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

[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]

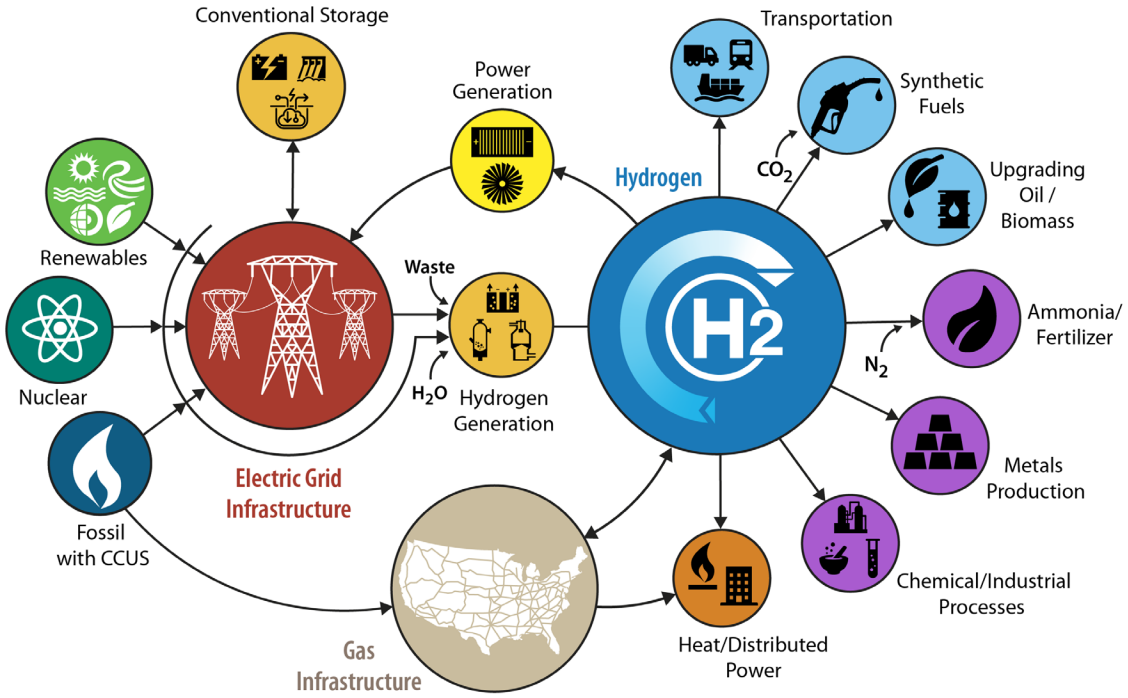

Figure 1. Schematic of H2@Scale

[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,

[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,

[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.

[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.

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[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.

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[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.