some in the private sector state that hydrogen supply projects can be funded privately, the question becomes how to quantify the demand for hydrogen and what can have an impact on the quantification. It is not clear if the demand side of the anchor tenant of the hydrogen hubs would be able to keep up, nor (if the technology for the hydrogen hubs is available) that the private-sector user community would “pull” the hydrogen produced. In addition to the H2 Matchmaker, another dimension of this problem/question relates to today’s geopolitics; regardless of companies’ interest in explaining the demand, it remains to be seen how that explanation could change if the war in Europe continues or drought conditions in the United States worsen. The Matchmaker tool should help. Perhaps the results of the Matchmaker could be made public prior to the hub solicitation, and it is recommended that the comments on the hydrogen hub RFI be made public. For the Clean Hydrogen Electrolysis Program and Clean Hydrogen Manufacturing and Recycling, it would be good to know how any hesitancy of returning equipment to the equipment supplier after it is spent would have an impact on the adoption. It is recommended that the equipment supplier industry perhaps be “required” to receive, dispose of, and learn from used equipment as a condition of receiving DOE funding.
- There is a need to really think critically about the scale of hydrogen production/distribution/use that can/will be supported by the BIL provisions and funds. The goal should not be simply to help fund what sounds or seems like a large investment project today but to fund what will actually be a large investment project a bit further in the future. The whole goal is jump-starting industry development and helping to accelerate the industry’s approach to large-scale projects, given the short timeline for the potential need and the large amount of growth potential for hydrogen in the country’s energy system.
- The nature and complexity of the hydrogen hubs are such that it will be difficult and time-consuming to award, contract, permit, and build in the stated timeframe. Despite their nominal large size, the relative scale of these hubs compared to the overall energy market needs to be recognized. Inadequate attention is being placed on the materials infrastructure regarding what will be needed for a successful energy transition, particularly with regard to indigenous supply of raw materials. This will be important for cost-effectiveness, long-term jobs, and energy security. The BIL notice of intent lacks emphasis on technical attributes in lieu of political attributes. The concern is that it will not be effective in its stated goal to advance technology. It is important for the implementation of the BIL to also be bipartisan, or it has significant political risk to long-term acceptance and success.
- There are two concerns. First, low-TRL technologies will be considered and not be able to meet Program goals in 2026 or even 2031. The funding required for true hydrogen hubs across the United States, even with existing high-TRL technology (PEM and alkaline), will take \$100–\$500 billion (see Princeton’s Net-Zero America report). DOE needs to be realistic that this \$9 billion will not go far if it is not focused. The second concern is that the funding is not being obligated quickly enough and will be swept up.
- As presented during the AMR, it was sometimes hard to see if the HFTO funding was increasing or decreasing because the money went to other sections of DOE. A more comprehensive summation would be useful. While it is understood that this is because of Congress’ direction, the majority of the BIL goes to the national laboratories (via the \$8 billion for four regional hubs). While the national laboratories do good and groundbreaking work, a more even split of the money with industry might spur innovation (as well as the development side of R&D).
- Creating hydrogen hubs will allow the hydrogen technologies to really go at scale, but this will consider “only” a few locations. Strategies ensuring spillover effects of these hubs should be considered from the beginning.
- It is recommended that there be a laser focus on the long-term viability of the hydrogen hubs beyond DOE funding (as it is not known how long that will last beyond the current legislation). Projects and locations really need to provide clear evidence of plans for commercial sustainability.

- There is a large amount of funding for the Regional Clean Hydrogen Hubs. It was not clear whether they will be focused on state-of-the-art hydrogen and fuel cell technologies or how new technology would be introduced to the hubs.
- Regarding the Regional Clean Hydrogen Hubs, this is an extremely difficult task that will require many technical reviewers and experienced project managers to put it in place. For the Clean Hydrogen Electrolysis Program, the Program is encouraged to put more emphasis on hydrogen compression to improve system-level reliability. The Clean Hydrogen Manufacturing and Recycling effort is early in the process, such that there are no particular recommendations at this time.
- For the Clean Hydrogen Electrolysis Program, inclusion of basic research is needed to address several fundamental issues in developing PEM and SO electrolyzers.
- The Program FOAs and subsequent management should be as streamlined and simple as possible.
- The administrative burden of reporting and data-collection requirements should be reduced.

14. Based on DOE's hydrogen activities, and given the BIL funding across the RDD&D spectrum, how likely do you think:

(a) Hydrogen Shot will be achieved ($1/kg clean H2 by 2031)?*

Note: these are modeled levelized costs of production only, at high volumes (e.g., GW scale). Rate your response on a scale of 1 through 10, with 1 indicating not likely and 10 indicating very likely.

Average Score	**6.4**
Number of Responses	37

(b) The BIL target of $2/kg clean H2 be achieved by 2026?*

Note: these are modeled levelized costs of production only, at high volumes (e.g., GW scale). Rate your response on a scale of 1 through 10, with 1 indicating not likely and 10 indicating very likely.

Average Score	**6.5**
Number of Responses	37

** Note: these are modeled levelized costs of production only, at high volumes (e.g., gigawatt-scale).*

Appendix B: 2022 Hydrogen Program Annual Merit Review and Peer Evaluation Meeting Attendee List

Last Name	First Name	Organization
Abbuehl	Christopher	Apex Clean Energy
Abdelrahman	Mohamed	Carnegie Mellon University
Aborn	Justin	TerraPraxis
Abraham	Prashanth	W. L. Gore & Associates, Inc.
Abruña	Héctor	Cornell University
Acevedo	Yaset	Strategic Analysis, Inc.
Aceves	Salvador	Lawrence Livermore National Laboratory
Achtelik	Gerhard	California Air Resources Board (retired)
Adair	Sarah	Duke Energy
Adhikari	Santosh	Los Alamos National Laboratory
Afzal	Shaik	Gas Technology Institute
Afzali	Mehdi	BP p.l.c.
Agarwal	Apoorv	Ingineering Innovation, LLC
Agarwal	Tanya	Los Alamos National Laboratory
Agarwal	Vishal	Washington State University
Agnani	Milan	Sandia National Laboratories
Agustin	Melody	D3
Ahluwalia	Rajesh	Argonne National Laboratory
Ahsan	Syed	California Energy Commission
Ai	Chengying	Momentum Materials Solutions Corp.
Akita	Yasuhiro	Toyota Motor Corporation
Alano	Eduardo	FORVIA
Albayed	Abdullah	Argonne National Laboratory
Albayrak	Feridun	BCS, LLC
Albertus	Paul	University of Maryland
Aldas	Rizaldo	California Energy Commission
Alfeo	Joseph	Individual Investor
Alfonsin	Jose	U.S. Air Force Civil Engineer Center
Alfonso Vargas	Nicolas	University of Southern California
Alfred	Joseph	Ally Power, Inc.

Last Name	First Name	Organization
Alia	Shaun	National Renewable Energy Laboratory
Al-Imarah	Kifah	Ministry of Science and Technology, Iraq
Alink	Robert	AeroStack
Allan	Cam	Norfolk County, Ontario, Canada
Allen	Corinne	Clark Street Associates
Allen	Jeff	Michigan Technological University
Allendorf	Sarah	Sandia National Laboratories
Allen-Orren	Lauren	3M Company
Allhusen	John	First Mode
Alnaqash	Zaid	Ford Motor Company
Alves	Eduardo	Alxma
Ambrosini	Andrea	Sandia National Laboratories
Amrit	Surajit	Parsons Corporation
Anderson	Art	AH Anderson Consulting, LLC
Anderson	Dianne	KeyLogic
Anderson	Michele	Office of Naval Research
Anderson	Thomas	Central Ohio Transit Authority
Andrade, Jr.	Hely	Andrade & Andrade Consultores Associados Ltda
Annon	Michael	I & C Engineering Associates
Anson	Colin	Virent, Inc.
Antillon	Luis	Accenture
Antoni	Laurent	Alternative Energies and Atomic Energy Commission, France (CEA)
Anyenya	Gladys	Wabtec Corp.
Aphale	Ashish	Kennesaw State University
Appelgate	Bruce	Scripps Institution of Oceanography/University of California, San Diego
Ardani	Kristen	National Renewable Energy Laboratory
Ardo	Shane	University of California, Irvine
Arima	Takero	American Honda Motor Co., Inc.
Aristidou	Aristos	Cargill, Incorporated
Arjona	Vanessa	U.S. Department of Energy
Arlia	Nicola	Westinghouse Electric Company, LLC
Arman	Tanvir	University of Connecticut

Last Name	First Name	Organization
Arogyaswamy	Bernard	Nel Hydrogen
Asano	Masamichi	Mitsubishi Heavy Industries America
Ashby	Lindsay	Avangrid Renewables, LLC
Ashcraft	Robert	Samsung Advanced Institute of Technology
Askari	Neda	GKN Hydrogen
Atanassov	Plamen	University of California, Irvine
Austin-Ramsaran	Joy	BP p.l.c.
Autrey	Tom	Pacific Northwest National Laboratory
Avila	Armando	Honeywell International Inc.
Ayers	Katherine	Nel Hydrogen
Babe	Brandon	SAUERESSIG Group
Badgett	Alex	National Renewable Energy Laboratory
Baek	Kwang Hoon	Argonne National Laboratory
Baer	Claire	Utah Office of Energy Development
Bafana	Adarsh	Argonne National Laboratory
Baghalian	Amin	Phillips 66 Company
Bagli	Manjula	Bloom Energy
Bahar	Bamdad	FFI Ionix, Inc.
Baier	Gretchen	Dow Chemical Company
Bailey	Kevin	Wabtec Corp.
Bailey	Natalya	Bloom Energy
Bailey	Samuel	The Chemours Company
Baker	Andrew	Nikola Motor Company
Baker	Ryan	National Research Council Canada
Bala Chandran	Rohini	University of Michigan
Baldwin	Peter	base-e
Balema	Viktor	ProChem, Inc.
Balogun	Aisha	Moving Forward Network
Banerjee	Tanumoy	Lehigh University
Banner	Claudia	American Electric Power
Banner	Jane	Plug Power Inc.
Banwart	Neil	Cummins Inc.
Barclay	John	Pacific Northwest National Laboratory

Last Name	First Name	Organization
Barela	Sean	MoonWalker Associates
Barforoush	Joseph	Avium, LLC
Barilo	Nick	Pacific Northwest National Laboratory
Barker	Aaron	National Renewable Energy Laboratory
Barnett	Scott	Northwestern University
Baron	Richard	Temple of Kung Fu
Baronas	Jean	Patturns
Barone	Joe	Shale Directories, LLC
Baroody	Heather	AVL Fuel Cell Canada
Barrientos	Carolina	U.S. Embassy in Guatemala
Barron	Seth	Riveron
Bartelt	Norm	Sandia National Laboratories
Bashir	Murad	Daimler Trucks
Bashyam	Rajesh	Hyzon Motors Inc.
Basile	Barry	U.S. Department of Energy
Basualto	Mario	Gasmar SA
Batten	William	Energetics
Batts	Zachary	Plug Power Inc.
Bautista	Adrianne	U.S. Department of Energy
Bay	Christopher	National Renewable Energy Laboratory
Baylis	Nathan	Hyundai America Technical Center, Inc.
Bazylak	Aimy	University of Toronto
Beagle	Emily	University of Texas at Austin
Beardeaux	Kaycee	Strategic Marketing Innovations, Inc.
Beattie	Dan	Dassault Systèmes
Beaumont	Robert	Constellation Energy
Becejac	Tamara	Avangrid Renewables, LLC
Beckett	Jeannie	The Beckett Group
Beckman	Brad	Southern Company
Bedouin	Nicolas	Alternative Energies and Atomic Energy Commission, France (CEA)
Beeler	Bryant	FiveBeeTechnologies
Behar	Claire	Hy Stor Energy LP

Last Name	First Name	Organization
Bekemohammadi	Roxana	U.S. Hydrogen Alliance
Belarbi	Zineb	National Energy Technology Laboratory
Belt	Andrew	Giner, Inc.
Beltran	Diana	Carnegie Mellon University
Benard	Andre	Michigan State University
Benard	Pierre	University of Québec at Trois-Rivières
Bengal	Lawrence	Arkansas Department of Energy and Environment
Bennett	Brion	Battelle Energy Alliance
Bennett	Kristin	KB Science, LLC
Benson	Eric	AquaHydrex, Inc.
Berenblum	Sela	Electric Hydrogen
Berger	Elena	U.S. Department of Energy, Office of International Affairs
Berger	Jeffrey	Parker Hannifin Corporation
Bergeron	Gregory	Individual Investor
Berner	Jane	California Energy Commission
Bernstein	David	Bracewell, LLP
Berryman	Macy	Holland & Knight LLP
Berselli	Andrew	ATB Riva Calzoni USA
Berteletti	Dan	National Renewable Energy Laboratory
Bestrom	Stuart	Johnson Matthey Hydrogen Technologies, Ltd.
Bethune	Keith	University of Hawaii
Bian	Wenjuan	Idaho National Laboratory
Bilal	Shadi	Florida A&M University–Florida State University (FAMU-FSU) College of Engineering
Biradar	Mahesh	General Motors Company
Bisello	Andrea	UFI Innovation Center S.R.L.
Bishop	Scott	Lakeland Electric
Bishop	Sean	Sandia National Laboratories
Blalock	JT	Hy Stor Energy LP
Blanchard	Rémi	Symbio
Blanco	Herib	International Renewable Energy Agency
Blank	Hermann	Project & Business Development, LLC
Blankenship	Karen	AECOM

Last Name	First Name	Organization
Blaylock	Myra	Sandia National Laboratories
Blekhman	David	California State University, Los Angeles
Bliznakov	Stoyan	University of Connecticut
Blumeris	Patricia	Accenture
Boardman	Richard	Idaho National Laboratory
Boisvert	Sophie	Invariant
Bokorney	Jake	Gilbarco Veeder-Root
Boldon	Andrea	The Implementation Group
Bong	Gerry	Pacific Gas and Electric
Bongomin	Ocident	Moi University
Booher	Matthew	Solvay
Booras	George	Electric Power Research Institute
Borgerson	Scott	Independence Hydrogen
Borole	Abhijeet	Electro-Active Technologies, Inc.
Borup	Rod	Los Alamos National Laboratory
Bosch	Enrique	Avangrid Renewables, LLC
Bose	Ani	University of Houston
Boughey	Britt	OMC Hydrogen, Inc.
Bourgeois	Richard	New York State Energy Research and Development Authority
Bouwkamp	Nico	California Fuel Cell Partnership
Bouwman	Peter	Schaeffler Technologies AG & Co. KG
Bowan	Brad	Atkins
Bowden	Mark	Pacific Northwest National Laboratory
Bower	Stan	Ford Motor Company
Boyce	Scott	KB Science, LLC
Boyd	Caleb	Molten Industries
Boyd	Robert	Boyd Hydrogen, LLC
Boyette	Wesley	Ohio State University
Braaten	Jonathan	Robert Bosch LLC
Bracht	David	Kutak Rock LLP
Brack	Jason	Woodward, Inc.
Brady	Joe	Fuel Cell and Hydrogen Energy Association

Last Name	First Name	Organization
Brady	Rebecca	Clean Air Council
Bragg-Sitton	Shannon	Idaho National Laboratory
Brandenburg	Rachel	The Cohen Group
Brauch	Joe	National Renewable Energy Laboratory
Braun	Robert	Colorado School of Mines
Braun	Thilo	Stanford University
Bravo Diaz	Laura	European Commission DG Joint Research Centre
Bresolin	Sarah	ENGIE North America
Bridgewater	Katherine	Los Alamos National Laboratory
Briggs	Thomas	Southwest Research Institute
Brimmer	Dana	Green Play Ammonia
Britton	Nicholas	Energy Futures Initiative
Bromley	Ritu	Invenergy
Brookshire	Caitlyn	Technip Energies
Brouwer	Jack	University of California, Irvine
Brower	Kirk	AECOM
Brown	Frank	Wallswell
Brown	Heather	Maine Manufacturing
Brown	Kenneth	Safe Hydrogen, LLC
Brown	Kenneth	University of Virginia
Brown	Kevin	Manufacturers of Emission Controls Association
Browne	Zachary	Newpoint Gas
Bruce da Silva	Tatiana	Energy Futures Initiative
Bruderly	David	
Brummer	Monica	Pacific Northwest Center of Excellence for Clean Energy
Bryan	Lee Ann	International Technology and Trade Associates
Bucci	Giovanna	Palo Alto Research Center
Bucher	Lydia	Forschungszentrum Juelich
Buchholz	Matt	Hexagon Purus
Buckosh	Linda	Ohio Fuel Cell Coalition
Buek	Connor	Plug Power Inc.
Bulloch	Harmony	California Governor's Office of Business and Economic Development (GO-Biz)

Last Name	First Name	Organization
Burapornpong	Siree	Muroran Institute of Technology
Burdy	Chris	
Burford	Hazen	AECOM
Burgunder	AL	Linde plc
Burke	Dave	Covanta Energy
Burnside	Mike	Elevate Government Affairs
Butler	Tom	Tennessee Valley Authority
Buttner	William	National Renewable Energy Laboratory
Byron	Makini	Linde plc
Caliari	Felipe	Stony Brook University
Callahan	PJ	Center for Transportation and the Environment
Calloway	Bond	University of South Carolina
Calzonetti	Frank	University of Toledo
Camacho	Pedro	U.S. Department of Energy
Campbell	Benjamin	Tennessee Valley Authority
Cannon	Jayson	Monolith Materials
Cano	Marco	Canonetics LLC
Cao	Chase	Case Western Reserve University
Cao	Wei	Dingfeng Lab
Cappello	Vincenzo	Argonne National Laboratory
Capuano	Christopher	Nel Hydrogen
Carbone	Dylan	Terravent Environmental Inc.
Cargnello	Matteo	Stanford University
Carl	Amy	EDP Renewables
Carlisle	Des	Kimbro Oil Company
Carlson	Eric	Austin Power Engineering
Carlstrom	Charles	Plug Power Inc.
Carney	Jackie	Constellation Energy
Carroll	Mark	Honeywell Aerospace
Carttar	Paul	Kansas Department of Commerce
Casanova	Lorinda	Rhino Onward International
Castanheira	Luis	Fusion–Fuel
Castano	Geovanni	Dominion Energy

Last Name	First Name	Organization
Casteel	Micah	Idaho National Laboratory
Cato	Sierra	Lewis–Burke Associates LLC
Catueno	Matias	Y-TEC Corporation
Caughlan	Sean	Glosten, Inc.
Ceballos	Bianca	Los Alamos National Laboratory
Celestine	Asha-Dee	U.S. Department of Energy
Celt	Stephanie	Washington Department of Commerce
Centeck	Kevin	Army Combat Capabilities Development Command Ground Vehicle Systems Center
Cerveny	John	New York Battery and Energy Storage Technology
Chadderdon	David	NeoGraf Solutions, LLC
Chambon	Lorraine	Technip Energies
Chan	Chun Yin	University of California, Irvine
Chan	Shuk Han	U.S. Department of Energy
Chandrasekar	Aruna	Electric Power Research Institute
Chapman	Bryan	Exxon Mobil Corporation
Chara	Allan	W. L. Gore & Associates, Inc.
Charan	Abhinav	McKinsey & Company
Chastain	Brad	Alaska Gasline Development Corporation
Chen	Dejun	Georgetown University
Chen	Dongmei "Maggie"	University of Texas at Austin
Chen	Jingguang	Columbia University
Chen	Ru	UltraCell LLC
Chen	Yingying	W. L. Gore & Associates, Inc.
Chen	Yun	West Virginia University
Chen	Zixuan	Los Angeles Department of Water and Power
Chen	Zejie	University of California, Irvine
Cheng	Lei	Bosch Research and Technology Center, North America
Cheng	Yingwen	Northern Illinois University
Chenitz	Regis	National Research Council Canada
Cherif	Meryem	AP Ventures LLP
Chernetz	Janna	Amogy
Cherniack	Luke	University of Delaware

