Introduction

The U.S. Department of Energy (DOE) Hydrogen Program Annual Merit Review and Peer Evaluation Meeting (AMR) consists of a detailed merit review and technical expert peer evaluation of the DOE Hydrogen and Fuel Cell Technologies Office (HFTO). The AMR also provides an overview of the entire DOE Hydrogen Program (the Program), which includes activities across multiple DOE offices, including Energy Efficiency and Renewable Energy (EERE), Fossil Energy and Carbon Management (FECM), Nuclear Energy (NE), Electricity (OE), Science (SC), the Loan Programs Office (LPO), the Office of Clean Energy Demonstrations (OCED), and the Advanced Research Projects Agency–Energy (ARPA-E). In addition, the AMR highlights relevant activities across other federal and state agencies involved in the field of hydrogen and fuel cells.

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

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

The goals of the AMR include the following:

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

Organization of the Report

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

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

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

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

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

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

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

Overview of the Hydrogen Program

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

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

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

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

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

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

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

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

Background: National Clean Hydrogen Strategy and H2@Scale

One of the key accomplishments in 2023 was publication of the ***U.S. National Clean Hydrogen Strategy and Roadmap***,[vii] a comprehensive national framework for accelerating large-scale production, processing, delivery, storage, and use of clean hydrogen to help meet bold decarbonization goals across virtually all sectors of the economy. Released June 5, 2023, following public review of a draft version, the *Strategy and Roadmap* was informed by extensive stakeholder feedback, and the document will be updated at least every three years, as required

by the BIL. The *Strategy and Roadmap* provides a snapshot of hydrogen production, transport, storage, and use in the United States today and examines future demand scenarios—with strategic opportunities to expand domestic production of clean hydrogen to 10 million metric tonnes (MMT) annually by 2030, 20 MMT annually by 2040, and 50 MMT annually by 2050. The *Strategy and Roadmap* prioritizes three key strategies to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool—see Figure 1.