Last Name	First Name	Organization
Chiang	Lifang	University of California, Office of the President
Choi	Won Jae	Hyundai Motor Group
Chorpening	Benjamin	U.S. Department of Energy, National Energy Technology Laboratory
Chow	Erika	Air Conditioning, Heating and Refrigeration Institute
Christensen	Steven	Xcel Energy
Christopher	Braden	Steptoe & Johnson PLLC
Christophersen	Abbie	Iowa Economic Development Authority/Iowa Clean Cities
Chun	Charlie	Exxon Mobil Corporation
Chung	Mark	National Renewable Energy Laboratory
Chuy	Carmen	Unilia Fuel Cells Inc.
Cierpik-Gold	Kim	U.S. Department of Energy
Clancy	Ellie	Lot Sixteen
Clapper	Maureen	U.S. Department of Energy
Clark	Theresa	Nuclear Regulatory Commission
Coene	Eric	Southern California Gas Company
Cogliani	Leland	Lewis–Burke Associates LLC
Cogut	Gregory	7th Generation Advisors
Cohen	Joseph	Air Products and Chemicals, Inc.
Cole	Suzanne	Miller Cole LLC
Colella	Whitney	Gaia Energy Research Institute LLC
Colgrove	Ben	Catbird Consulting
Collado	Noemi	Air Liquide
Collier	Ruwa	TC Energy Marketing Inc.
Collins	David	Southern Company
Collins	Elizabeth	National Renewable Energy Laboratory
Combs	Todd	Idaho National Laboratory
Coms	Frank	General Motors Company
Connell	Nicholas	Green Hydrogen Coalition
Connelly	Elizabeth	International Energy Agency
Conroy	Thomas	Evolving Energy
Contreras	Edgardo	Puerto Rico Energy Bureau
Cook	Bridger	Oregon State University

Last Name	First Name	Organization
Cook	Korey	National Renewable Energy Laboratory
Cooper	Kristen	Duke Energy
Cooper	Phyllis	The Building People
Cordier	Ryan	University of Virginia
Cormack	Nell	Clean Air Council
Coronato	Cecile	New Jersey Economic Development Authority
Corpus	Joey	Praxair Surface Technologies
Corrigan	Thomas	The Lubrizol Corporation
Cortes	Tim	Plug Power Inc.
Cosacescu	Liviu	ZEV Station
Costall	Aaron	Costall Engineering Limited
Cotter	Gavin	Gaia Energy Research Institute LLC
Cotton	Chip	General Electric Global Research
Courtney	James	Arnold & Porter, LLP
Couto de Andrade	Alexandre	Airbus
Crain	Patrick	3M Company
Crampton	Genora	Plug Power Inc.
Crandall	Bradie	University of Delaware
Crary	Nathan	Green Play Ammonia
Crawford	Clark	GKN Hydrogen
Cremonesi	Jonathan	GKN Hydrogen
Crow	Peter	3M Company
Cruce	Jesse	National Renewable Energy Laboratory
Crum	Matt	W. L. Gore & Associates, Inc.
Cruz	Emily	Princeton University
Cullen	David	Oak Ridge National Laboratory
Curry-Nkansah	Maria	National Renewable Energy Laboratory
Curtin	Dennis	
Da Conceicao	Marcos	Air Liquide
Da Cruz	Flavio	Southern California Gas Company
Dadfarnia	Mohsen	Seattle University
Dahlke	Gregg	3M Company
Daloz	Will	BASF

Last Name	First Name	Organization
Daly	Christopher	The Chemours Company
Dames	Enoch	Monolith Materials
Dana	Janelle	Entergy Corporation
Danforth	Robert	Kohler Co.
Daniel	Claus	Carrier
Daniels	Jessica	U.S. Environmental Protection Agency
Danyi	Erick	BP p.l.c.
Danys	Žilvinas	Ministry of Energy of the Republic of Lithuania
Das	Sujit	Strategic Analysis, Inc.
Daugherty	Mark	Avium, LLC
Davenport	Tim	ACS Industries Inc.
Davies	Rich	Oak Ridge National Laboratory
Davis	Brendan	Sandia National Laboratories
Davis	Trina	Idaho National Laboratory
De Castro	Emory	Advent Technologies, Inc.
De Franca	Gabriel	Andritz AG
De Valladares	Mary Rose	M.R.S. Enterprises, LLC
Decès-Petit	Cyrille	National Research Council Canada
Demyan	Lewis	Southern Environmental Law Center
DePasquale	Allison	Macquarie Group Limited
Desai	Divyaraj	Exxon Mobil Corporation
Deshmane	Atul	Public Utility District No. 1 of Whatcom County
Deshmukh	Kshitij	Phillips 66 Company
Detwiler	John	
Detwiler	Michelle	Renewable Hydrogen Alliance
Deutsch	Todd	National Renewable Energy Laboratory
Devanathan	Ram	Pacific Northwest National Laboratory
Devlin	Pete	U.S. Department of Energy
Di Stefano	Amalia	Cummins Inc.
Diamond	Adam	Nutrien
Diaz Sokoloff	James	AP Ventures LLP
Didinger	Dennis	Did, Inc.
Diemler	Nathan	National Energy Technology Laboratory

Last Name	First Name	Organization
DiGiuseppe	Gianfranco	Robert Bosch LLC
Ding	Dong	Idaho National Laboratory
Ding	Hanping	Idaho National Laboratory
Ding	Lei	University of Tennessee, Knoxville
Ding	Yi	U.S. Army Tank Automotive Research, Development and Engineering Center
Dinh	Huyen	National Renewable Energy Laboratory
Divekar	Ashutosh	EvolOH, Inc.
Djukic	Milos B.	University of Belgrade, Mechanical Engineering
Dobkin	Daniel	Enigmatics
Doe	Tweedie	U.S. Department of Energy, Office of Indian Energy
Dogdibegovic	Emir	
Doherty	Bridget	Williams & Jensen PLLC
Dolan	Connor	Fuel Cell and Hydrogen Energy Association
Doll	David	Hyper Tech Research, Inc.
Dominguez-Faus	Rosa	Gas Technology Institute
Dong	Dongmei	Florida International University
Dong	Josh	Dongyue Group
Donovan	Michael	Advanced Ionics
Douglas	Gregory	The Williams Companies, Inc.
Dragoon	Ken	Obsidian Renewables
Duafala	Rich	CL-WV Holdings, LLC
Duan	Yaxin	Gaia Energy Research Institute LLC
DuBois	William	Coterra Energy
DuBose	Bratton	Absaroka Energy
Duffy	Joe	Climate Jobs Illinois
Dufour	Scott	Enterprise Products
Duggan	Conor	First Mode
Dukes	Hadassah	3M Company
Durst	Julien	Symbio
Dutta	Monica	Ballard Power Systems Inc.
Dweik	Badawi	Giner, Inc.
Dyer	Brian	ConocoPhillips

Last Name	First Name	Organization
Easton	Jacqueline	HyAxiom, Inc.
Eberle	Cliff	Institute for Advanced Composites Manufacturing Innovation
Eboh	Francis	Boson Energy
Eckerle	Tyson	California Governor's Office of Business and Economic Development (GO-Biz)
Edelman	Risa	U.S. Department of Energy
Edwards	David	Air Liquide
Effross	Dave	American Federation of Labor and Congress of Industrial Organizations
Efter	Fore	
Egbert	Scott	New York State Energy Research and Development Authority
Eglash	Steve	SLAC National Accelerator Laboratory
Ehrhart	Brian	Sandia National Laboratories
Eisemann	Maria	Colorado Energy Office
Eisman	Glenn A.	Eisman Technology Consultants
El Gabaly	Farid	Sandia National Laboratories
Elangovan	S. Elango	OxEon Energy, LLC
Elbaz	Lior	Bar-Ilan University
El-Gasseir	Mohamed	General Decarbonization LLC
Elgowainy	Amgad	Argonne National Laboratory
Elrick	Bill	California Fuel Cell Partnership
Elsen	Heather	Exxon Mobil Corporation
Elwell	Jessica	OxEon Energy, LLC
Endy	Grace	EDF Energy
Englander	Jacob	California Air Resources Board
Erickson	Nathan	Shivvers Manufacturing
Erlat	Ahmet Gün	Plug Power Inc.
Erne	Frank	Freudenberg Fuel Cell e-Power Systems (FFCPS) GmbH
Ertugrul	Tugrul	Lawrence Berkeley National Laboratory
Espindola	John	The State of Alaska
Esposito	Anne Marie	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Esposito	Peter	Crested Butte Catalysts LLC
Estrada	Cesar	The Water, Electricity and Transportation Museum

Last Name	First Name	Organization
Estrada	Roman	Nebraska Public Power District
Evans	Bruce	Owen Evans Ingols
Ewan	Mitch	Hawaii Natural Energy Institute
Giuffrida	F.S.	H2O Economy Energy
Fagundo	Kathy	Electricore, Inc.
Fahy	Kieran	Cummins Inc.
Fairclough	Dale	Messer Americas
Fairlie	Matthew	Next Hydrogen
Fajimi	Victoria	
Fakhry	Rachel	Natural Resources Defense Council
Falta	Steven	General Motors Company
Fan	Wenqiang	ABB Ltd.
Fang	Xiaopeng	Weichai Power Co., Ltd.
Farese	David	Air Products and Chemicals, Inc.
Farfan	Juan	Aequatis LLC
Farghaly	Ahmed	Argonne National Laboratory
Farnsworth	Will	Q Hydrogen
Farrell	Dane	Cascade Associates/Plug Power Inc.
Farrugia	Valerie	Xerox Research Centre of Canada
Feaver	Aaron	Washington State University, Joint Center for Deployment and Research in Earth Abundant Materials
Fecko	Chris	U.S. Department of Energy, Office of Basic Energy Sciences
Feenstra	Paul	PACCAR Inc.
Feitshans	Erick	DEEM Enterprises, LLC
Feldhake	Michael	Feldhake Consulting LLC
Feldmann	John	World Resources Institute
Feng	Zhili	Oak Ridge National Laboratory
Fentas	Zubayr	New Energy and Industrial Technology Development Organization (NEDO)
Ferguson	Calum	AP Ventures LLP
Ferner	Kara	Carnegie Mellon University
Ferris	Kenneth	DENSO International, Inc.
Fickett	Brian	Tohono O'odham Utility Authority
Finck	Dale	Future Energy Technologies

Last Name	First Name	Organization
Findle	Pat	Gas Technology Institute
Findley	Kip	Colorado School of Mines
Fini	John	ETCH, Inc.
Fisher	Cassidy	Washington Maritime Blue
Fisher	Hannah	FTI Consulting
Fisher	Paul	Fuel Cell Enabling Technologies, Inc.
Fletcher	Noel	Transport Topics
Flignor	Max	West Monroe
Floerchinger	Gus	Colorado School of Mines
Fong	Henry	SRI International
Fornaciari	Julie	Lawrence Berkeley National Laboratory
Forrest	Kate	University of California, Irvine
Forrest	Matthew	Daimler Trucks
Fortuna	Dominick	Turner Construction Company
Fouts	AJ	Plumbers and Steamfitters United Association Local 598
Fox	Melissa	Los Alamos National Laboratory
Fox	Michelle	Boston Government Services
Fox	Rachel	American Petroleum Institute
Fracas	Paolo	Genport
Francis	Martin	ArcelorMittal S.A.
Frank	Ed	Argonne National Laboratory
Franson	Jarrod	Sun Pacific Energy
Fredrikson	Göran	Waves4Power
Freer	Alex	Exxon Mobil Corporation
Frew	Bethany	National Renewable Energy Laboratory
Freyermuth	Vincent	Argonne National Laboratory
Fring	Lisa	Pacific Northwest National Laboratory
Frischknecht	Amalie	Sandia National Laboratories
Fritz	James	U.S. Department of Energy, Office of Technology Transitions
Fritz	Katrina	Stationary Fuel Cell Collaborative
Frye	Evan	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
Fu	Cehuang	State University of New York at Buffalo

Last Name	First Name	Organization
Fuchs	Michel	Siemens Energy AG
Fuge	Dylan	New Mexico Department of Energy, Minerals, and Natural Resources
Fujimoto	Cy	Sandia National Laboratories
Fujimoto	David	Port of Seattle
Fujita	Mitsumasa	Japan Atomic Power Company
Fujiwara	Hirotada	Kyushu University
Fukumoto	Mas	
Funk	John	RTO Insider, LLC
Furukawa	Hiroyasu	University of California, Berkeley
Galante	Dan	Connected DMV
Galdo	Luis	Fusion–Fuel
Gallego Dias	Fernando	Idaho National Laboratory
Gallier	Susan	American Nuclear Society
Gallina	Robert	Linde plc
Gangi	Jennifer	Fuel Cell and Hydrogen Energy Association
Garcia	Al	Accenture
Garcia	Julio	New Energy Coalition
Garfunkel	Alan	Marine Dolphin Enterprises LLC
Garland	Nancy	U.S. Department of Energy (retired)
Garlock	Sarah	Bennett Pump
Garriz	Abel	Y-TEC Corporation
Gaspar	Daniel	Pacific Northwest National Laboratory
Ge	Nan	Global Risk Institute
Geary	Joan	Linde plc
Gedvilas	Tara	Boston Government Services
Gefken	Paul	SRI International
Geller	Michael	Manufacturers of Emission Controls Association
Gellrich	Thomas	TopLine Analytics
Gennett	Tom	National Renewable Energy Laboratory
Gervasio	Dominic	University of Arizona
Ghassemzadeh	Lida	Ballard Power Systems Inc.
Gheewala	Sapna	American Gas Association

Last Name	First Name	Organization
Ghezel-Ayagh	Hossein	FuelCell Energy, Inc.
Ghosh	Debabrata	XRG Energytech Solutions Inc.
Giannino	Pete	TotalEnergies SE
Gibbons	William	U.S. Department of Energy
Gilleon	Spencer	National Renewable Energy Laboratory
Gillette	Baxter	Grant County Public Utility District, Washington State
Gillman	Mark	Strategic Marketing Innovations, Inc.
Gilroy	Roger	Transport Topics
Ginosar	Daniel	Idaho National Laboratory
Ginter	David	Caterpillar Inc.
Giordano	David	HyAxiom, Inc.
Giorgi	David	General Atomics
Giosa	Thomas	Hy Stor Energy LP
Girard	Francois	National Research Council Canada
Gittleman	Craig	General Motors Company
Gitushi	Kevin	North Carolina State University
Glaser	Paul	General Electric Company
Goldstein	Brian	Energy Independence Now
Gomez	Joshua	Idaho National Laboratory
Gonzales-Calienes	Giovanna	National Research Council Canada
Gonzalez	Christine	IFC Energy Services Inc.
Gonzalez	Laura	Eichleay, Inc.
Goodman	Angela	U.S. Department of Energy
Goodrich	Grant	Case Western Reserve University, Great Lakes Energy Institute
Gopal	Raj	
Gopalan	Srikanth	Boston University
Gordon	John	Entergy Corporation
Gordon	Jon	Universal Hydrogen
Gore	Colin	U.S. Department of Energy
Goto	Risei	AP Ventures LLP
Gough Eschrich	Ivo	GKN Hydrogen
Gould	Ben	Office of Naval Research, U.S. Naval Research Laboratory

Last Name	First Name	Organization
Grace	Gene	American Clean Power Association
Gracida	Jonathan	Toyota Motor Corporation
Granatino	Jacob	Booz Allen Hamilton
Grantham	David	RedwoodAdaptive
Graves	Ron	Oak Ridge National Laboratory
Greaves	Tyler	West Monroe
Green	Brian	National Renewable Energy Laboratory
Green	Malcolm	Taconic
Green	Tomas	U.S. Department of Energy
Green	Zachary	Plug Power Inc.
Greene	Chet	Par Pacific Holdings
Gregory	Kate	Atkins
Griffith	James	Utah Office of Energy Development
Griffiths	Brian	Xcel Energy
Grimes	Jerren	Northwestern University
Grimm	Hannah	
Groenemans	Hugo	HYGRO Technology BV
Gronich	Sigmund	Charisma Consulting
Gross	Karl	H2 Technology Consulting, LLC
Groth	Katrina	University of Maryland
Grubel	Katarzyna	Battelle Energy Alliance
Gu	Hengfei	Rutgers University
Guan	Panpan	Shanghai Jiao Tong University
Guidry	Tariq	U.S. Hydrogen Alliance
Gumeci	Cenk	Nissan Technical Center North America
Gupta	Anish Kumar	Garrett Motion
Gupta	Erika	Siemens Corporate Technology
Gupta	Neeraj	Battelle Energy Alliance
Gurau	Marc	The Chemours Company
Guth	Michael	Messer Americas
Guthrey	Aaron	Los Angeles Department of Water and Power
Gutterman	Jeff	Comtech Solutions LLC
Ha	Jessy	Carnegie Mellon University

Last Name	First Name	Organization
Haas	Andreas	BASF
Habib	Paul	Los Angeles Department of Water and Power
Habibzadeh	Bahman	U.S. Department of Transportation, National Highway Traffic Safety Administration
Hackett	Gregory	National Energy Technology Laboratory
Hadidi	Kamal	Isklen LLC
Haggerty Perrault	Maryette	Bloom Energy
Hah	Phillip	U.S. Department of Energy, Office of Technology Transitions
Hahn	Michael	U.S. Department of Energy
Hajbabaei	Maryam	South Coast Air Quality Management District
Hall	Cullen	TÜV SÜD America Inc.
Hall	Shoji	Johns Hopkins University
Hall	William Jason	Rheem Manufacturing Co.
Halliday	Devin	Gas Technology Institute
Ham	Yunsik	ILJIN Hysolus Co., Ltd.
Hamilton	Jennifer	California Fuel Cell Partnership
Hammond	Steve	National Renewable Energy Laboratory
Hancock	Mike	Ansys, Inc.
Hanna	Tavis	National Renewable Energy Laboratory
Hara	Daishu	New Energy and Industrial Technology Development Organization (NEDO)
Hara	Toshinori	Toray Industries, Inc.
Harenbrock	Michael	MANN+HUMMEL GmbH
Harmon	Jeffrey	
Harris	Alexander	Brookhaven National Laboratory
Harris	Jim	Hexagon Purus
Harris	Kevin	Hexagon Purus
Harris	Timothy	EN Engineering
Hart	Katie	ClearPath
Hartikainen	Toni	Aurelia Turbines
Harting	Karen	Boston Government Services
Hartmann	Kevin	National Renewable Energy Laboratory
Hartvigsen	Jeremy	Idaho National Laboratory

Last Name	First Name	Organization
Hasa	Bjorn	University of Delaware
Hasegawa	Sho	Isuzu Motors Ltd.
Hasegawa	Takuya	Birdy Fuel Cells LLC
Hashimoto	Michio	Kyoto University
Hatten	Bryant	Stäubli Corporation
Hauber	Jerry	Forest County Potawatomi Community
Haug	Peter	Garrett Motion
Haungs	David	The Lubrizol Corporation
Havig	Sara	National Renewable Energy Laboratory
Hawley	Chris	Blackstone Green Energy, Inc.
Hayat	Mazhar	Ministry of Water Resources, Pakistan
He	Cheng	Nikola Motor Company
He	Rong	New Mexico State University
He	Xiaoyi	Phillips 66 Company
He	Xin	Aramco Americas
He	Yanghua	Los Alamos National Laboratory
Heben	Michael J.	University of Toledo
Hecht	Ethan	Sandia National Laboratories
Hedges	Michael	Hydrogen Capital Partners LLC
Hedreen	Siri	S&P Global
Heidarinejad	Mohammad	Illinois Institute of Technology
Heinze	Peyton	Port of Corpus Christi
Heller	Greg	HNO International, Inc.
Hellring	Stuart	PPG Industries, Inc.
Hemphill	Jeff	Schaeffler Technologies AG & Co. KG
Hendrickson	Stephen	U.S. Department of Energy
Henning	Mark	Cleveland State University
Hennington	Monique	University of Texas at Austin
Henrichsen	Lars	Cummins Inc.
Henry	Bill	Pacific Ocean Energy Trust
Herman	Steve	SAHEnergy
Herrera	Maria S.	Y-TEC Corporation
Hershey	Robert	Robert L. Hershey, P.E.

Last Name	First Name	Organization
Hershner	Kevin	Tributary Strategy LLC
Hertz	Kristin	Sandia National Laboratories
Heske	Clemens	University of Nevada, Las Vegas
Hess	Richard	Idaho National Laboratory
Hewitt	Chris	BASF
Heyboer	Eric	Boston Government Services
Hickey	Darren	Upstart Power, Inc.
Higashi	Keita	Toyota Motor Corporation
Higgins	Russ	First Mode
Hildebrand	Cody	Swagelok Denver
Hill	Caroline	University of Florida
Hill	David	Plastic Omnium
Hill	John	Cleveland-Cliffs Inc.
Hill	Laura	U.S. Department of Energy
Hill	Michael	Federal Energy Regulatory Commission
Hines	Spencer	Bennett Pump
Hinkel	Brian	U.S. Department of Energy
Hintz	Greg	Air Liquide
Hirai	Takeshi	Associated General Contractors of America
Hirano	Shinichi	Hyzon Motors Inc.
Ho	Donna	U.S. Department of Energy
Holby	Edward	Los Alamos National Laboratory
Holeman	Isaac	The Croft Company
Holladay	Jamie	Pacific Northwest National Laboratory
Holland	Jason	ENGIE North America
Holmes	Dan	Atlas Agro
Holmes	Nigel	Scottish Hydrogen and Fuel Cell Association
Holt	Lorna	Southern California Gas Company
Holtz	Alisa	Ministry of Energy, Mines and Low Carbon Innovation, British Columbia
Holubnyak	Eugene	University of Wyoming
Hom	Andrew	California Energy Commission
Hong	John	General Electric Company

Last Name	First Name	Organization
Hong	Junsung	Phillips 66 Company
Hopkins	Tim	The Chemours Company
Horita	Teruhisa	National Institute of Advanced Industrial Science and Technology (AIST)
Hornback	Jerry	FORVIA
Horne	Craig	Energy Vault
Horner	Kendall	Hawaii Gas
Hosler	Christian	Gladstein Neandross & Associates
Hotta	Yoshihiro	Toyota Motor Corporation
Houchins	Cassidy	Strategic Analysis, Inc.
Houghtalen	Natalie	ClearPath
Houghton	Kayo	Mitsubishi Heavy Industries America
Howard	Randy	Northern California Power Agency
Hsu	Alex	National Governors Association
Hu	Hongxing	Amsen Technologies LLC
Hu	Leiming	National Renewable Energy Laboratory
Hu	Qinhong (Max)	University of Texas at Arlington
Hu	Zhendong	Toyota Motor Corporation
Huang	Kevin	University of South Carolina
Huang	Yu	Technip Energies/Genesis Oil and Gas Consultants Ltd.
Hubert	McKenzie	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Huckaby	Steven	Humble Midstream, LLC
Hudzinski	Michael	Tucker Ellis LLC
Huerta	Nicolas	Pacific Northwest National Laboratory
Huff	Taylor	H Cycle, LLC
Hui	Linda	Bay Area Air Quality Management District
Hulvey	Zeric	U.S. Department of Energy
Humphrey	Chris	Express Energy Services, Inc.
Hunter	Brian	U.S. Department of Energy
Hurley	Hope	FGS Global
Hurst	Katherine	National Renewable Energy Laboratory
Huscher	Fred	Delta h, LLC
Hussey	Christopher	Zero Emission Advisors

Last Name	First Name	Organization
Huttula	Marko	University of Oulu
Huya-Kouadio	Jennie	Strategic Analysis, Inc.
Hwang	Euichun	ILJIN Electric Co., Ltd.
Hwang	Jee	Hyundai Motor Group
Hwang	Kevin Kwangsup	3M Company
Iiyama	Akihiro	University of Yamanashi/Fuel Cell Nanomaterials Center
Ikeda	Maki	Baker Hughes
Ingram	David	Phillips 66 Company
Isaksen	Erik	
Isherwood	Todd	Sovereign Resiliency Partners
Ishikawa	Katsuya	Kawasaki Heavy Industries, Ltd.
Islam	Ehsan Sabri	Argonne National Laboratory
Islamoglu	Timur	Northwestern University
Iyer	Rakesh Krishnamoorthy	Argonne National Laboratory
Jackson	Noah	Yosemite Clean Energy
Jain Figueroa	Anjuli	U.S. Department of Energy
Jakupca	Ian	NASA
James	Brian	Strategic Analysis, Inc.
James	Will	Savannah River National Laboratory
Jang	Darren	Nuclear Regulatory Commission
Jankovic	Jasna	University of Connecticut
Jansto	Steven	Research and Development Resources
Jaramillo	David	Verne
Jaramillo	Thomas	Stanford University/SLAC National Accelerator Laboratory
Jayasinghe	Rahula	Tetramer Technologies LLC
Jelen	Deborah	Electricore, Inc.
Jenks	Steven	Jacobs Solutions Inc.
Jensen	Brian	Allegheny Conference on Community Development
Jensen	Michael	Xcel Energy
Jezierski	Kelly	General Motors Company
Jia	Hongfei	Toyota Motor Corporation
Jia	Qingying	Plug Power Inc.
Jiang	R.	General Motors Company

Last Name	First Name	Organization
Jiao	Li	Northeastern University
Jin	Xinfang	University of Massachusetts, Lowell
Jochum	Johanna	American Clean Power Association
Johnson	Jillian	DNV
Johnson	Michael	Florida A&M University–Florida State University (FAMU-FSU) College of Engineering
Johnson	Robert	Exxon Mobil Corporation
Joiner	Gina	Jacobs Solutions Inc.
Jokinen	Kristian	CALSTART
Jones	Joshua	JTEKT
Jones	Peter	University of Pennsylvania
Jones	Sean	Airbus
Jonnavittula	Divya	Eichleay, Inc.
Jorgensen	Scott	Hyrax Intercontinental
Joseck	Fred	Idaho National Laboratory
Joseck	Frederick	Consultant
Josefik	Nicholas	U.S. Army Corps of Engineers, Engineer Research and Development Center, Construction Engineering Research Laboratory
Joshi	Prasanna	Environmental Resources Management (ERM Group)
Joy	Nadene	
Kabir	Zakiul	Yosemite Clean Energy
Kak	Ashu	Genesis Oil and Gas Consultants Ltd.
Kakani	Mahima	J.P. Morgan
Kakinuma	Katsuyoshi	University of Yamanashi
Kalakoti	Jyotsna	Utah Office of Energy Development
Kaminsky	Robert	Exxon Mobil Corporation
Kamisono	Koi	DNP Corporation USA
Kanach	Brianne	Exxon Mobil Corporation
Kane	Sue	North Central Educational Service District
Kanesaka	Hiroyuki	FC-Cubic TRA
Kang	Donghyeon	Argonne National Laboratory
Kang	ShinYoung	Lawrence Livermore National Laboratory
Kang	Soon Hyung	National Renewable Energy Laboratory

Last Name	First Name	Organization
Kang	Sunggju	Doosan Heavy Industries
Kania	Alex	Wolfe Research
Kanuri	Sridhar	HyAxiom, Inc.
Karan	Kunal	University of Calgary
Kariuki	Nancy	Argonne National Laboratory
Karp	Nicola	First Mode
Kasai	Masahiro	Kyushu University
Kashat	Andrew	DT Midstream
Kashuba	Michael	California Governor’s Office of Business and Economic Development (GO-Biz)
Kassam	Salima	Schlumberger Limited
Kastantin	Matthew	Moleaer Inc.
Kaszubski	Glen	PPG Industries, Inc.
Kato	Ryogo	Associated General Contractors of America
Kau	Kam	Argonne National Laboratory
Kaufman	Aaron	University of Oregon
Kaufman	Liisa	Energy Independence Now
Kawasaki	Satoshi	Honda R&D
Keairns	Dale	Deloitte Consulting LLP
Keefer	Randall	American Electric Power
Keil	George	AECOM
Keller	Jay	Zero Carbon Energy Solutions Inc.
Kelley	Patricia	New Day Hydrogen, LLC
Kelly	Amy	Shell
Kelly	Henry	Boston University
Kelly	Nelson	Macomb Community College
Kelly	Peter	International Association of Plumbers and Mechanical Officials
Kelpsas	Josie	Gas Technology Institute
Kendrick	Ian	Northeastern University
Kennedy	Alex	Corban Energy Group
Kennedy	James	Hycamite TCD Technologies OY
Kennedy	Michael	AirChem Energy LLC
Kenney	Adam	Gannon & Scott

Last Name	First Name	Organization
Kent	Andrew	WGL Energy
Kent	Emily	Clean Air Task Force
Kent	Ronald	
Kerber	Jackie	Battelle Energy Alliance
Kessler	Joseph	New York Power Authority
Khademi	Mahdi	Chevron
Khan	Genghis	General Electric Company
Khanna	Raghav	University of Toledo
Kian	Cyrus	U.S. Department of Energy
Kienitz	Brian	Palo Alto Research Center
Killingsworth	Nicholas	Lawrence Livermore National Laboratory
Kilmer	Burrell	Connected DMV
Kim	Chulong	Colorado School of Mines
Kim	Daejin	National Energy Technology Laboratory
Kim	Jai-woh	U.S. Department of Energy
Kim	Jonglyul	ILJIN Hysolus Co., Ltd.
Kim	Kil Jung	KEPCO E&C
Kim	Moon Jung	University of Southern California
Kim	Namdoo	Argonne National Laboratory
Kim	NamHoon	Lawrence Livermore National Laboratory
Kim	Nayoung	Hyundai Oilbank Co.
Kim	Taeeun	Hyundai Oilbank Co.
Kim	Yu Seung	Los Alamos National Laboratory
Kimble	Mike	Skyhaven Systems, LLC
Kimery	Scott	HDR, Inc.
Kinoshita	Shinji	AGC Inc.
Kirsch	Matt	Obsidian Renewables LLC
Kirschbaum	Asher	National Renewable Energy Laboratory
Kiser	Lee-Ann	Oak Ridge Institute for Science and Education
Kishi	Katsuyuki	
Klass	Alexandra	U.S. Department of Energy
Kleen	Gregory	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office

Last Name	First Name	Organization
Klein	Martin	Hydrogen Electro Systems Inc.
Klein	Ryan	National Renewable Energy Laboratory
Klembara	Melissa	U.S. Department of Energy
Kling	Meredith	Robert Bosch LLC
Knapik	Benjamin	Xerox Research Centre of Canada
Knez	Stan	Fortescue Future Industries
Knighton	Todd	Idaho National Laboratory
Knights	Shanna	Ballard Power Systems Inc.
Knipping	Eladio	Electric Power Research Institute
Knobloch	Kevin	Knobloch Energy LLC
Kobayashi	Kosuke	AP Ventures LLP
Kocha	Shyam	Shyam Kocha Consulting
Kocs	Elizabeth	Gas Technology Institute
Kocur	Chris	GKN Hydrogen
Koleva	Mariya	U.S. Department of Energy
Komini Babu	Siddharth	Los Alamos National Laboratory
Kong	Shuang	RIKEN
Kong	Szelim	Naval Nuclear Laboratory
Kongkanand	Anusorn	General Motors Company
Konishi	Takashi	Toray Industries, Inc.
Kopasz	John	Argonne National Laboratory
Kort-Kamp	Wilton	Los Alamos National Laboratory
Kothandaraman	Jothi	Pacific Northwest National Laboratory
Koti	Archit	Cummins Inc.
Kovach	Dennis	American Electric Power
Kovvali	Sarma	Exxon Mobil Corporation
Kowalski	Peter	Argonne National Laboratory
Koyama	Hiroki	Toyota Motor Corporation
Krause	Taylor	Boundary Stone Partners
Krause	Theodore	Argonne National Laboratory
Krenz	Shannon	University of Cincinnati
Krieg	Jim	Arup
Kristjansson	Thor	Roland Berger

Last Name	First Name	Organization
Kuang	Wenbin	Pacific Northwest National Laboratory
Kuehn	Ryan	U.S. Department of Energy
Kumar	Ashok	Cummins Inc.
Kumar	Gaurav	BP p.l.c.
Kumar	Sharun	Haas School of Business
Kumaraguru	Swami	General Motors Company
Kung	Bryan	Ballard Power Systems Inc.
Kuo	Chih-Hsiang	Exxon Mobil Corporation
Kuroki	Taichi	National Renewable Energy Laboratory
Kushner	Sandy	Air Products and Chemicals, Inc.
Kusoglu	Ahmet	Lawrence Berkeley National Laboratory
Kusserow	Nicolas	1s1 Energy
Kwan	Kermit	Solvay
Kweon	Kyoung	Lawrence Livermore National Laboratory
Kyle	Page	Pacific Northwest National Laboratory
Laffen	Melissa	Energetics
LaFleur	Chris	Sandia National Laboratories
Lafon	Alejandro	Avangrid Renewables, LLC
Lai	Eikar	U.S. Department of Transportation
Lai	Yeh-hung	General Motors Company
Lambertini	Griselda	Universidad de Buenos Aires
Lancione	Tony	Noble Gas
Landin	Niko	Caterpillar Inc.
Landreville	Nancy	NML Computer Consulting Company LLC
Lane	Blake	University of California, Irvine
Lane	Jonathan	Linde plc
Lang	Alan	GKN Hydrogen
Lang	Sabrina	Linde plc
Lange	Adam	Plug Power Inc.
Lasam	Baldomero	California Energy Commission
Latimer	Ian	New York State Energy Research and Development Authority
Lattimer	Judith	Giner, Inc.

Last Name	First Name	Organization
Lau	Geoff	Humble Midstream, LLC
Lau	Ryan	Technip Energies
Lauria	Rich	
Lauritzen	Mike	Ballard Power Systems Inc.
Lauteri	David	
Lawler	John	Plug Power Inc.
Lawrence	Svetlana	Idaho National Laboratory
Lawson	Riley	National Renewable Energy Laboratory
Laycook	Wade	OCI N.V.
Leachman	Jacob	Washington State University
Leavitt	Mark	General Motors Company
Lebowitz	Jacob	
Lederer	Klaus	H2-Industries Inc.
Lee	ChungHyuk	Los Alamos National Laboratory
Lee	Heonjoong	Cummins Inc.
Lee	Janggil	ILJIN Hysolus Co., Ltd.
Lee	Jayne	Hephas Energy Co., Ltd.
Lee	Judy	6K Inc
Lee	Juyeon	KEPCO E&C
Lee	Maddie	Enel North America
Lee	Moo	Hydrofrac.com
Lee	Paul	City of Los Angeles
Lee	Richard	IMECS LLC
Lee	Yunsu	Hyundai Motor Group
Leff	Stephen	Shell Hydrogen
Lehner	William	Independence Hydrogen, Inc.
Leighton	Daniel	National Renewable Energy Laboratory
Leighton	DeLisa	IGX Group, Inc./Bayotech
Leighty	Bill	The Leighty Foundation
Leo	Anthony	FuelCell Energy, Inc.
Leonard	Daniel	Los Alamos National Laboratory
Leon-Cazares	Fernando	Sandia National Laboratories
Leslie	Tracy	Electric Power Research Institute

Last Name	First Name	Organization
Levy	Scott	Bluefish.org
Lewis	Eric	National Energy Technology Laboratory
Lewis	Michael	University of Texas at Austin
Li	Ailong	RIKEN
Li	Chenzhao	Indiana University
Li	Jianlin	Oak Ridge National Laboratory
Li	Jie	Argonne National Laboratory
Li	Juan	Linde plc
Li	Jun	Kansas State University
Li	Kui	Los Alamos National Laboratory
Li	Shuyun	Pacific Northwest National Laboratory
Li	Sichi	Lawrence Livermore National Laboratory
Li	Ted	Air Liquide
Li	Wen	AATC
Li	Wei	West Virginia University
Li	Xianglin	University of Kansas
Li	Xiaodong	University of Virginia
Li	Yijin	National Renewable Energy Laboratory
Li	Yue	Redox Power Systems
Lidicker	Jeff	California Public Utilities Commission
Liguori	Simona	Clarkson University
Lim	Catherine	ILJIN Hysolus Co., Ltd.
Lim	Hyunjung	Fraunhofer IWKS
Lin	Haiqing	State University of New York at Buffalo
Lin	Hongfei	Washington State University
Lin	Honghong	Toyota Motor Corporation
Lin	Paul	Southern California Gas Company
Linard	Yohann	
Lindell	Matthew	3M Company
Ling	Yansong	University of California, Los Angeles
Linton	Bill	Linton Consulting
Lipman	Timothy	University of California, Berkeley/Lawrence Berkeley National Laboratory

Last Name	First Name	Organization
Lipp	Ludwig	T2M Global
Lipton	Jeff	University of Washington
Litster	Shawn	Carnegie Mellon University
Litwiler	Dena	Westinghouse Electric Company, LLC
Liu	Bin	Kansas State University
Liu	Chang	National Renewable Energy Laboratory
Liu	Di-Jia	Argonne National Laboratory
Liu	Dongxia	University of Maryland
Liu	Jiawei	Carnegie Mellon University
Liu	Meilin	Georgia Institute of Technology
Liu	Mingfei	Phillips 66 Company
Liu	Ru-Fen	CDTi Advanced Materials, Inc.
Liu	Xingbo	West Virginia University
Liu	Yi	BASF
Liu	Ying	Phillips 66 Company
Liu	Zengcai	Alchemr Inc
Liu	Zeyan	University of California, Los Angeles
Liu	Zheng	Weichai Power Co., Ltd.
Liu	Zhenyu	Plug Power Inc.
Liyanage	Wipula	Los Alamos National Laboratory
Lloyd	Alan	University of Texas at Austin
Lock	Connor	City of Long Beach
Longman	Douglas	Argonne National Laboratory
Loon	Tim	Southern California Gas Company
Lopez	Evelyn	National Energy Technology Laboratory
Lord	Nathan	Shale Crescent USA
Lou	Kun	National Renewable Energy Laboratory
Loughrin	Casey	Sargent & Lundy
Love-Baker	Cole	University of Virginia
Lozano	Luis Miguel	DESMASA
Lu	Alan	Avangrid Renewables, LLC
Lu	Yunxiang	Cummins Inc.
Lu	Amy	BP p.l.c.