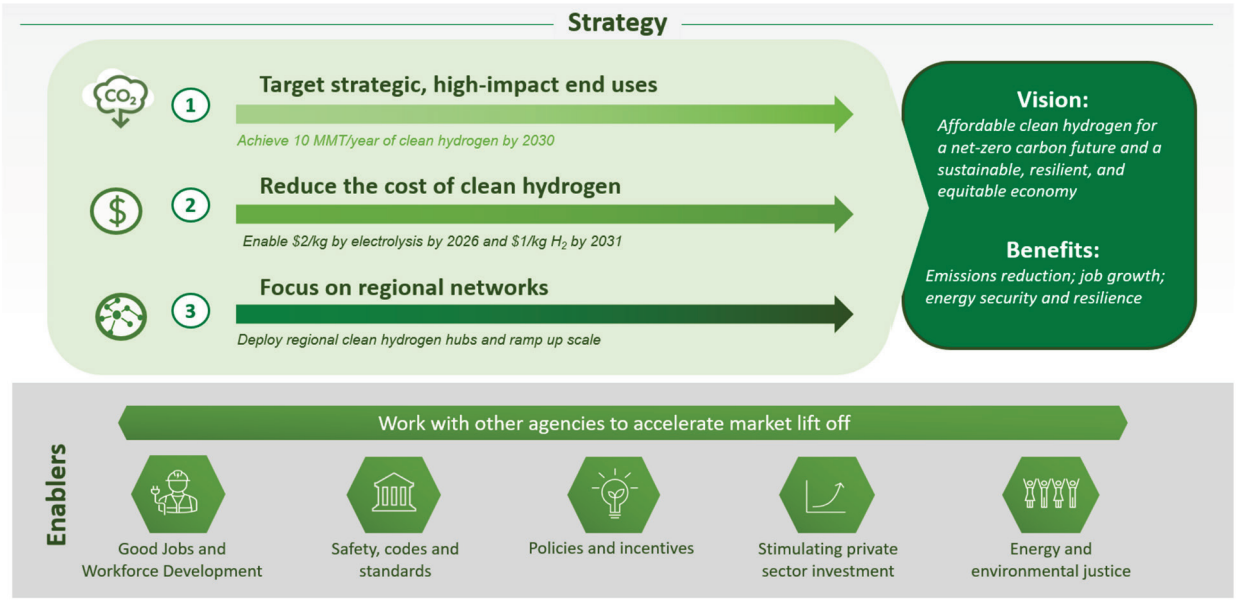

Figure 1. Strategies and key enablers for realizing the clean hydrogen vision

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

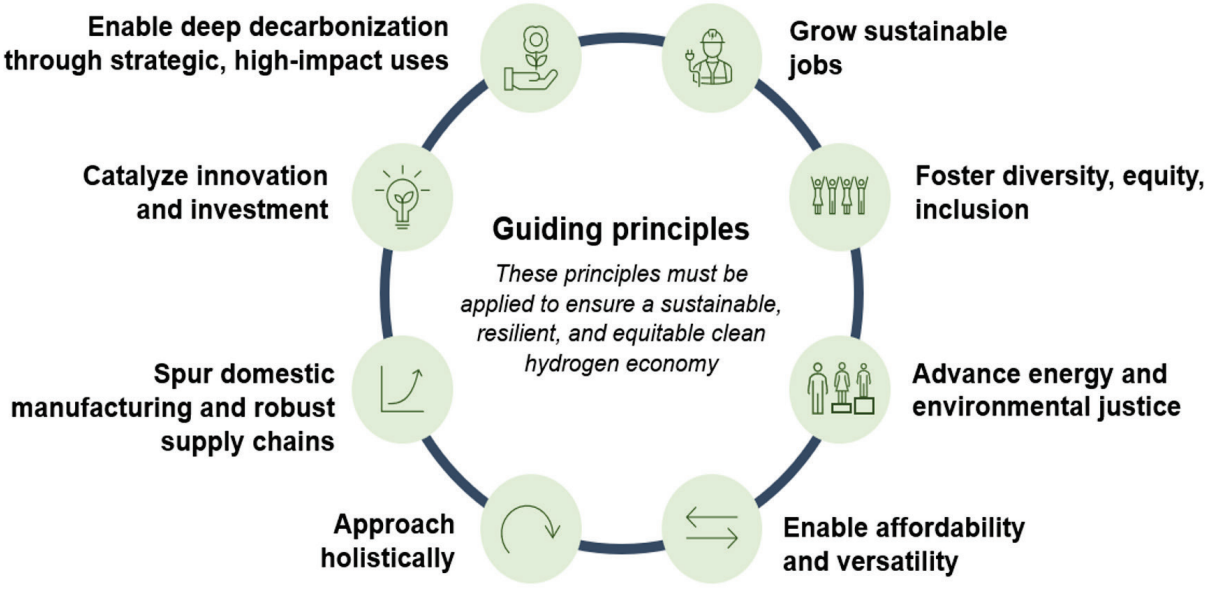

Figure 2. Eight guiding principles for the development of clean hydrogen production, transport, delivery, storage, and use