Last Name	First Name	Organization
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Ludwig	Dan	Xcel Energy
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Luo	Jessica	Ballard Power Systems Inc.
Luo	Jian	University of California, San Diego
Luo	Jinyong	Cummins Inc.
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Lyu	Xiang	Oak Ridge National Laboratory
Ma	Xiao	Wake Forest University
Ma	Xiaoli	University of Wisconsin–Milwaukee
Ma	Zhiwen	National Renewable Energy Laboratory
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Macauley	Natalia	Giner, Inc.
Mace	Alan	Ballard Power Systems Inc.
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MacLean	Alex	Enbridge
MacLeod	Bill	Emerald Advisory LLC
Maddalena	Kevin	Bennett Pump
Mahajan	Devinder	Stony Brook University
Makar	Ellen	Energy Concepts Co.
Makwana	Anand	
Makwinski	Mark	Carrier
Malcore	Jason	Association of Equipment Manufacturers
Maloney	Thomas	Skyre, Inc.
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Manigan	Sumiko	
Mao	Wade	Gas Technology Institute
Marechaux	Toni	Booz Allen Hamilton
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Last Name	First Name	Organization
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Martin	Josh	National Renewable Energy Laboratory
Martin	Cameron	Westinghouse Electric Company, LLC
Martinez	Luis	Southern California Gas Company
Martinez	Andrew	California Air Resources Board
Martinez	Alex	Johnson Matthey Hydrogen Technologies, Ltd.
Maruta	Akiteru	Technova Inc.
Marxen	Sara	CSA Group
Masel	Rich	Alchemr Inc
Mason	Mark	University of Toledo
Mason	David C.	Air Liquide
Mason	Chad	Advanced Ionics
Mastropasqua	Luca	University of California, Irvine
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Mathuraiveeran	Thangaraj	Cummins Inc.
Matsumoto	Takako	Toray Industries, Inc.
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McAndrew	James	Air Liquide
McAuliffe	Brenda	Bloomberg Green Markets
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McDaniel	Anthony	Sandia National Laboratories
McDonald	Zane	Gas Technology Institute
McDonald	Nikkia M.	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
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McEleney	Michael	U.S. Department of Energy, Arctic Energy Office
McGee	Brandon	McKinsey & Company

Last Name	First Name	Organization
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Meeks	Noah	Southern Company
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Mehta	Darius	Garrett Motion
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Meikle	Grace	Emissions Reduction Alberta
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Mench	Matthew	University of Tennessee
Menon	Nalini	Sandia National Laboratories
Merlo	Luca	Solvay
Mesa	Juan	Carnegie Mellon University
Mesrobian	Chris	Monolith Materials
Mhibik	Oumaima	Alternative Energies and Atomic Energy Commission, France (CEA)
Mihelic	Rick	North American Council for Freight Efficiency
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Miller	Birgit	Department of Revenue
Miller	Daniel	Lawrence Berkeley National Laboratory
Miller	Eric	U.S. Department of Energy
Miller	Jeff	ETCH2 Mobility Management LLC
Miller	Michael	Xcel Energy
Milliken	Joann	New Jersey Fuel Cell Coalition

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Minelli	Simone	University of Milan
Minh	Nguyen	University of California, San Diego
Minier	John	Rotoflow of Air Products
Miranda	Raul	U.S. Department of Energy
Mirisola	Lisa	
Mittelsteadt	Cortney	Plug Power Inc.
Mittica	Nick	Verdagy
Miura	Shinichi	Kobe Steel, Ltd.
Mizutani	Yasunobu	National Institute of Advanced Industrial Science and Technology (AIST)
Moddrell	Jeremy	The United Association
Moe	Jon	Xcel Energy
Moen	Chris	Sandia National Laboratories
Moffett	Hilary	Fortescue Future Industries
Mohamed	Ahmed El-Mutasim	El-Tesmanians International for Sustainable Development Co. Ltd.
Mohammadi	Abbas	The Ohio State University
Mohite	Aditya	Rice University
Mohr	Jeffrey	National Renewable Energy Laboratory
Mohtadi	Rana	Toyota Motor Corporation
Mokrini	Asmae	National Research Council
Moller	Francois	Sasol Limited
Molsbee	Richard	COH2 Energy
Monroe	Nicholas	Hornblower Energy, LLC
More	Karren	Oak Ridge National Laboratory
Moreland	Greg	Oak Ridge National Laboratory
Moreno	Charlotte	Clean Air Council
Moriya	Takashi	American Honda Motor Co., Inc.
Moriyama	Koji	American Honda Motor Co., Inc.
Morris	Ashley	University of Kentucky, Center for Applied Energy Research

Last Name	First Name	Organization
Morris	Matt	Holland & Hart LLP
Moss	Diane	Lawrence Berkeley National Laboratory
Motealleh	Behrooz	Electric Power Research Institute
Motupally	Sathya	HyAxiom, Inc.
Mrozewski	Stefan	Oceanit Laboratories, Inc.
Mueller	Edgar	
Muisener	Richard	Evonik Industries AG
Mukerjee	Sanjeev	Northeastern University
Mukundan	Rangachary	Los Alamos National Laboratory
Mulcare	Michael	Mott MacDonald
Mulder	Brandon	S&P Global
Mulhall	Michael	New York Power Authority
Mullen	John	International Association of Plumbers and Mechanical Officials
Mullins	Richard	Infinity Fuel Cell and Hydrogen, Inc.
Münster	Ingo	BASF
Muras	Bill	Alytic, Inc.
Murata	Hajime	Toyota Central R&D Laboratories, Inc.
Murawa	Jeff	Daimler Trucks
Murph	Simona	Savannah River National Laboratory
Murphy	Diana	Brookhaven National Laboratory
Murphy	MacCrea	U.S. Hydrogen Alliance
Murphy	Mike	MJM Business Solutions LLC
Murray	Bill	Advanced Ionics
Murray	Kyle	Robert Bosch LLC
Murray	Lynn	LMM Innovation Group
Murthi	Vivek	Nikola Motor Company
Muscher	Philipp	EvolOH, Inc.
Musial	Dustin	Robert Bosch LLC
Myers	Charles	General Dynamics Information Technology
Myers	Deborah	Argonne National Laboratory
Myhre	Richard	Frontier Energy, Inc.
Nagai	Tomoyuki	Toyota Central R&D Laboratories, Inc.

Last Name	First Name	Organization
Nagasawa	Kazunori	National Renewable Energy Laboratory
Nagimov	Ruslan	Microsoft Corporation
Nair	Asalatha	Florida International University
Namhyun	Kim	ILJIN Hysolus Co., Ltd.
Naskar	Amit	Oak Ridge National Laboratory
Nazemi	Reza	Yale University
Neal	Matthew	Siemens Energy AG
Nelson	Amy	AVL Fuel Cell Canada
Nelson	Todd	Environmental Resources Management (ERM Group)
Nemec	Tomas	Institute of Thermomechanics, Czech Academy of Sciences
Newhouse	Norman	Hexagon R&D, LLC
Newman	Matthew	New Era Advisors
Newman-Ford	Jane	Burns & McDonnell
Neyerlin	Kenneth	National Renewable Energy Laboratory
Nguyen	Hien	University of Freiburg
Nguyen	Natasha	National Renewable Energy Laboratory
Ni	Qian	Cabot Corporation
Nishimura	Shin	Kyushu University
Noritake	Yosuke	NGK Automotive Ceramics USA, Inc.
Norko	Natalia	WGL Energy
Norley	Julian	Norley Carbon & Graphite Consultants, LLC
Norris	Robert	Oak Ridge National Laboratory
Northrup	James	VERBIO North America
Notes	Jackson	Williams & Jensen PLLC
Novy	Melissa	Virginia Polytechnic Institute and State University
Nowinka	Jaroslaw	Eiger Energy Engineering
Nunez	Daniel	International Association of Plumbers and Mechanical Officials
Ocampo	Minette	pH Matter, LLC
Ocko	Ilissa	Environmental Defense Fund
Odgaard	Madeleine	IRD Fuel Cells, LLC
Odom	Sara	Electricore, Inc.
Offner	Arnold	Phoenix Contact

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Ogitsu	Tadashi	Lawrence Livermore National Laboratory
Oglesbee	Drew	Vallourec ETO
Ogundele	Peter	Gladstein Neandross & Associates
Oh	Tae-Sik	Auburn University
Oh	Songi	Hyundai Motor Group
Ohnuma	Akira	Toyota Motor Corporation
Ohyama	Keiko	Kyushu University
Okazaki	Nobutaka	ISHIFUKU Metal Industry Co., Ltd.
Okubo	Keiichi	Toyota Motor Corporation
Okumura	Ryota	DENSO International, Inc.
Okuyama	Takumi	AGC Inc.
Olowu	Temitayo	Idaho National Laboratory
Olson	Greg	U.S. Department of Energy (contractor)
Olszewski	Cassie	The Chemours Company
Olumoroti	Akin	Environmental Defense Fund
O'Malley	Ronald	Missouri University of Science and Technology
Omura	Takeo	Daiwa Institute of Research Ltd.
Ong	Gary	Celadyne Technologies, Inc.
Onorato	Shaun	National Renewable Energy Laboratory
Ordonez	Juan	Florida A&M University–Florida State University (FAMU-FSU) College of Engineering
Orofino	Nick	The Cohen Group
Orr	Robert	Texas 2036
Ortega	Alberto	Ministry of Energy, Chile
Osisanlu	Titi	The Williams Companies, Inc.
Osmieri	Luigi	Los Alamos National Laboratory
Osterman	Travis	Bennett Pump
Osvatics	Cassie	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Otgonbaatar	Uuganbayar	Constellation Energy
Ott	Kevin	
Overton	Philip	Ballard Power Systems Inc.
Ovshinsky	Rosa	
Owejan	Jon	Plug Power Inc.

Last Name	First Name	Organization
Owens	Michael	U.S. Department of Energy, Office of Technology Transitions
Ozkan	Soner	General Electric Company
Padgett	Elliot	National Renewable Energy Laboratory
Paffhausen	Chad	Bennett Pump
Paige	Stephen	IAC Partners
Pal	Narendra	Hornblower Group, Inc.
Pal	Pinaki	Argonne National Laboratory
Pan	Mu	Wuhan University of Technology
Pandey	Rahul	Palo Alto Research Center
Pann	Serge	Northeastern University
Papadias	Dionissios	Argonne National Laboratory
Papageorgopoulos	Dimitrios	U.S. Department of Energy
Parashar	Aadarsh	Colorado School of Mines
Parenteau	Richard	No Carbon Fuel
Parilla	Philip	National Renewable Energy Laboratory
Park	Ahhyeon	Hyundai Motor Group
Park	Andrew	The Chemours Company
Park	Cheolwoong	ILJIN Hysolus Co., Ltd.
Park	Gu-Gon	Korea Institute of Energy Research
Park	Hyounmyung	Hyundai Motor Group
Park	Jae Hyung	Argonne National Laboratory
Park	Sarah Eun Joo	Los Alamos National Laboratory
Parker	Eric	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Parker	Kendall	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Parsons	Christy	U.S. Environmental Protection Agency
Pasaogullari	Ugur	University of Connecticut
Pasmay	Fausto	Carnegie Mellon University
Pastor	Dan	Tetra Tech Inc.
Patch	Keith D.	
Patel	Reecha	Office of Senator Robert P. Casey
Paterson	Jack	City of Denver/JA Paterson LLC

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Patrie	Mitch	U.S. Environmental Protection Agency
Patt	Jeremy	AquaHydrex, Inc.
Paul	John	PacifiCorp (retired)
Paul	Devproshad	
Paulauskas	Felix	Oak Ridge National Laboratory
Paulson	Scott	University of Calgary
Paulsson	Bjorn	Paulsson, Inc.
Pavageau	Bertrand	Solvay
Pavlicek	Ryan	Advent Technologies, Inc.
Pavlik	Thomas	Advent Technologies, Inc.
Paxson	Adam	Plug Power Inc.
Pearman	David	National Renewable Energy Laboratory
Pearson	Jeremy	San Rafael Energy Research Center
Pederson	Keriann	Exxon Mobil Corporation
Pederzoli	Andrea	Snam North America
Peer	Drew	Wanzek Construction
Pei	Yuanjiang	Aramco Americas
Pekarek	Christian	
Pena	Willians	Toyota Motor Corporation
Pena	Santiago	AVEVA Group plc
Penev	Michael	National Renewable Energy Laboratory
Peng	Bosi	University of California, Los Angeles
Peng	Xiong	Lawrence Berkeley National Laboratory
Peng	Peng	Lawrence Berkeley National Laboratory
Penn	Roger	AVL Fuel Cell Canada
Perea	Samantha	Sandia National Laboratories
Perellón	Alejandro	Hy24
Periasamy	Chendhil	Air Liquide
Perlman	Brett	Center for Houston's Future
Perpall	Mark	Praxair Surface Technologies
Perry	Robert	Synergistic Solutions
Perry	Mike	Largo Clean Energy
Peters	Michael	Energy Services and Solutions

Last Name	First Name	Organization
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Peterson	David	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Peterson	Jeffrey	First Mode
Petri	Randy	Idaho National Laboratory
Petrovic	John	Petrovic and Associates
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Philips	Matthew	TreadStone Techologies, Inc.
Pien	Michael	Giner, Inc.
Pierre	Fritz	
Pierson	Rachel	U.S. Department of Energy
Pietras	John	Saint-Gobain
Pietrasz	Patrick	Ionomr Innovations, Inc.
Pike	Jenna	OxEon Energy, LLC
Pillay	Gautam	University of Cincinnati
Pinney	Reese	Gulf South Holding, Inc.
Pintauro	Peter	Vanderbilt University
Pisu	Pierluigi	Clemson University
Pivovar	Bryan	National Renewable Energy Laboratory
Plagmann	Heath	Hy Stor Energy LP
Pli	Dimitra	Ministry of Environment and Energy, Greece
Poggi	Gian Luca	Fitch Ratings
Polevaya	Olga	Nuvera Fuel Cells
Pollino	Joel	Solvay
Pollock	Jared	Sandia National Laboratories
Pomerantz	Mike	Gilbarco Veeder-Root/ANGI Energy Systems
Pontau	Arthur	
Posen	David	H2 Capital Partners
Post	Matthew	National Renewable Energy Laboratory
Pottow	Victor	GCP Capital Partners LLC
Poudel	Sajag	Argonne National Laboratory
Powell	Joseph	University of Houston/ChemePD LLC
Prager	McKinley	University of Hawaii

Last Name	First Name	Organization
Pranda	Pavol	Air Liquide
Prasad	Ajay	University of Delaware
Prasse	Marc	Sargent & Lundy
Preece	Jeffery	Electric Power Research Institute
Prendergast	David	Lawrence Berkeley National Laboratory
Prestano	Salvatore	Jacobs Solutions Inc.
Pretyman	David	West Monroe
Procter	Michael	cellcentric
Proctor	Leslie	Sandia National Laboratories
Prunzel	Paulo	Petrobras
Pylypenko	Svitlana	Colorado School of Mines
Qi	Manman	State University of New York at Buffalo
Qin	Feng	PBI Performance Products
Qiu	Chang	Rice University
Qiu	Ryan	H2 Economics Canada Inc.
Quackenbush	Karen	Fuel Cell and Hydrogen Energy Association
Quarrie	Collin	GNS Science
Quevedo	Jorge	Novare Corporation
Quintero	Alyssa	FGH
Quintus	Martin	AeroStack
Quiroz	David	Colorado State University
Quong	Spencer	QAI
Ragothaman	Sowmya	Burns & McDonnell
Ramachandran	Gopakumar	Sandia National Laboratories
Ramani	Dilip	Ballard Power Systems Inc.
Ramaswamy	Nagappan	General Motors Company
Rambach	Glenn	Third Orbit Power
Ramesh	Ashwin	Robert Bosch LLC
Ramig	Christopher	U.S. Environmental Protection Agency
Ramnath	Neeta	Accenture
Ramotowski	Michael	Solar Turbines Incorporated
Ramsey	Evan	Bonneville Environmental Foundation
Rana	Vishrut	University of California, Berkeley

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Randolph	Katie	U.S. Department of Energy
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Rao	Pradyumna	Weichai Power Co., Ltd.
Rashilla	Rick	Hexagon R&D, LLC
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Ravelojaona	Lucie	Universal Hydrogen
Ravesteijn	Elizabeth	Air Products and Chemicals, Inc.
Reddi	Krishna	Argonne National Laboratory
Reddoch	Tom	Electric Power Research Institute
Redinger	Gene	
Reihl	Keith	Houston Airport System
Reis	Signo	Fuel Cell Enabling Technologies, Inc.
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Reshetenko	Tatyana	Hawaii Natural Energy Institute, University of Hawaii
Revers	Ed	De Nora S.p.A.
Revina	Lucy	Lawrence Berkeley National Laboratory
Reyes	Ilse	NASA White Sands Test Facility
Reyes	Jesse	Womble Bond Dickinson (US) LLP
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Reznicek	Evan	National Renewable Energy Laboratory
Ricci	Lily	Boundary Stone Partners
Rice	Brian	University of Dayton Research Institute
Rice	Cynthia	Plug Power Inc.
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Richards	Nadia	California Energy Commission
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Riley	Taryn	Siemens Energy AG
Rimoldi	Matteo	FRIEM America
Rincon	James	Avangrid Renewables, LLC
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Rivera	Joseph	NeoGraf Solutions, LLC
Rivera	Marina	The Cohen Group
Robb	Dan	Frontier Energy, Inc.
Robb	Gary	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Roberts	George	TechScale Solutions, LLC
Roberts	Holly	Akoya
Roberts	Rory	Tennessee Technological University
Robertson	Jessica	The Chemours Company
Robson	Michelle	AP Ventures LLP
Rockward	Tommy	Los Alamos National Laboratory
Rodezno	Eva	U.S. Department of Energy
Rodriguez	Jesse	Constellation Energy
Roenning	Frida	University of Tennessee, Knoxville
Roh	Hee-Seok	Argonne National Laboratory
Roizen	Jennifer	U.S. Department of Energy
Rojas	Jimmy	EvolOH, Inc.
Rojas-Carbonell	Santiago	Electric Hydrogenbrace
Romeri	Mario Valentino	
Ronevich	Joseph	Sandia National Laboratories
Root	Jeffrey	RQT Energy Storage Corp
Ropchock	Keith	National Renewable Energy Laboratory
Rosenfeld	John	Proteum Energy, LLC
Rosenthal	Chris	
Rosewell	David	Transport America Project
Ross	Nathan	W. L. Gore & Associates, Inc.
Ross	Ned	Ned Ross Strategic Services
Rossi	Ruggero	The Pennsylvania State University
Routh	Robert	Clean Air Council
Rowe	Meg	Oregon Department of Transportation

Last Name	First Name	Organization
Roy	Molly	U.S. Department of Energy
Roy	Anirban	University of Tennessee
Roy Chowdhury	Bikram	Air Liquide
Rubery	Hugh	American Gas Association
Rubio	Omar	Siemens Energy AG
Rufael	Tecle	SLR Consulting
Ruple	Matt	National Renewable Energy Laboratory
Rupnowski	Peter	National Renewable Energy Laboratory
Rustagi	Neha	U.S. Department of Energy
Ruszkowski	Shelley	Exxon Mobil Corporation
Ruth	Mark	National Renewable Energy Laboratory
Rutty	Craig	Daimler Trucks
Ruz	Ana Maria	Corfo (Production Development Corporation, Chile)
Ryan	Amy	Toyota Motor Corporation
Ryan	Lexie	FTI Consulting
Ryan	Liam	Toyota Motor Corporation
Saadi	Fadl	C-Zero
Saddler	Kylie	National Renewable Energy Laboratory
Safro	Sandra	The Edison Electric Institute
Sagraves	Brandon	LNE Group
Sakaue	Tomohiro	Toray Industries, Inc.
Saleh	Hassan	DEEL/GenCell Ltd.
Salmon	Natalie	FGS Global
San Marchi	Chris	Sandia National Laboratories
Santos	Bruce	Marine Dolphin Enterprises
Saraidaridis	James	Raytheon Technologies Research Center
Sarasombath	Soranut	B. I. Ag. Development Co., Ltd.
Sardar	Hashim	
Sasaki	Kotaro	Brookhaven National Laboratory
Satomi	Tomohide	Fuel Cell Commercialization Conference of Japan
Satyapal	Sunita	U.S. Department of Energy
Saur	Genevieve	National Renewable Energy Laboratory
Sautter	Jeremie	Business France North America

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Saveski	Tomi	DENSO International, Inc.
Scarcelli	Riccardo	Argonne National Laboratory
Schall	Constance	University of Toledo
Schaller	Adam	Lakeshore Die Cast, Inc
Schath	Brian	New Mexico Environment Department
Scheffe	Jonathan	University of Florida
Scherschel	Alexander	University of Virginia
Schlatre	Alexis	Harris, DeVille & Associates, Inc.
Schlueter	Debbie	IRD Fuel Cells, LLC
Schlueter	John	National Science Foundation
Schmid	Michael	Micro Nano Technologies
Schneeberger	Chad	ONEOK, Inc.
Schneider	Jesse	ZEV Station
Schoff	Patrick	Natural Resources Research Institute
Scholten	Tom	
Schrecengost	Robert	Fossil Energy and Carbon Management HQ
Schroeder	Benjamin	Sandia National Laboratories
Schultz	Charles	De Nora S.p.A.
Schultz	Melanie	National Offshore Wind Research and Development Consortium
Schultz	Paul	Los Angeles Department of Water and Power
Schutt	Anna	AJW, Inc.
Schwartz	Viviane	U.S. Department of Energy
Schwier	Garrett	U.S. Department of Energy
Seetharam	Ram	University of Houston, Energy Program
Segalman	Lily Anna	Invariant
Seger	Jeff	LHP Energy Holdings
Selch	Jason	Enchant Energy
Seligman	Arthur	
Serov	Alexey	Oak Ridge National Laboratory
Serrato	Sebastian	California Energy Commission
Severin	Erik	H2U Technologies
Severs	Linda	Oak Ridge Associated Universities

Last Name	First Name	Organization
Shah	Jignesh	Phillips 66 Company
Shah	Minish	Linde plc
Shah	Vatsal	Shell
Shah	Vishal	Hydrogen Technology Ventures
Shain	Lily	Sandia National Laboratories
Shank	Kelsey	theEDGE, LLC
Shannahan	Kevin	Robert Bosch LLC
Shao	Yuyan	Pacific Northwest National Laboratory
Shappell	Charles	Faurecia Clean Mobility
Sharma	Preetam	University of Tennessee, Knoxville
Shaw	Robert	Arete Venture Management
Shen	Victor	University of Virginia
Shepherd	Gregory	Toyota Motor Corporation
Shere	Ani	Rogers Corporation
Sherif	SA	University of Florida
Sherman	James	Vertical Flight Society
Shi	Ken	National Research Council Canada
Shibutani	Mitsuo	Kyushu University Research Center for Hydrogen Industrial Use and Storage
Shieh	Tom	Toyota Motor Corporation
Shih	Andrew	Applied Spectra
Shiino	Keisuke	Toshiba Energy Systems & Solutions Corporation
Shimotori	Soichiro	Toshiba Energy Systems & Solutions Corporation
Shimpalee	Sirivatch	University of South Carolina
Shin	Dongwon	Korea Institute of Energy Research
Shin	Jae Eun	Korea Institute of Geoscience and Mineral Resources
Shin	Sung-Hee	Hyundai Motor Group
Shinohara	Akihiro	Toyota Central R&D Laboratories, Inc.
Shinozaki	Kazuma	Toyota Central R&D Laboratories, Inc.
Shrestha	Rakish	Sandia National Laboratories
Shrivastava	Udit	Cummins Inc.
Shulda	Sarah	National Renewable Energy Laboratory
Shuster	Mark	Bureau of Economic Geology, University of Texas at Austin

Last Name	First Name	Organization
Simmons	Daniel	Simmons Energy and Environmental Strategies
Simmons	Kevin	Pacific Northwest National Laboratory
Simon	Nima	ICF International, Inc.
Simonoff	Ethan	Southern California Gas Company
Sinanan	Anson	Cummins Inc.
Singh	Jaswinder	Caterpillar Inc.
Singh	Prabhakar	University of Connecticut
Singhal	Subhash	
Sinha	Manish	General Motors Company
Siroky	Mark	California Air Resources Board
Si-Won	Kim	Hyundai Motor Group
Skafte	Theis	Noon Energy Inc.
Skriba	Louis	Gigajoule Jug Consultants
Skrzypczak	Luke	University of Virginia
Slack	John	Nikola Motor Company
Sloan	Connor	IAC Partners
Small	Kathryn	Sandia National Laboratories
Smith	Andrew	Sandia National Laboratories
Smith	Christopher	Infinity Fuel Cell and Hydrogen, Inc.
Smith	Kevin	Falcon Cougar Management Consultants LLC
Smith	Owen	National Renewable Energy Laboratory
Smith	Rebecca	Oregon Department of Energy
Smith	Rick	Ameren Corporation
Smith	Samuel	University of New Mexico
Smith	Wil	Electric Power Research Institute
Snyder	Seth	Idaho National Laboratory
Sofronis	Petros	University of Illinois at Urbana–Champaign
Sokaras	Dimosthenis	SLAC National Accelerator Laboratory
Solomon	Todd	ZeroAvia
Soloveichik	Grigorii	Advanced Research Projects Agency–Energy (ARPA E)
Somerday	Brian	Somerday Consulting LLC
Song	Sophia	Solvay
Song	Xueyan	West Virginia University

Last Name	First Name	Organization
Sosa	Siari	Southern California Gas Company
Sosa Peña	Roxana	Continental Automotive
Sotsky	Leela	National Renewable Energy Laboratory
Soucoup	Kayla	Virent, Inc.
South	David	West Monroe
Spalding	Las	Entergy Corporation
Spatz	Sean	
Spatz	John	
Spendelow	Jacob	Los Alamos National Laboratory
Spiteri	Vincent	National Grid
Spott	Perry	Advanced Ionics
Springer	Ben	FGH
Srikanth	Pradyumna	FORVIA
Stadie	Nicholas	Montana State University
Stafshede	Patric	Celcibus AB
Staller	Corey	Celadyne Technologies, Inc.
Stanford	Joseph	U.S. Department of Energy
Stanford	Lateefah	BP p.l.c.
Stanis	Ronald	Gas Technology Institute
Star	Andrew	Argonne National Laboratory
States	Jennifer	Washington Maritime Blue
St. Clair	Tracy	Energy Harbor
Stebbins	Lauren	Clean Air Council
Stechel	Ellen	Arizona State University
Steele	Lindsay	Pacific Northwest National Laboratory
Stege	Alex	CF Industries
Steinbach	Andy	3M Company
Steiner	Dietmar	Robert Bosch LLC
Steinkusz	Martina	Renewable Hydrogen Alliance
Steinlechner	Johann	Heppolt Hydrogen
Stekli	Joseph	Electric Power Research Institute
Stern	Lesley	California Air Resources Board
Stettner	Jennifer	Washington Gas Light Company

Last Name	First Name	Organization
Stevens	Jason	EDP Renewables
Stevens	Jeff	U.S. Environmental Protection Agency
Stevens	Robert	U.S. Department of Energy
Stewart	Frederick	Idaho National Laboratory
Stigge	Ryan	Omaha Public Power District
Stinner	Charles	Allegheny Technologies Incorporated
Stivala	Michael	Suburban Propane Partners, L.P.
Storck	Sebastian	BASF
Stottler	Gary	Stottler Development LLC
St. Pierre	Jean	Cummins Inc.
Strand	Vernon	La Mancha Mills
Strasser	Molly	Xcel Energy
Strauch	Michael	Mitsubishi Heavy Industries America
Stuckert	Ines	Solvay
Stuckert	Nicki	Linde plc
Stuckey	Philip	FC Renew, LLC
Stultz	Kevin	Emerson Automation Solutions
Sturm	Etienne	Vopak New Energies
Stuver	Susan	Gas Technology Institute
Su	Gregory	Lawrence Berkeley National Laboratory
Suda	Andrew	Rolls-Royce Solutions America Inc.
Sulic	Martin	U.S. Department of Energy
Sullivan	George	Bloom Energy
Sullivan	Joshua	Local Impact Analytics, LLC
Sumba	Kelvin	Gilbarco Veeder-Root/ANGI Energy Systems
Sun	Fuxia	3M Company
Sun	Pingping	Argonne National Laboratory
Sun	Qiang	Northeastern University
Sun	Tianyi	EDF Energy
Sun	Xin	Oak Ridge National Laboratory
Sunderrajan	Suresh	Argonne National Laboratory
Surratt	Leah	Florida Power & Light Company
Suryanarayana	Harish	ABB Ltd.

Last Name	First Name	Organization
Sushchenko	Andriy	University of Virginia
Sutherland	Ian	General Motors Company
Swanson	Guy	Exactrix Global Systems
Swider-Lyons	Karen	Plug Power Inc.
Swisz-Hall	Naima	U.S. Environmental Protection Agency
Tadros	Maged	Cummins Inc.
Taha	Naser	King Abdulaziz University
Taie	Zac	U.S. Department of Energy
Takahashi	Eri	AGC Inc.
Takahiro	Ono	Toshiba Energy Systems & Solutions Corporation
Takeuchi	Esther	Stony Brook University/Brookhaven National Laboratory
Talipova	Amina	Air Liquide
Tamim	Naimuddin	HydroCosm
Tanaka	Manabu	Tokyo Metropolitan University
Tang	Zhihong	Praxair Surface Technologies
Tavakoli Mehrabadi	Bahareh Alsadat	General Motors Company
Tawfik	Hazem	Farmingdale State College, State University of New York
Terada	Ichiro	AGC Inc.
Terrie	Omar	Neste US Inc.
Tesfaye	Meron	Bipartisan Policy Center
Tessier	Pascal	FuelCell Energy, Inc.
Tew	David	Advanced Research Projects Agency–Energy (ARPA E)
Thiruvengadam	Pragalath	Daimler Trucks
Thobe	Zachary	MPLX LP
Thoma	Grant	3M Company
Thomas	Amy	CSA Group
Thomas	Charles	Delaware Authority for Regional Transit
Thomas	Sandy	
Thomas-Kerr	Elena	U.S. Department of Energy
Thompson	Alexa	Rocky Mountain Institute
Thompson	Simon	U.S. Department of Energy
Thorson	Jacob	National Renewable Energy Laboratory

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Thyer	Joseph	Florida A&M University–Florida State University (FAMU-FSU) College of Engineering
Tian	Hanchen	West Virginia University
Tian	Lucia	U.S. Department of Energy, Office of Technology Transitions
Tilford	Kelly	
Ting	Louis	Los Angeles Department of Water and Power
Tiwari	Nicholas	Carnegie Mellon University
Todd	Jacob	Yosemite Clean Energy
Toelle	Sascha	Umicore
Tolk	Tracy	Van Ness Feldman
Toma	Francesca Maria	Lawrence Berkeley National Laboratory
Tomashefsky	Scott	Northern California Power Agency
Tommaso	Anne	
Toolson	Bailey	Utah Office of Energy Development
Toops	Todd	Oak Ridge National Laboratory
Topolski	Kevin	National Renewable Energy Laboratory
Torres	Antonio	Puerto Rico Energy Bureau
Torres	George	Rapid Global Aerospace
Tosca	Michael	Center for Transportation and the Environment
Townsend	Justin	Oak Ridge Institute for Science and Education
Tran	Linh	Queen Mary University of London
Treat	Nic	Solvay
Trimm	Kathryn	University of Florida
Tsai	Yu-Han	University of California, Los Angeles
Tsuchitani	Makiko	Toyota Motor Corporation
Tucker	David	U.S. Department of Energy, National Energy Technology Laboratory
Tun	Hla	Argonne National Laboratory
Turner	Alexa	Sempra
Turner	Rose	Nutrien
Tusing	Richard	National Renewable Energy Laboratory
Tygard	Ed	Wishgard LLC
Ugarte	Sylvia	Puerto Rico Energy Bureau

Last Name	First Name	Organization
Ulsh	Michael	National Renewable Energy Laboratory
Ung	Poh Boon	BP p.l.c.
Urazaliyeva	Aida	Washington State University Everett, Consortium for Hydrogen and Renewably Generated Electrofuels (CHARGE)
Urban	Marek	Clemson University
Usami	Takatada	Isuzu Motors Ltd.
Ustuner	Gozde	Stony Brook University/Brookhaven National Laboratory
Vacin	Gia	California Governor's Office of Business and Economic Development (GO-Biz)
Valdez	Thomas	Plug Power Inc.
Valdivia	Cindy	City of Lancaster
Valente	Patrick	Ohio Fuel Cell Coalition
Van Den Assem	David	Alberta Innovates
Van Der Ende	Alice	The Chemours Company
Van Hassel	Bart	Carrier
Van Wagener	David	Gas Technology Institute
Van Werden	Doug	Rock Island Arsenal
Vangala	Shreyas	West Monroe
Vangtook	Prapapong	Electricity Generating Authority of Thailand
Vasquez	Camila	Ministry of Energy, Chile
Veenstra	Mike	Ford Motor Company
Vega	Elvira Loana	Inter-American Development Bank
Venkataraman	Venkat	
Verbofsky	Russel	
VerShaw	Jim	Trane Technologies
Vetrano	John	U.S. Department of Energy, Office of Basic Energy Sciences
Vickers	James	U.S. Department of Energy
Victor	Claire	National Renewable Energy Laboratory
Vidic	Karl Jojo	Linde plc
Vijayagopal	Ram	Argonne National Laboratory
Vijayakumar	Vishnu	University of California, Davis
Villarreal	Aaron	Taylor-Wharton America Inc.
Villeneuve	Darek	Daimler Trucks

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Viswanatham	Abhishek	Garrett Motion
Vitis	Jonathon	National Australia Bank Limited
Volent	Marian	International Trade Administration, U.S. Commercial Service
Volovar	Dena	Bechtel National Inc.
Voss	David	Solar Turbines Incorporated
Wachsman	Eric	University of Maryland
Wagener	Earl H.	Tetramer Technologies LLC
Wagner	Andrew	Mainstream Engineering Corporation
Wagner	Emanuel	Palamedes Strategies
Wagner	Eric	Technip Energies
Wagner	Hugo	Airbus
Wakabayashi	Makoto	Nissan Chemical America Corporation
Walker	David	American Bureau of Shipping
Walls	Christina	U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
Walters	Dennis	STARS Technology Corporation
Waltz	Kirk	American Bureau of Shipping
Wang	Conghua	TreadStone Technologies, Inc.
Wang	Hanson	University of California, Irvine
Wang	Heli	Phillips 66 Company
Wang	Liang	Toyota Research Institute of North America
Wang	Lucun	Idaho National Laboratory
Wang	Paul	Caterpillar Inc.
Wang	Shiyi	Lawrence Berkeley National Laboratory
Wang	Timothy	Numat Technologies
Wang	Weitian	University of Tennessee Space Institute
Wang	Wennie	University of Texas at Austin
Wang	Xiaojing	Los Alamos National Laboratory
Wang	Xiaoping	Argonne National Laboratory
Wang	Yan	Shell
Watanabe	Shuto	Daiwa Institute of Research Ltd.
Watson	Andrew	CleanInnoGen Energy Solutions Ltd.
Watson	Christine	U.S. Department of Energy

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Watts	Kenneth	Implevation, LLC
Weber	Adam	Lawrence Berkeley National Laboratory
Weber	Jorg	Exxon Mobil Corporation
Weber	Joseph	General Electric Company
Weeks	Brian	Gas Technology Institute
Wegeng	Robert	STARS Technology Corporation
Wehrle	Lukas	Karlsruhe Institute of Technology
Wei	Austin	Palo Alto Research Center
Weiland	Nathan	National Energy Technology Laboratory
Wein	Agatha	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
Weisenberger	Matthew	University of Kentucky
Weiser	Steven	Weiser Glass Solutions, LLC
Weismiller	Michael	U.S. Department of Energy
Welch	Kristin	Apex Clean Energy
Wells	Alexander	NGK Automotive Ceramics USA, Inc.
Wells	Nathan	Accenture
Welty	Anthony	Highly Innovative Fuels
Wendt	Daniel	Idaho National Laboratory
Wendt	Gregory	Siemens Energy AG
Wentlent	Luke	Plug Power Inc.
Westerhof	Katrina	National Grid
Westhoff	Casey	Umicore
Westlake	Brittany	Electric Power Research Institute
Westover	Tyler	Idaho National Laboratory
Wheeler	Robert	Sandia National Laboratories
Wheeler	Douglas	DJW Technology, LLC
Whitaker	Bruce	Clean Tech
White	Kristian	Bindus Manufacturing, LLC
White	Sean	Amentum Government Services Holding LLC
White	Trey	Hy Stor Energy LP
White	Zakar	Carnegie Mellon University
Wieliczko	Marika	U.S. Department of Energy