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

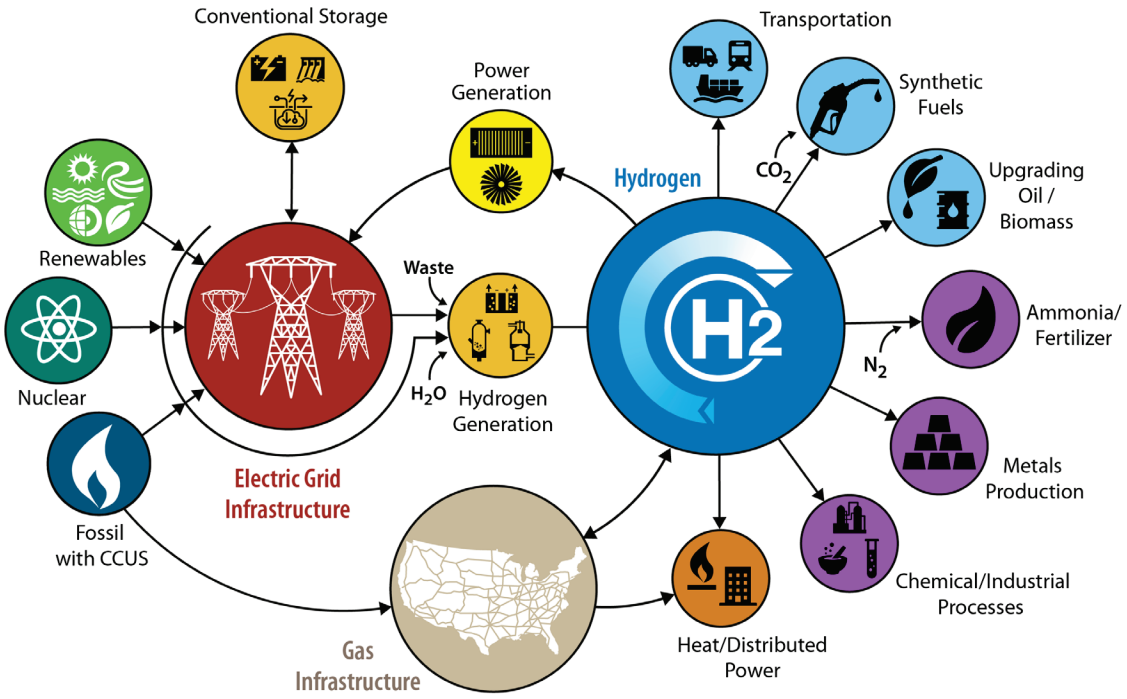

Figure 3. Schematic of H2@Scale

Program Highlights

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

Actions in Response to the Bipartisan Infrastructure Law

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

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

Hydrogen Shot and Related Developments

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

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

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

Inflation Reduction Act

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

Funding for Hydrogen and Fuel Cell RD&D

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

Hydrogen Project Recognitions

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

Reports, Program Records, and Tools

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

  - HFTO's "Progress in Hydrogen and Fuel Cells" fact sheet[xxiv] was updated to include the latest information on accomplishments achieved through HFTO efforts, including reducing cost and improving durability of fuel cells; advancing technologies for producing, delivering, and storing hydrogen; spurring deployments; and catalyzing innovation.
- **Program Records:** To document the source of key numbers and facts, the Program develops and publishes records that explain inherent assumptions, source data, and calculation methodologies. Four new Program records have been published since the 2022 AMR: *Heavy-Duty Fuel Cell System Cost–2022*, *Electrolyzer Installations in the United States*, *Historical Cost Reduction of PEM Electrolyzers,* and *PEM Electrolyzer Capacity Installations in the United States*. The full library of Program records (published since 2005) is available on the Program website.[xxv]

Workshops

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

Interagency Collaboration

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

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

International Collaboration

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

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

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

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

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

Recent international activities include the following:

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

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

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

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

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

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

Office Overviews and Updates

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

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

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

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

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

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

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

Hydrogen Production Technologies

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

Hydrogen Infrastructure Technologies

Hydrogen Storage

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

Hydrogen Infrastructure

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

Fuel Cell Technologies

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

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

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

Systems Development and Integration

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

Analysis, Codes and Standards

Systems Analysis

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

Safety, Codes and Standards

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

Workforce Development and Diversity, Equity, Inclusion, and Accessibility

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

Office of Clean Energy Demonstrations

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

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

Office of Fossil Energy and Carbon Management

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

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

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

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

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

Table 4. Selected Examples of FECM 2023 Progress and Accomplishments

Office of Resource Sustainability

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

Office of Carbon Management

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

Office of Nuclear Energy

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

Table 5. Selected Examples of NE 2023 Progress and Accomplishments

Projects in Collaboration with HFTO

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

Light Water Reactor Sustainability Program

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

Office of Science, Basic Energy Sciences

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

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

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

Advanced Research Projects Agency–Energy

In FY 2023, ARPA-E funding for hydrogen-related activities was more than $5 million across all programs. ARPA-E catalyzes transformational energy technologies to enhance the economic and energy security of the United States. The agency funds high-potential, high-impact projects that are at too early a development stage for private-sector investment but could disruptively advance the ways energy is generated, stored, distributed, and used. Some programs at ARPA-E have sought to develop technologies involving renewable energy, carbon-neutral liquid fuels, and natural gas, with applications in the transportation, commercial, and industrial power sectors. In these areas, there are a number of efforts related to hydrogen. ARPA-E programs with projects relevant to hydrogen or related technologies include:

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

Introduction to the AMR Peer Review Process and Methodology

The AMR peer review process follows the guidelines in the *Peer Review Guide* developed by EERE. Project reviewers provide comments about selected HFTO-funded projects presented during the event. (Note that not all ongoing HFTO-funded projects were reviewed; Appendix D provides a list of projects that were presented but not reviewed.) Panel members include experts from a variety of backgrounds related to hydrogen and fuel cells. As shown in Table 6, this year, these experts represented national laboratories; universities; various government and non-government organizations; and developers and manufacturers of hydrogen production, storage, delivery, and fuel cell technologies. Each reviewer was screened for conflicts of interest, as prescribed by the *Peer Review Guide*. The project comments, recommendations, and scores are provided in the following sections of this report, grouped by subprogram.

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

Table 6. Peer Review Panel: Represented Organizations

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

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

Analysis Methodology

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

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

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

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

- Score 1: Approach to performing the work (20%)
- Score 2: Accomplishments and progress toward overall project and DOE goals (35%)
- Score 3: Collaboration and coordination with other institutions (10%)
- Score 4: Potential impact on Hydrogen Program goals and objectives (20%)
- Score 5: Proposed future work (15%)

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

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

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

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

- Score 1: Approach to performing the work (20%)
- Score 2: Accomplishments and progress toward overall project and DOE goals – the degree to which progress has been made and measured against performance indicators, and the degree to which the project has demonstrated progress toward DOE goals as well as the HydroGEN Consortium mission (30%)
- Score 3: Collaboration effectiveness with HydroGEN and, if applicable, other research entities (25%)
- Score 4: Potential impact – the degree to which the project supports and advances progress toward the DOE Hydrogen Program goals and objectives, and also supports and advances the HydroGEN Consortium mission (15%)
- Score 5: Proposed future work (10%)

The 2023 AMR also included one recently awarded project that was placed in a separate scoring panel with modified scoring criteria and weights. The scores for this new project were based on the following five criteria and weights:

- Score 1: Approach to performing the work (40%)
- Score 2: Accomplishments and progress toward overall project and DOE goals (5%)

- Score 3: Collaboration and coordination with other institutions (10%)
- Score 4: Relevance/potential impact on Hydrogen Program goals (20%)
- Score 5: Proposed future work (25%)

For this new project, reviewers were given the option not to evaluate Score 2 (Accomplishments). In cases where a reviewer exercised this option, the other criteria were re-weighted to total 100%.