Last Name	First Name	Organization
Wiese	Morgan	Gaia Energy Research Institute LLC
Wiggins	Joseph	Katabasis, Inc.
Wiley	Kristine	Gas Technology Institute
Wiley	Kyle	Connector Labs
Wilkins	Paul	Bloom Energy
Willard	Linda	Dentons
Willats	Robin	FORVIA
Williams	Mark	KLS, Inc.
Williams	Seqen	Booz Allen Hamilton
Williams	Travis	University of Southern California
Wilson	Greg	JERA Americas Inc.
Wilson	Mark	Sandia National Laboratories
Winter	Dylan	Hexagon R&D, LLC
Wipke	Keith	National Renewable Energy Laboratory
Wirdak	Carl	Environmental Resources Management (ERM Group)
Wishart	Anna	Monolith Materials
Wissmiller	Derek	Gas Technology Institute
Wochner	David	K & L Gates LLP
Wolak	Frank	Fuel Cell and Hydrogen Energy Association
Wolden	Colin	Colorado School of Mines
Wolffe	Vaughn	
Wong	Elaine	National Australia Bank Limited
Wong	Robin	Lawrence Livermore National Laboratory
Wood	Brandon	Lawrence Livermore National Laboratory
Woods	Stephen	NASA White Sands Test Facility
Wooley	David	University of California, Berkeley
Wright	Kevin	ProtoGen, Inc.
Wright	Ruishu	National Energy Technology Laboratory
Wrigley	Krystal	Exxon Mobil Corporation
Wu	Fengping	Nulyzer Inc.
Wu	Gang	State University of New York at Buffalo
Wu	Tao	Southern Methodist University
Wulfert	David	Sandia National Laboratories

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Wyatt	Cat	The AES Corporation
Wycisk	Ryszard	Vanderbilt University
Wyman	Christine	Bracewell, LLP
Xia	Rong	University of Delaware
Xiao	Ryan	China Hydrogen Alliance Research Institute
Xie	Zhiqiang	University of Tennessee, Knoxville
Xing	Yangchuan	University of Missouri
Xu	Chao	Argonne National Laboratory
Xu	Hui	Giner, Inc.
Xu	Siguang	General Motors Company
Xue	ZhiJing	University of Virginia
Yadhati	Vennela	Ørsted A/S
Yamaguchi	Yuta	Mizuho Research & Technologies, Ltd.
Yamamoto	Atsushi	Toyota Motor Corporation
Yamano	Naoki	American Honda Motor Co., Inc.
Yamaya	Tim	3M Company
Yandrasits	Michael	Johnson Matthey Hydrogen Technologies, Ltd.
Yang	Bo	California Air Resources Board
Yang	Derek	Sinocat Environmental Technology Co., Ltd.
Yang	Fan	Plug Power Inc.
Yang	Jae Choon	Doosan FCP
Yang	Yong	Austin Power Engineering
Yang	Zhiwei (J.V.)	Raytheon Technologies Research Center
Yao	Yan	University of Houston
Yaremchuk	Kevin	GlobalBridge Solutions, LLC
Yasuda	Satoko	Associated General Contractors of America
Ye	Siyu	Guangzhou University
Yeang	Andrew	University of Colorado Boulder
Yellamilli	Sai	Hyzon Motors Inc.
Yelvington	Paul	Obantarla Corp.
Yi	Yaofan	Chevron
Yilmaz	Abdurrahman	Los Alamos National Laboratory
Yoo	Gyehyoung	ILJIN Hysolus Co., Ltd.

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Yoon	Songhak	Fraunhofer IWKS
Yoshida	Toshihiko	
Young	James	National Renewable Energy Laboratory
Young	John	Mitsubishi Heavy Industries America
Young	Ryan	Iowa Economic Development Authority
Young	Brian	Washington Department of Commerce
Yu	Haoran	Oak Ridge National Laboratory
Yu	Hongmei	Dalian Institute of Chemical Physics, Chinese Academy of Sciences
Yu	Paul	General Motors Company
Yu	Rick	Starwood Energy
Yu	Yang	Southern University of Science and Technology (SUSTech)
Yuan	Xiaozi	Nuclear Regulatory Commission
Yuh	Chao-Yi	FuelCell Energy, Inc.
Yüzügüllü	Elvin	Energetics
Zacharopoulos	Athanasios	Ministry of the Environment and Energy, Renewable Energy Sources and Alternative Fuels Directorate, Greece
Zachman	Michael	Oak Ridge National Laboratory
Zammataro	Frank	HydroCosm
Zelenay	Piotr	Los Alamos National Laboratory
Zeng	Yachao	State University of New York at Buffalo
Zhai	Shang	Ohio State University
Zhai	Yunfeng	University of Hawaii
Zhang	Ao	University of California, Los Angeles
Zhang	Bingzhang	State University of New York at Buffalo
Zhang	Feng-Yuan	University of Tennessee
Zhang	Jiaqi	Shell
Zhang	Jing	Schlumberger Limited
Zhang	Kun	Shell
Zhang	Qi	Indiana University–Purdue University Indianapolis
Zhang	Tianyu	Giner, Inc.
Zhang	Wenlin	Schlumberger Limited
Zhang	Yunzhu	General Motors Company
Zhang	Zhifeng	Air Liquide

Last Name	First Name	Organization
Zhao	Li	California Plug Load Research Center
Zhao	Nana	Nuclear Regulatory Commission
Zhao	Xueru	Brookhaven National Laboratory
Zhao	Zeyu	Idaho National Laboratory
Zheng	Xueli (Sherry)	Stanford University
Zhou	Meng	New Mexico State University
Zhou	Michelle	Hyundai Motor Group
Zhou	Xiao-Dong	University of Louisiana at Lafayette
Zhu	Gaohua	Toyota Motor Corporation
Zhu	Guangqi	Indiana University–Purdue University Indianapolis
Zhu	Paul	Chongqing Dubail Import & Export Trading Company
Zhu	Tianli	Raytheon Technologies Research Center
Zhu	Yujie	Xerox Holdings Corporation
Ziec	Irena	BP p.l.c.
Zinn	William	Trane Technologies
Zokoe	James	Cummins Inc.
Zulevi	Barr	Pajarito Powder
Zunner	Lauren	Johnson Matthey Hydrogen Technologies, Ltd.

Appendix C: 2022 AMR Hydrogen Program Review Questions

Dear Hydrogen Program Reviewer: We appreciate your input on the U.S. Department of Energy (DOE) Hydrogen Program and subprograms. 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.

For each question you answer, please provide comments (as applicable) on the overall Hydrogen Program (including activities in the Office of Energy Efficiency and Renewable Energy [EERE], Office of Fossil Energy and Carbon Management, Office of Science, Office of Nuclear Energy, and ARPA-E) as well as the subprogram/activity areas in the EERE Hydrogen and Fuel Cell Technologies Office (HFTO). (Note: Hydrogen Technologies includes activities in hydrogen production, delivery/infrastructure, and storage. Technology Acceleration includes technology demonstrations/validation, manufacturing research and development [R&D], and market transformation activities.)

Please refer to the AMR's plenary program for overview presentations on the overall DOE Hydrogen Program. Information on specific research, development, demonstration, and deployment (RDD&D) subprograms and activities being carried out by different offices within DOE can be found in the plenary, oral, and poster AMR presentations—see the "AMR Reviewer Information" email sent to you for a list of relevant presentations.

1a. The Hydrogen Program and strategy were clearly articulated and well-aligned with mission and goals of the National Clean Hydrogen Strategy 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
Score	

Comments:

1b. Were the important challenges to meeting goals identified, and were plans to address the challenges articulated?

Comments:

2. The Hydrogen Program is aligned well with industry and stakeholder needs and is appropriate given complementary private-sector, state, and other non-DOE investments.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion.

	Hydrogen Program Overall
Score	

Comments: Please describe any areas that you feel are not well aligned with industry needs or that require more (or less) federal funding support.

3. The Hydrogen Program is collaborating with and gathering feedback from appropriate groups of stakeholders, including those with a focus on workforce development and justice, equity, diversity, and inclusion.

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
Score	

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.

4. 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 R&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 Overall
Score	

Comments: Please describe any over- or under-represented areas, including any gaps in the portfolio or any comments you may have on whether funding levels in each area are appropriate.

5a. The subprograms of HFTO have clearly articulated their missions and strategies and have appropriate goals, milestones, and quantitative metrics.

For the HFTO subprogram(s) you are evaluating, 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 Technologies	Fuel Cell Technologies	Technology Acceleration	Safety, Codes and Standards	Systems Analysis
Score					

Comments:

5b. Were the important challenges to meeting these goals identified, and were plans to address the challenges articulated?

Comments:

6. HFTO subprograms are effectively fostering innovation and advancing the state of technology for hydrogen and fuel cell technologies to be competitive and achieve widespread commercialization and adoption by industry.

For the HFTO subprogram(s) you are evaluating, 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 Technologies	Fuel Cell Technologies	Technology Acceleration	Safety, Codes and Standards	Systems Analysis
Score					

Comments: Please include recommendations on any novel or innovative ways to address the challenges and achieve the Hydrogen Program goals, including the challenge to meet the Hydrogen Shot production cost goal of $1 per kilogram of hydrogen in 1 decade.

7. The HFTO subprogram’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 R&D.

For the HFTO subprogram(s) you are evaluating, 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 Technologies	Fuel Cell Technologies	Technology Acceleration	Safety, Codes and Standards	Systems Analysis
Score					

Comments: Please describe any over- or under-represented areas, including any gaps in the portfolio or any comments you may have on whether funding levels in each area are appropriate.

8. 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:

9. Do you have any comments or recommendations on the Hydrogen Program’s research consortia approach for conducting laboratory-supported research (e.g., H2NEW, M2FCT, HydroGEN, HyMARC, ElectroCat, and H-Mat)? Please state what is working effectively and areas that may benefit from further improvement.

Comments:

10. Is the Hydrogen Program sufficiently incorporating a diversity of approaches for improving justice, equity, diversity, and inclusion in the execution and impacts of its RDD&D activities (e.g., multi-disciplinary approaches to project/research design, demographic diversity in project input and execution, diversity in geographic applications/impact of research efforts)? Please provide any recommendations for additional approaches or strategies the Hydrogen Program can employ.

Comments:

11. Is the Hydrogen Program doing enough to advance goals for workforce development and science, technology, engineering, and mathematics (STEM) education? How can we build on and/or adjust our current portfolio to accomplish our goals in workforce development and STEM?

Comments:

12. Please comment on the overall effectiveness, strengths, or weaknesses of the Hydrogen Program or the individual subprograms and provide any additional suggestions you may have for improvement. Do any of the projects, subprograms, or activities stand out as particularly strong or weak (and if so, why?)

Comments: Please include comments or recommendations on how the Hydrogen Program can better coordinate RDD&D among DOE offices (Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy and Carbon Management, Office of Nuclear Energy, Office of Science, ARPA-E, Office of Electricity, Office of Clean Energy Demonstrations).

13. Do you have any specific comments on the Hydrogen Program's plans for the funding provided under the Bipartisan Infrastructure Law (BIL) for (1) Regional Clean Hydrogen Hubs, (2) Clean Hydrogen Electrolysis Program, or (3) Clean Hydrogen Manufacturing and Recycling?

Comments:

14. Based on DOE's hydrogen activities, and given the BIL funding across the RDD&D spectrum, how likely do you think it is that:

a) **Hydrogen Shot will be achieved ($1/kg clean H_2 by 2031)?***

	10 – very likely 1 – not likely
Score	

b) **The BIL target of $2/kg clean H_2 will be achieved by 2026?***

	10 – very likely 1 – not likely
Score	

** Note: these are modeled levelized costs of production only, at high volumes (e.g., gigawatt-scale).*

Appendix D. List of Projects

Oral Presentations

Project ID	Project Title	Principal Investigator Name	Organization
ARPAE-001	Co-Synthesis of Hydrogen and High-Value Carbon Products from Methane Pyrolysis	Matteo Cargnello	Stanford University
ARPAE-002	High-Power-Density Carbon-Neutral Electrical Power Generation for Air Vehicles	Rory Roberts	Tennessee Technological University
BES-001	Electrocatalysis in Alkaline Media at the Center for Alkaline-Based Energy Solutions (CABES)	Hector “Tito” Abruńa	Cornell University
BES-002	Critical Importance of Renewable Hydrogen for Carbon-Neutral Carbon Dioxide Conversion	Jingguang Chen	Columbia University
FC-160	ElectroCat 2.0 (Electrocatalysis Consortium)	Deborah Myers and Piotr Zelenay	Argonne National Laboratory and Los Alamos National Laboratory
FC-167	Fiscal Year 2020 Small Business Innovation Research (SBIR) IIA: Multi-Functional Catalyst Support	Minette Ocampo	pH Matter, LLC
FC-323	Durable Fuel Cell Membrane Electrode Assembly through Immobilization of Catalyst Particle and Membrane Chemical Stabilizer	Nagappan Ramaswamy	General Motors, LLC
FC-326	Durable Membrane Electrode Assemblies for Heavy-Duty Fuel Cell Electric Trucks	John Slack	Nikola Motor Company
FC-327	Durable High-Power-Density Fuel Cell Cathodes for Heavy-Duty Vehicles	Shawn Litster	Carnegie Mellon University
FC-333	Advanced Membranes for Heavy-Duty Fuel Cell Trucks	Andrew Barker	Nikola Motor Company
FC-334	Extending Perfluorosulfonic Acid Membrane Durability through Enhanced Ionomer Backbone Stability	Gregg Dahlke	3M Company
FC-335	Additive Functionalized Polymers for Extended Heavy-Duty Polymer Electrolyte Membrane Lifetimes	Tom Corrigan	The Lubrizol Corporation
FC-336	A Systematic Approach to Developing Durable, Conductive Membranes for Operation at 120°C	Tom Zawodzinski	University of Tennessee, Knoxville

Project ID	Project Title	Principal Investigator Name	Organization
FC-337	Cummins Polymer Electrolyte Membrane Fuel Cell System for Heavy-Duty Applications	Jean St-Pierre	Cummins Inc.
FC-338	Domestically Manufactured Fuel Cells for Heavy-Duty Applications	John Lawler	Plug Power Inc.
FC-339	M2FCT: Million Mile Fuel Cell Truck Consortium	Rod Borup and Adam Weber	Los Alamos National Laboratory and Lawrence Berkeley National Laboratory
FC-353	Fuel Cell Cost and Performance Analysis	Brian James	Strategic Analysis, Inc.
FC-354	L'Innovator Program	Emory De Castro	Advent Technologies
FC-356	Fiscal Year 2021 Small Business Innovation Research (SBIR) I: Durable High-Efficiency Membrane and Electrode Assemblies for Heavy-Duty Fuel Cell Vehicles	Hui Xu	Giner, Inc.
FE-001	Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA)	Angela Goodman, Joshua White, and Nicolas Huerta	National Energy Technology Laboratory, Lawrence Livermore National Laboratory, and Pacific Northwest National Laboratory
FE-002	A Highly Efficient and Affordable Hybrid System for Hydrogen and Electricity Production	Ying Liu	Phillips 66 Company
FE-003	Performance Improvements for Reversible Solid Oxide Fuel Cell Systems	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.
FE-004	Performance Validation of a Thermally Integrated 50 kW High-Temperature Electrolyzer System	Tyler Westover	Idaho National Laboratory
FE-005	Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies	Eric Lewis	National Energy Technology Laboratory
IA-001	H2@Rescue: Design and Deployment of Polymer Electrolyte Membrane Fuel Cell–Battery-Powered Hybrid Emergency Relief Truck	Archit Koti	Cummins Inc.
IN-015	Optimizing the Heisenberg Vortex Tube for Hydrogen Cooling	Jacob Leachman	Washington State University

Project ID	Project Title	Principal Investigator Name	Organization
IN-016	Free-Piston Expander for Hydrogen Cooling	Devin Halliday	Gas Technology Institute
IN-034	HyBlend: Pipeline Cooperative Research and Development Agreement Cost and Emissions Analysis	Mark Chung	National Renewable Energy Laboratory
IN-035	HyBlend: Pipeline Cooperative Research and Development Agreement Materials Research and Development	Chris San Marchi	Sandia National Laboratories
NE-001	Dynamic Nuclear Thermal Energy Integration for High-Temperature Electrolysis	Shannon Bragg-Sitton	Idaho National Laboratory
NE-002	Nuclear Hydrogen and Synthetic Diesel and Jet Fuel	Amgad Elgowainy and Richard Boardman	Argonne National Laboratory and Idaho National Laboratory
P-148	HydroGEN Overview: A Consortium on Advanced Water-Splitting Materials	Huyen Dinh	National Renewable Energy Laboratory
P-196	H2NEW Consortium: Hydrogen from Next-Generation Electrolyzers of Water	Bryan Pivovar and Richard Boardman	National Renewable Energy Laboratory and Idaho National Laboratory
P-197	Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzer Oxygen Evolution Reaction Catalysts and Electrodes	Andrew Steinbach	3M Company
P-198	Enabling Low-Cost Polymer Electrolyte Membrane Electrolysis at Scale Through Optimization of Transport Components and Electrode Interfaces	Chris Capuano	Nel Hydrogen
P-199	Integrated Membrane Anode Assembly and Scale-Up	Monjid Hamdan	Plug Power Inc.
SA-174	Life Cycle Analysis of Hydrogen Pathways	Amgad Elgowainy	Argonne National Laboratory
SA-175	Regional Hybrid Energy Systems Technoeconomic Analysis	Mark Ruth	National Renewable Energy Laboratory
SA-181	Global Change Analysis Model Expansion – Hydrogen Pathways	Page Kyle	Pacific Northwest National Laboratory
SA-182	Biomass Gasification Optimal Business Case Analysis Tool	Bridger Cook	Oregon State University

Project ID	Project Title	Principal Investigator Name	Organization
SA-183	H2X: A Tool to Run Green Hydrogen Business Analysis Scenarios in Seconds	Sharun Kumar	University of California, Berkeley
SA-185	Hydrogen Business Appraisal Tool	Nicolas Alfonso Vargas	University of Southern California
SCS-010	Research and Development for Safety, Codes and Standards: Hydrogen Behavior	Ethan Hecht	Sandia National Laboratories
SCS-011	Hydrogen Quantitative Risk Assessment	Brian Ehrhart	Sandia National Laboratories
SCS-019	Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources	Nick Barilo	Pacific Northwest National Laboratory
SCS-021	National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory	William Buttner	National Renewable Energy Laboratory
SCS-028	Hydrogen Education for a Decarbonized Global Economy (H2EDGE)	Thomas Reddoch	Electric Power Research Institute
ST-236	Low-Cost, High-Performance Carbon Fiber for Compressed Natural Gas Storage Tanks	Xiaodong Li	University of Virginia
ST-237	Carbon Composite Optimization Reducing Tank Cost	Dylan Winter	Hexagon R&D LLC
ST-238	Low-Cost, High-Strength Hollow Carbon Fiber for Compressed Gas Storage Tanks	Matthew Weisenberger	University of Kentucky
ST-239	Melt-Spun Polyacrylonitrile Precursor for Cost-Effective Carbon Fibers in High-Pressure Compressed Gas Tankage	Erin Brophy	Collaborative Composite Solutions Corporation
ST-240	Cost-Optimized Structural Carbon Fiber for Hydrogen Storage Tanks	Amit Naskar	Oak Ridge National Laboratory
ST-241	First Demonstration of a Commercial-Scale Liquid Hydrogen Storage Tank Design for International Trade Applications	Jo-Tsu Liao	Shell
TA-001	Membrane Electrode Assembly Manufacturing Research and Development	Michael Ulsh	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
TA-018	High-Temperature Electrolysis Test Stand	Micah Casteel	Idaho National Laboratory
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
TA-037	Demonstration and Framework for H2@Scale in Texas and Beyond	Rich Myhre	Frontier Energy, Inc.
TA-039	Solid Oxide Electrolysis System Demonstration	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.
TA-043	Electrolyzer Stack Development and Manufacturing	Olga Marina	Pacific Northwest National Laboratory
TA-044	System Demonstration for Supplying Clean, Reliable, and Affordable Electric Power to Data Centers using Hydrogen Fuel	Paul Wang	Caterpillar, Inc.
TA-045	Waterfront Maritime Hydrogen Demonstration Project	Narendra Pal	Hornblower Group
TA-048	Advanced Research on Integrated Energy Systems (ARIES) / Flatirons Facility – Hydrogen System Capability Buildout	Daniel Leighton	National Renewable Energy Laboratory
TA-049	High-Pressure, High-Flow-Rate Dispenser and Nozzle Assembly for Heavy-Duty Vehicles	Spencer Quong	Electricore Inc.
TA-051	Low Total Cost of Hydrogen by Exploiting Offshore Wind and Polymer Electrolyte Membrane Electrolysis Synergies	Hui Xu	Giner, Inc.
TA-052	Solid Oxide Electrolysis Cells Integrated with Direct Reduced Iron Plants for Producing Green Steel	Jack Brouwer	University of California, Irvine
TA-053	Grid-Interactive Steelmaking with Hydrogen	Ronald Omalley	Missouri University of Science and Technology
TA-054	Anion Exchange Membrane Water Electrolyzer for Hydrogen Production from Offshore Wind	Richard Masel	Alchemr, Inc.
TA-060	U.S. Wind-to-Hydrogen Modeling, Analysis, Testing, and Collaboration	Sam Sprik	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
TA-065	Total Cost of Ownership Analysis of Hydrogen Fuel Cells in Off-Road Heavy-Duty Applications – Preliminary Results	Rajesh Ahluwalia	Argonne National Laboratory

Poster Presentations

Project ID	Project Title	Principal Investigator Name	Organization
AMO-000	Advanced Manufacturing Office Overview of Hydrogen-Related Activities	Joe Cresko	U.S. Department of Energy, Advanced Manufacturing Office
AMO-001	Flexible Natural Gas/Hydrogen Engine for Combined Heat and Power Applications	Jaswinder Singh	Caterpillar, Inc.
AMO-002	Smart Gas Quality Sensor for HyBlends in Support of Combined Heat and Power Demonstration in District Energy Systems	Sreenath Gupta	Argonne National Laboratory
ARPAE-000	ARPA-E Hydrogen and Fuel Cell Portfolio	Grigorii Soloveichik	U.S. Department of Energy, Advanced Research Projects Agency – Energy
ARPAE-003	A Hybrid Electrochemical and Catalytic Compression System for Direct Generation of High-Pressure Hydrogen at 700 bar	Chengxiang Xiang	California Institute of Technology
ARPAE-004	Solid Oxide Fuel Cell–Turbine Hybrid Power System	Scott Swartz	Nexceris, LLC
ARPAE-005	Adaptive Solid Oxide Fuel Cell for Ultra-High-Efficiency Systems	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.
ARPAE-006	Micro-Hybrid Development with Enabling Controls	David Tucker	National Energy Technology Laboratory
ARPAE-007	Metal-Supported Solid Oxide Fuel Cells for Ethanol-Fueled Vehicles	Mike Tucker	Lawrence Berkeley National Laboratory
ARPAE-008	Hybrid Solid Oxide Fuel Cell–Turbogenerator for Aircraft	Chris Cadou	University of Maryland
ARPAE-009	Ammonia: Key to Expanding Deployment and Utilization of Green Hydrogen	Colin Wolden	Colorado School of Mines

Project ID	Project Title	Principal Investigator Name	Organization
ARPAE-010	Carbon-Dioxide-Free Hydrogen and Solid Carbon from Natural Gas via Metal Salt Intermediates	Jonah Erlebacher	Johns Hopkins University
ARPAE-011	Channeling Engineering of Hydroxide Ion Exchange Polymers and Reinforced Membranes	Chulsung Bae	Rensselaer Polytechnic Institute
ARPAE-012	Bipolar Membranes with an Electrospun Three-Dimensional Junction	Peter Pintauro	Vanderbilt University
ARPAE-013	High-Efficiency and Low-Carbon Energy Storage and Power Generation System for Electric Aviation	Nguyen Minh	University of California, San Diego
BES-000	Office of Basic Energy Sciences Overview of Hydrogen-Related Activities	John Vetrano	U.S. Department of Energy, Office of Science
FC-170	ElectroCat: Durable Manganese-Based Platinum-Group-Metal-Free Catalysts for Polymer Electrolyte Membrane Fuel Cells	Hui Xu	Giner, Inc.
FC-172	ElectroCat: Highly Active and Durable Platinum-Group-Metal-Free Oxygen Reduction Reaction Electrocatalysts through the Synergy of Active Sites	Yuyan Shao	Pacific Northwest National Laboratory
FC-304	ElectroCat: Fuel Cell Membrane Electrode Assemblies with Platinum-Group-Metal-Free Nanofiber Cathodes	Peter Pintauro	Vanderbilt University
FC-307	Cyclic Olefin Copolymer-Based Alkaline Exchange Polymers and Reinforced Membranes	Chulsung Bae	Rensselaer Polytechnic Institute
FC-308	Advanced Anion Exchange Membranes with Tunable Water Transport for Platinum-Group-Metal-Free Anion Exchange Membrane Fuel Cells	Michael Hickner	The Pennsylvania State University
FC-309	Polymerized Ionic Liquid Block Co-Polymer/Ionic Liquid Composite Ionomers for High-Current-Density Performance	Joshua Snyder	Drexel University
FC-314	Efficient Reversible Operation and Stability of Novel Solid Oxide Cells	Scott Barnett	Northwestern University
FC-317	Stationary Direct Methanol Fuel Cells Using Pure Methanol	Xianglin Li	University of Kansas
FC-328	Fiscal Year 2019 Small Business Innovation Research (SBIR) II: Novel Fluorinated Ionomer for Polymer Electrolyte Membrane Fuel Cells	Hui Xu	Giner, Inc.

Project ID	Project Title	Principal Investigator Name	Organization
FC-330	High-Efficiency Reversible Solid Oxide System	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.
FC-331	A Novel Stack Approach to Enable High Round-Trip Efficiencies in Unitized Polymer Electrolyte Membrane Regenerative Fuel Cells	Katherine Ayers	Nel Hydrogen
FC-332	Reversible Fuel Cell Cost Analysis	Max Wei	Lawrence Berkeley National Laboratory
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
FC-343	Fiscal Year 2020 Small Business Innovation Research (SBIR) II: Improved Ionomers and Membranes for Fuel Cells	Chris Topping	Tetramer Technologies, LLC
FC-344	Low-Cost Corrosion-Resistant Coated Aluminum Bipolar Plates by Elevated Temperature Formation and Diffusion Bonding	J.V. Yang	Raytheon Technologies Research Center
FC-345	Development and Manufacturing for Precious-Metal-Free Metal Bipolar Plate Coatings for Polymer Electrolyte Membrane Fuel Cells	CH Wang	Treadstone Technologies, Inc.
FC-346	Fully Unitized Fuel Cell Manufactured by a Continuous Process	Jon Owejan	Plug Power Inc.
FC-347	Development of Low-Cost Thin Flexible Graphite Bipolar Plates for Heavy-Duty Fuel Cell Applications	David Chadderdon	NeoGraf Solutions, LLC
FC-348	Fuel Cell Bipolar Plate Technology Development for Heavy-Duty Applications	Siguang Xu	General Motors, LLC
FC-349	Foil-Bearing-Supported Compressor–Expander	Giri Agrawal	R&D Dynamics Corporation
FC-350	High-Efficiency and Transient Air Systems for Affordable Load-Following Heavy-Duty Truck Fuel Cells	Doug Hughes	Eaton Corporation
FC-351	Durable and Efficient Centrifugal Compressor-Based Filtered Air Management System and Optimized Balance of Plant	Mike Bunce	Mahle Powertrain, LLC

Project ID	Project Title	Principal Investigator Name	Organization
FC-352	Leveraging Internal Combustion Engine Air System Technology for Fuel Cell System Cost Reduction	Rich Kruiswyk	Caterpillar, Inc.
FC-355	Los Alamos National Laboratory Minority-Serving Institution Program	Tommy Rockward	Los Alamos National Laboratory
FC-357	Fiscal Year 2021 Small Business Innovation Research (SBIR) I: Nanocoating for Increased Nafion Membrane Durability and Efficiency	Corey Staller	Celedyne Technologies, Inc.
FC-358	Fiscal Year 2021 Small Business Innovation Research (SBIR) I: Fine Gradient Electrode and Microporous Layer Structures for Improved Heavy-Duty Fuel Cells	Barr Zulevi	Pajarito Powder, LLC
FC-359	Fiscal Year 2021 Small Business Technology Transfer (STTR) I: Optimizing Liquid Free Ionomer Binders for High-Temperature Polymer Electrolyte Membrane Fuel Cells for Heavy-Duty Vehicles	Chris Arges	Ionomer Solutions, LLC
FC-360	Fiscal Year 2021 Small Business Technology Transfer (STTR) I: Development of a Direct Fuel Cell for the Perhydrodibenzyltoluene/Dibenzyltoluene Fuel Pair	Guido Pez	Energy 18H, LLC
FE-000A	Hydrogen with Carbon Management Program – Program Overview	Bob Schrecengost	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
FE-000B	Natural Gas Decarbonization and Hydrogen Technologies Program – Program Overview	Evan Frye	U.S. Department of Energy, Office of Fossil Energy and Carbon Management
FE-007	Geographical Assessment of Natural Gas Infrastructure and Pipeline Materials for Blended Gas Transport	Yarom Polsky	Oak Ridge National Laboratory
FE-008	Progress on Natural Gas Pyrolysis for Low-Carbon Hydrogen Production	Daniel Haynes	National Energy Technology Laboratory
FE-009	Optical Fiber Sensor Technologies for Subsurface Hydrogen Storage Monitoring	Ruishu Wright	National Energy Technology Laboratory
H2-041	H2@Scale Cooperative Research and Development Agreement: California Research Consortium (Reference Station, Fueling Performance Test Device, Station Capacity Model)	Sam Sprik	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
H2-056	Hydrogen Safety Outreach to Expedite Hydrogen Fueling and Energy Project Deployment and Promote Public Acceptance for Zero-Emission Vehicles and Reliable Distributed Power Generation	Nick Barilo	Pacific Northwest National Laboratory
H2-057	Electrolyzer–Bioreactor Integration	Kevin Harrison	National Renewable Energy Laboratory
H2-059	Electrolytic Renewable Fuel Production Optimal Operation Investigation	Omar Guerra	National Renewable Energy Laboratory
H2-060	Hydrogen Blending into Natural Gas Pipelines	Chris San Marchi	Sandia National Laboratories
H2-061	Innovating Hydrogen Stations: Heavy-Duty Fueling	Shaun Onorato	National Renewable Energy Laboratory
IN-001a	Hydrogen Materials Consortium (H-Mat) Overview: Metals	Chris San Marchi	Sandia National Laboratories
IN-001b	Hydrogen Materials Consortium (H-Mat) Overview: Polymers	Kevin Simmons	Pacific Northwest National Laboratory
IN-004	Magnetocaloric Hydrogen Liquefaction	John Barclay	Pacific Northwest National Laboratory
IN-014	Non-Destructive Evaluation Techniques for Pressure Vessels (Small Business Innovation Research [SBIR]): Detection of Micron-Scale Flaws through Nonlinear Wave Mixing	Marcus Grimes	Luna Innovations Inc.
IN-018	Heavy-Duty Compressor Development	Kathy Ayers	Nel Hydrogen
IN-019	Ultra-Cryopump for High-Demand Transportation Fueling	Kyle Gross	RotoFlow
IN-020	Self-Healable Copolymer Composites for Extended-Service Hydrogen-Dispensing Hoses	Marek Urban	Clemson University
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

Project ID	Project Title	Principal Investigator Name	Organization
IN-022	Tailoring Carbide-Dispersed Steels: A Path to Increased Strength and Hydrogen Tolerance	Gregory Thompson	The University of Alabama
IN-025	Argonne National Laboratory – Hydrogen Delivery Technologies Analysis	Amgad Elgowainy	Argonne National Laboratory
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
IN-029	Reducing the Cost of Fatigue Crack Growth Testing for Storage Vessel Steels in Hydrogen Gas	Kevin Nibur	Hy-Performance Materials Testing LLC
IN-030	Micro-Mechanically Guided High-Throughput Alloy Design Exploration towards Metastability-Induced Hydrogen Embrittlement Resistance	C. Cem Tasan	Massachusetts Institute of Technology
NE-000	Office of Nuclear Energy – Overview of Hydrogen-Related Activities	Jason Marcinkoski	U.S. Department of Energy, Office of Nuclear Energy
NE-003	High-Temperature Steam Electrolysis Process Performance and Cost Estimates	Dan Wendt	Idaho National Laboratory
NE-004	High-Temperature Electrolysis Stack Manufacturing Cost Estimation	Brian James	Strategic Analysis, Inc.
P-152	Proton-Conducting Solid Oxide Electrolysis Cells for Large-Scale Hydrogen Production at Intermediate Temperatures	Prabhakar Singh	University of Connecticut
P-154	Thin-Film, Metal-Supported High-Performance and Durable Proton-Solid Oxide Electrolyzer Cell	Tianli Zhu	Raytheon Technologies Research Center
P-170	Benchmarking Advanced Water-Splitting Technologies: Best Practices in Materials Characterization	Olga Marina	Pacific Northwest National Laboratory
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-179	BioHydrogen (BioH2) Consortium to Advance Fermentative Hydrogen Production	Katherine Chou	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
P-182	Binary Chloride Salts as Catalysts for Methane to Hydrogen and Graphitic Powder	Eric McFarland	C-Zero, LLC
P-183	Extremely Durable Concrete Using Methane Decarbonization Nanofiber Co-Products with Hydrogen	Alan W. Weimer	University of Colorado, Boulder
P-184	Scalable and Highly Efficient Microbial Electrochemical Reactor for Hydrogen Generation from Lignocellulosic Biomass and Waste	Hong Liu	Oregon State University
P-185	High-Performance Anion Exchange Membrane Low-Temperature Electrolysis with Advanced Membranes, Ionomers, and Platinum-Group-Metal-Free Electrodes	Paul A. 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	Emir Dogdibegovic	Nexceris, LLC
P-190	A Multifunctional Isostructural Bilayer Oxygen Evolution Electrode for Durable Intermediate-Temperature Electrochemical Water Splitting	Kevin Huang	University of South Carolina
P-191	Perovskite/Perovskite Tandem Photoelectrodes for Low-Cost Unassisted Photoelectrochemical Water Splitting	Yanfa Yan	The University of Toledo
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
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
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 (LTE): Durability and Accelerated Stress Test Development	Deborah Myers	Argonne National Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
P-196b	Hydrogen from Next-Generation Electrolyzers of Water (H2NEW) Low-Temperature Electrolysis (LTE): Benchmarking and Performance	Adam Weber	Lawrence Berkeley National Laboratory
P-196c	Hydrogen from Next-Generation Electrolyzers of Water (H2NEW) Low-Temperature Electrolysis (LTE): Manufacturing, Scale-Up, and Integration	Michael Ulsh	National Renewable Energy Laboratory
P-196d	Hydrogen from Next-Generation Electrolyzers of Water (H2NEW) Low-Temperature Electrolysis (LTE): System and Technoeconomic Analysis – Hydrogen from Next-Generation Electrolyzers	Mark Ruth	National Renewable Energy Laboratory
P-196e	Hydrogen from Next-Generation Electrolyzers of Water (H2NEW) High-Temperature Electrolysis (HTE): 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 (HTE): Cell Characterization	David Ginley	National Renewable Energy Laboratory
P-196g	Hydrogen from Next-Generation Electrolyzers of Water (H2NEW) High-Temperature Electrolysis (HTE): Multiscale Degradation Modeling	Brandon Wood	Lawrence Livermore National Laboratory
P-200	Low-Cost Manufacturing of High-Temperature Electrolysis Stacks	Scott Swartz	Nextech Materials, Ltd.
P-201	Automation of Solid Oxide Electrolyzer Cell and Stack Assembly	Todd Striker	Cummins Inc.
P-202	Novel Microbial Electrolysis Cell Design for Efficient Hydrogen Generation from Wastewaters	Bruce Logan	The Pennsylvania State University
P-203	Novel Microbial Electrolysis System for Conversion of Biowastes into Low-Cost Renewable Hydrogen	Noah Meeks	Southern Company Services, Inc.
P-204	Hydrogen Production Cost and Performance Analysis	Brian James	Strategic Analysis, Inc.
PRA-001	Formulation Strategies for the Large-Scale Manufacturing of Crack-Free Electrodes	Carlos Baez-Cotto	National Renewable Energy Laboratory
PRA-002	High-Performing and Durable Electrodes for Polymer Electrolyte Membrane Fuel Cells	ChungHyuk Lee	Los Alamos National Laboratory
PRA-003	Protonic Ceramic Electrochemical Cells for Hydrogen Production and Electricity Generation	Wenjuan Bian	Idaho National Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
PRA-004	Characterizing Hydrogen Storage Materials Using Neutron Scattering Techniques	Ryan Klein	National Renewable Energy Laboratory
SA-177	Analysis of Hydrogen Export Potential	Mark Chung	Argonne National Laboratory
SA-178	Cradle-to-Grave Transportation Analysis	Amgad Elgowainy	Argonne 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
SCS-001	Component Failure Research and Development	Kevin Hartmann	National Renewable Energy Laboratory
SCS-005	Research and Development for Safety, Codes and Standards: Materials and Components Compatibility	Joe Ronevich	Sandia National Laboratories
SCS-007	Fuel Quality Assurance Research and Development and Impurity Testing in Support of Codes and Standards	Tommy Rockward	Los Alamos National Laboratory
SCS-022	Fuel Cell and Hydrogen Energy Association Codes and Standards Support	Karen Quackenbush	Fuel Cell and Hydrogen Energy Association
SCS-030	MC [Total Heat Capacity] Formula Protocol for H35HF Fueling	Taichi Kuroki	National Renewable Energy Laboratory
SCS-031	Assessment of Heavy-Duty Fueling Methods and Components	Shaun Onorato	National Renewable Energy Laboratory
SCS-033	Risk Assessments of Design and Refueling for Hydrogen Locomotive and Tender	Brian Ehrhart	Sandia National Laboratories
SETO-000	Solar Energy Technologies Office Overview of Hydrogen-Related Activities	Avi Shultz	U.S. Department of Energy, Solar Energy Technologies Office
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	Matt Thornton	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
ST-127	Hydrogen Materials Advanced Research Consortium (HyMARC) Overview	Mark Allendorf	Sandia National Laboratories
ST-148	Novel Plasticized Melt Spinning Process of Polyacrylonitrile Fibers Based on Task-Specific Ionic Liquids	Sheng Dai	Oak Ridge National Laboratory
ST-202	Hydrogen Materials Advanced Research Consortium (HyMARC)— National Renewable Energy Laboratory Activities	Tom Gennett	National Renewable Energy Laboratory
ST-204	Hydrogen Materials Advanced Research Consortium (HyMARC)— Pacific Northwest National Laboratory Activities	Tom Autrey	Pacific Northwest National Laboratory
ST-207	Hydrogen Materials Advanced Research Consortium (HyMARC)— Lawrence Livermore National Laboratory Activities	Brandon Wood	Lawrence Livermore National Laboratory
ST-209	Hydrogen Materials Advanced Research Consortium (HyMARC) Seedling: Theory-Guided Design and Discovery of Materials for Reversible Methane and Hydrogen Storage	Omar Farha	Northwestern University
ST-210	Hydrogen Materials Advanced Research Consortium (HyMARC) Seedling: Metal–Organic Frameworks Containing Frustrated Lewis Pairs for Hydrogen Storage at Ambient Temperature	Shengqian Ma	University of South Florida
ST-211	Hydrogen Materials Advanced Research Consortium (HyMARC) Seedling: Optimal Adsorbents for Low-Cost Storage of Natural Gas and Hydrogen: Computational Identification, Experimental Demonstration, and System-Level Projection	Don Siegel	University of Michigan
ST-212	Hydrogen Materials Advanced Research Consortium (HyMARC) Seedling: Methane and Hydrogen Storage with Porous Cage-Based Composite Materials	Eric Bloch	University of Delaware
ST-213	Hydrogen Materials Advanced Research Consortium (HyMARC) Seedling: Uniting Theory and Experiment to Deliver Flexible Metal–Organic Frameworks for Superior Methane (Natural Gas) Storage	Brian Space	University of South Florida
ST-214	Hydrogen Materials Advanced Research Consortium (HyMARC) Seedling: Heteroatom-Modified and Compacted Zeolite-Templated Carbons for Gas Storage	Nicholas Stadie	Montana State University
ST-216	Hydrogen Materials Advanced Research Consortium (HyMARC) Seedling: Hydrogen Release from Concentrated Media with Reusable Catalysts	Travis Williams	University of Southern California