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

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

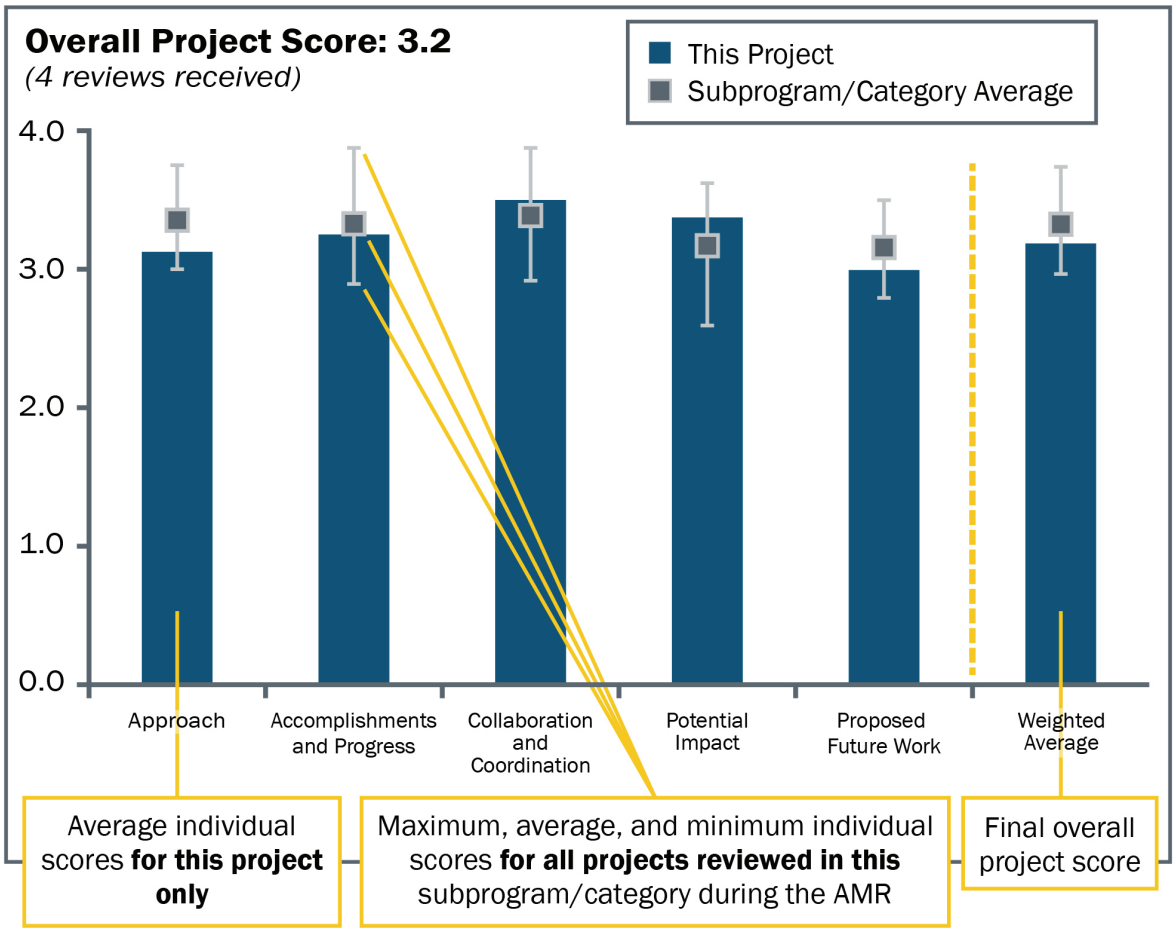

Figure 4. Sample project score graph with explanation

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

Table 7. Sample Project Scores

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

Using these data, the chart for Project A would contain five bars representing the values listed for that project in Table 7. A gray hash mark indicating the related maximum, average, and minimum values for all of the projects in Project A's subprogram or category (the last three lines in Table 7) would overlay each corresponding bar to facilitate comparison. In addition, each project's criteria scores would be weighted and combined to produce a final, overall project score that would permit meaningful comparisons to other projects. Below is a sample calculation for the Project A weighted score.

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

Endnotes

[i] DOE. "2023 Annual Merit Review Proceedings." https://www.hydrogen.energy.gov/library/annual-review/annual_review23_proceedings.

[ii] 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).

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

[iv] 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/.

[v] FY 2024 Budget Justification. March 13, 2023. https://www.energy.gov/cfo/articles/fy-2024-budget-justification.

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

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