Project ID	Project Title	Principal Investigator Name	Organization
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	Hydrogen Materials Advanced Research Consortium (HyMARC) Seedling: High-Capacity Step-Shaped Hydrogen Adsorption in Robust, Pore-Gating Zeolitic Imidazolate Frameworks	Michael McGuirk	Colorado School of Mines
ST-222	Hydrogen Materials Advanced Research Consortium (HyMARC): Characterization of Hydrogen Storage Materials at Oak Ridge National Laboratory's Spallation Neutron Source	Anibal Ramirez-Cuesta	Oak Ridge National Laboratory
ST-224	Hydrogen Materials Advanced Research Consortium (HyMARC)—Lawrence Berkeley National Laboratory Activities	Jeffrey Long	Lawrence Berkeley National Laboratory
ST-225	Hydrogen Materials Advanced Research Consortium (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	Troy Semelsberger	Los Alamos National Laboratory
ST-243	FueL Additives for Solid Hydrogen (FLASH) Carriers for Electric Aviation	Steven Christensen	National Renewable Energy Laboratory
ST-244	Hydrogen Carriers for Renewable Energy Farm Application	Rajesh Ahluwalia	Argonne National Laboratory
TA-005	In-Line Quality Control of Polymer Electrolyte Membrane Materials	Andrew Wagner	Mainstream Engineering
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

Project ID	Project Title	Principal Investigator Name	Organization
TA-016	Fuel Cell Hybrid Electric Delivery Van	Jason Hanlin	Center for Transportation and the Environment
TA-017	Innovative Advanced Hydrogen Mobile Fueler	Sara Odom	Electricore Inc.
TA-027	Catalyst Layer Design, Manufacturing, and In-Line Quality Control	Radenka Maric	University of Connecticut
TA-035	Power Electronics for Electrolyzer Applications to Enable Grid Services	Robert Hovsapian	National Renewable Energy Laboratory
TA-041	Truck Duty Cycle Analysis	Jason Lustbader	National Renewable Energy Laboratory
TA-042	Next-Generation Hydrogen Station Analysis	Genevieve Saur	National Renewable Energy Laboratory
TA-050	Overall Research on Electrode Coating Processes (OREO)	Michael Ulsh	National Renewable Energy Laboratory
TA-056	Ultra-Efficient Long-Haul Hydrogen Fuel Cell Tractor	Derek Rotz	Daimler Trucks North America
TA-057	High-Efficiency Fuel Cell Application for Medium-Duty Truck Vocations	Stan Bower	Ford Motor Company
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	Kurt Wellenkotter	General Motors, LLC
TA-059	Medium-Duty Vehicle Total Cost of Ownership and Target Development	Ram Vijayagopal	Argonne National Laboratory
TA-061	Optimal Wind Turbine Design for Hydrogen Production	Chris Bay	National Renewable Energy Laboratory
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
TA-063	High-Efficacy Validation of Hydride Mega Tanks at the ARIES [Advanced Research on Integrated Energy Systems] Lab (HEVHY METAL)	Steven Christensen	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
TA-064	Hydrogen Production, Grid Integration, and Scaling for the Future	Sam Sprik	National Renewable Energy Laboratory
TA-066	In-Line Membrane Thickness Mapping with Real-Time Data Processing	Peter Rupnowski	National Renewable Energy Laboratory
WETO-000	Wind Energy Technologies Office Overview of Hydrogen-Related Activities	Jian Fu	U.S. Department of Energy, Wind Energy Technologies Office
WETO-001	Clusters of Flexible Photovoltaic–Wind–Storage Hybrid Generation (FlexPower)	Vahan Gevorgian	National Renewable Energy Laboratory
WPTO-000	Water Power Technologies Office Overview of Hydrogen-Related Activities	William McShane	U.S. Department of Energy, Water Power Technologies Office

Appendix E. Funding Opportunity Announcement Selections

This appendix lists Hydrogen Program Funding Opportunity Announcements (FOAs) and project selections, May 2021–November 2022.

Funding Selection Announcements

The U.S. Department of Energy (DOE) Hydrogen Program has announced the following funding selections since the 2021 Annual Merit Review.

- $52.5 million for 31 projects to accelerate progress in clean hydrogen, jointly funded by the Hydrogen and Fuel Cell Technologies Office (HFTO) and Office of Fossil Energy and Carbon Management (FECM) (July 7, 2021)
- $29 million for 15 projects to advance clean hydrogen production from biomass, blended feedstocks, and natural gas, funded by FECM (August 26, 2022)
- $25 million for 6 projects to develop technologies that will advance the use of clean hydrogen for electricity generation, funded by FECM (May 19, 2022)
- $20 million to demonstrate technology to produce clean hydrogen from nuclear power, jointly funded by HFTO and the Office of Nuclear Energy (NE) (October 7, 2021)
- Nearly $8 million for 9 national laboratory H2@Scale cooperative research and development (CRADA) projects to help reach Hydrogen Shot goals, funded by HFTO (October 6, 2021)
- $4.7 million for 6 projects to advance the development of ceramic-based materials to improve the efficiency of hydrogen-fueled turbines, funded by FECM (September 13, 2022)
- $1.5 million for 5 projects that will advance key clean hydrogen technologies while growing the skills and knowledge of science and engineering students at minority-serving institutions, funded by HFTO through an amendment to an FECM funding opportunity announcement (FOA) (November 10, 2022)
- $4.7 million for 2 concentrating solar thermal power projects that include hydrogen production, funded by the Solar Energy Technologies Office (SETO) (September 27, 2022)
- $76.8 million for 3 SuperTruck 3 projects to develop and demonstrate medium- and heavy-duty hydrogen fuel cell trucks, jointly funded by HFTO ($60 million) and the Vehicle Technologies Office (VTO) ($16.8 million) (November 1, 2021)
- $6.2 million for 8 University Turbines Systems Research projects focused on hydrogen combustion for gas turbines, funded by FECM (May 12, 2021)
- Funding for 11 hydrogen-related chemical and materials sciences research projects to advance clean energy technologies and low-carbon manufacturing, funded by the Basic Energy Sciences (BES) program (August 25, 2022)
- Funding for 1 hydrogen-related research project through the Energy Frontier Research Centers, funded by BES (August 25, 2022)
- Funding for 6 hydrogen-related Early Career Research Program projects in Fiscal Year (FY) 2022, funded by the Office of Science (n.d.)
- Funding for 2 hydrogen-related Early Career Research Program projects in FY 2021, funded by the Office of Science (May 26, 2021)

In addition, HFTO announced winning teams for H2 Twin Cities and Phase 1 winners of the Hydrogen Shot Incubator Prize, a $2.6 million competition to foster innovative concepts for producing clean hydrogen.

Table A-1. FY 2022 DOE Hydrogen-Related FOAs and Other Funding Opportunities[a]

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Hydrogen Shot and a University Research Consortium on Grid Resilience (DE-FOA-0002792)

- HydroGEN: Solar Fuels from Photoelectrochemical and Solar Thermochemical Water Splitting ($12.5 million)
- Development and Validation of Sensor Technology for Monitoring and Measuring of Hydrogen Losses ($8.0 million)
- Materials-Based Hydrogen Storage Demonstrations ($10.0 million)
- M2FCT: High-Performing, Durable, and Low-PGM [platinum group metal] Catalysts/Membrane Electrode Assemblies (MEAs) for Medium- and Heavy-Duty Applications ($10.0 million)
- University Research Consortium on Grid Resilience (URCGR) ($20.0 million[b])

HFTO FOA 2792 Announcement

H2 Twin Cities

H2 Twin Cities is a program under the Clean Energy Ministerial Clean Hydrogen Initiative to accelerate hydrogen progress by incentivizing the pairing of communities around the world to collaborate, share ideas, and learn from each other. These community-level partnerships between cities help connect activities where hydrogen and fuel cell technologies have energy, environmental, and economic benefits.

HFTO H2 Twin Cities Announcement

Selections

Hydrogen Shot Incubator Prize

The Hydrogen Shot Incubator Prize is a $2.6 million prize for identifying, developing, and testing disruptive technologies to reduce the cost of clean hydrogen production. The Prize supports the Hydrogen Energy Earthshot goal of achieving clean hydrogen production at $1/kg in one decade.

HFTO Hydrogen Shot Incubator Prize Announcement

Selections

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Fiscal Year 2022 Vehicle Technologies Office Program-Wide (DE-FOA-0002611)

Hydrogen-related topics include:

- Advanced Opposed Piston 2-Stroke (OP2S) Hydrogen Combustion Architecture for Heavy-Duty Transportation, Including On-Road and Non-Road (Off-Road, Rail, and Marine) Applications ($5.0 million)
- Innovative Medium- and Heavy-Duty Electric Vehicle (EV) Charging and Hydrogen Regional Fueling Corridor Infrastructure Plans ($2.5 million)
- Natural Gas Engine Demonstration for Non-Road, Including Off-Road, Rail, and Marine Applications ($5.0 million)

VTO FOA 2611 Announcement

Selections – Innovative Medium- and Heavy-Duty EV Charging and Hydrogen Regional Fueling Corridor Infrastructure Plans

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EERE AMO	**Industrial Efficiency and Decarbonization FOA (DE-FOA-0002804)** Hydrogen-related topics include: • Decarbonizing Iron and Steel • Decarbonizing Cement and Concrete AMO FOA 2804 Announcement
EERE SETO	**Concentrating Solar Thermal Power Fiscal Year 2022 Research, Development, and Demonstration (DE-FOA-0002630)** Hydrogen-related topics include: • Concentrating Solar Thermal for Industrial Decarbonization • Concentration Solar Thermal Particle Technologies for Generation 3 CSP [concentrating solar power] and Beyond (Gen3++) SETO FOA 2630 Announcement Selections
OCED	**Bipartisan Infrastructure Law: Regional Clean Hydrogen Hubs (DE-FOA-0002779)** Will fund 6–10 regional clean hydrogen hubs across the country, for a combined total of $6 billion to $7 billion dollars in federal funding. OCED FOA 2779 Announcement
NE	**Fiscal Year 2022 Consolidated Innovative Nuclear Research (DE-FOA-0002516)** Hydrogen-related topics include: • Implementation Consideration for Alternative Applications of Advanced Nuclear Reactors • Integrated Energy Systems • Developing the Technical Basis and Risk Assessment Tools for Flexible Plant Operation FOA 2516 Announcement **U.S. Industry Opportunities for Advanced Nuclear Technology Development (DE-FOA-0001817)** Hydrogen-related topics include: • Nuclear-Coupled Hydrogen Production and Use ($20 million–$40 million) o Nuclear Plant Thermal Integration o Hydrogen Coupled End Uses NE FOA 1817 Announcement

SC	**Chemical and Materials Sciences to Advance Clean Energy Technologies and Low-Carbon Manufacturing (DE-FOA-0002676)** Hydrogen-related topics include: • Carbon-Neutral Hydrogen • Solar-to-Hydrogen Conversion and Chemical-to-Hydrogen Conversion SC FOA 2676 Announcement SC FOA 2676 Project Selections **Energy Frontier Research Centers (DE-FOA-0002653)** Hydrogen-related topics include: • Carbon-Neutral Hydrogen • Solar-to-Hydrogen Conversion and Chemical-to-Hydrogen Conversion SC FOA 2653 Announcement SC FOA 2653 Project Selections **DOE Early Career Research Program for FY 2022 (DE-FOA-0002821)** SC FOA 2821 Announcement SC FOA 2821 Project Selections
FECM	**Advanced Energy Materials for Hydrogen Turbines for Stationary Power Generation (DE-FOA-2613)** • Benchmark of Ceramic Matrix Composite Performance with Predicative Modeling ($0.8 million) • Improvement to Temperature Performance of Ceramic Matrix Composite Materials ($3.9 million) FECM FOA 2613 Announcement FECM FOA 2613 Project Selections **Clean Hydrogen Production, Storage, Transport, and Utilization to Enable a Net-Zero Carbon Economy (DE-FOA-0002400)** • Clean Hydrogen Cost Reductions via Process Intensification and Modularization for Hydrogen Shot ($4.8 million) • Clean Hydrogen from High-Volume Waste Materials and Biomass ($4.8 million) • Sensors and Controls for Co-Gasification of Waste Plastics in Production of Hydrogen with Carbon Capture ($1.0 million) • Front-End Engineering Design Studies for Carbon Capture Systems at Domestic Industrial Facilities Producing Hydrogen from Natural Gas ($18.0 million) • Advanced Air Separation for Low-Cost Hydrogen Production via Modular Gasification ($5.0 million) • Clean Hydrogen Production and Infrastructure for Natural Gas Decarbonization (up to $21.0 million) • Technologies for Clean Hydrogen Production and Enabling the Safe and Efficient Transportation of Hydrogen Within the U.S. Natural Gas Pipeline System ($2.3 million)

	• Fundamental Research to Enable High-Volume, Long-Term Subsurface Hydrogen Storage ($6.0 million) FECM FOA 2400 Announcement **Fossil-Energy-Based Production, Storage, Transport, and Utilization of Hydrogen Approaching Net-Zero or Net-Negative Carbon Emissions (DE-FOA-0002400)** • Front-End Engineering Design Studies for Carbon Capture Systems at Domestic Industrial Facilities Producing Hydrogen from Natural Gas ($1.4 million) • Hydrogen Combustion Systems for Gas Turbines ($22.0 million) • Ammonia Combustion Systems for Gas Turbines ($6.0 million) FECM FOA 2400 Announcement FECM FOA 2400 Project Selections
FECM / HFTO	**University Training and Research for Fossil Energy and Carbon Management – Minority Serving Institutions (MSIs)[c] (DE-FOA-0002598)** • Hydrogen Storage Materials Development • PGM-Free Catalysts and Electrodes for Fuel Cells and Electrolyzers • Hydrogen Materials Compatibility – RD&D [research, development, and demonstration] and Knowledge and Gap Analysis • Decarbonization and Net-Zero Greenhouse Gas Emission Technology R&D [research and development] FECM/HFTO FOA 2598 Announcement
OTT	**Technology Commercialization Fund (TCF) Base Annual Appropriations National Laboratory Call** The Office of Technology Transitions (OTT) coordinated with the following DOE program offices to make funding available for 2022: the Office of Nuclear Energy; the Office of Electricity; and the Office of Energy Efficiency and Renewable Energy's Building Technologies Office, Geothermal Technologies Office, Hydrogen and Fuel Cell Technologies Office, Solar Energy Technologies Office, Water Power Technologies Office, and Wind Energy Technologies Office to make funding available. • Market Needs Assessment • Curation of Intellectual Property • Matchmaking • Streamlining Lab Processes and/or Requirements • Increasing Partnerships with External Commercialization Parties OTT TCF Announcement TCF Project Selections

[a] Funding shown reflects funds expected to be available; funding is subject to annual appropriations.

[b] The URCGR funding will support R&D for multiple technologies, including hydrogen-related technologies.

[c] For the topics shown here, HFTO contributed $1.5 million for an amendment to an existing FECM FOA.

Table A-2. FY 2021 DOE Hydrogen-Related FOAs[a]

EERE HFTO	**Hydrogen and Fuel Cell RD&D (DE-FOA-0002446)** • Fuel Cell R&D for Heavy-Duty Applications ($15 million) • Efficient and Innovative Hydrogen Production ($10 million) • High-Flow Fueling Applications ($7 million) • Cost and Performance Analysis for Fuel Cells, Hydrogen Production, and Hydrogen Storage ($4 million) HFTO FOA 2466 Announcement HFTO FOA 2446 Project Selections
EERE VTO	**SuperTruck 3 (DE-FOA-0002456)** • Joint SuperTruck FOA with VTO – anticipated HFTO funding of $60 million over five years ($5 million in FY 2021 and $15 million, pending appropriations, in FY 2022) VTO FOA 2456 Announcement VTO FOA 2456 Project Selections
FECM	**Fossil-Based Hydrogen Production, Transport, Storage and Utilization (DE-FOA-0002400; FECM with HFTO Collaboration)** • Solid Oxide Electrolysis Cell (SOEC) Technology Development for Hydrogen Production ($7 million) • Advanced Carbon Capture, Utilization, and Storage Systems ($4 million) • Hydrogen Combustion Systems for Gas Turbines – Industrial Class ($4.5 million) FECM FOA 2400 Announcement FECM FOA 2400 Project Selections **University Turbines Systems Research (UTSR) – Focus on Hydrogen Fuels** • Hydrogen Combustion Fundamentals for Gas Turbines ($3 million) • Hydrogen Combustion Applications for Gas Turbines ($2.4 million) • Hydrogen–Air Rotating Detonation Engines ($1.6 million) FECM FOA Project Selections
NE, EERE HFTO	**Hydrogen Production and End-Use Demonstration** • HFTO contribution: $12 million • NE contribution: $8 million NE/HFTO Project Selections
SC	**DOE Early-Career Research Program for FY 2022** SC Announcement SC Selection

[a] Funding shown reflects funds expected to be available; funding is subject to annual appropriations.