Introduction

The U.S. Department of Energy's (DOE's) Hydrogen and Fuel Cells Program (the Program) provides funding and strategic direction for research, development, and demonstration (RD&D) activities to enable the commercialization of hydrogen and fuel cell technologies by the private sector. The Program, which is led through the Fuel Cell Technologies Office (FCTO), coordinates activities within the Offices of Energy Efficiency and Renewable Energy (EERE), Fossil Energy (FE), Nuclear Energy (NE), Science (SC), and the Advanced Research Projects Agency–Energy (ARPA-E). A growing network of stakeholders, including international counterparts, state and regional organizations, and industry representatives across applications and sectors, informs the Program, whose activities are guided by the Energy Policy Act of 2005, Title VIII.

Every year, the Hydrogen and Fuel Cells Program publishes an Annual Progress Report documenting progress, accomplishments, and technology status with respect to performance metrics. This report includes several hundred pages of accomplishments that DOE-funded projects achieved in the last year. The following summary includes only a few examples. More details can be found in the individual subprogram introductions, subsequent project reports, and in the corresponding 2019 Annual Merit Review and Peer Evaluation Report.

In Fiscal Year (FY) 2019, Congress appropriated approximately $120 million for hydrogen and fuel cell activities in EERE's FCTO and approximately $30 million for FE's solid oxide activities. In addition, funding within ARPA-E, NE, and SC relevant to hydrogen and fuel cell activities amounted to approximately $20 million, $11.2 million, and $20.5 million, respectively. This represents a total DOE budget for FY 2019 of almost $202 million related to hydrogen and fuel cell technologies. While FCTO is the primary office related to hydrogen and fuel cells in DOE's congressional budget request, the Program coordinates across all relevant offices, and pertinent activities are identified during the year based on gap analyses and merit-reviewed project proposals that may be selected through competitive funding opportunities, which vary from year to year. In addition to FCTO-funded progress, this report includes examples of progress provided by managers within other DOE offices.

H2@Scale Activities

H2@Scale is a DOE initiative that supports innovations to produce, store, transport, and utilize hydrogen across multiple sectors. H2@Scale also covers collaborations between various industry stakeholders and National Laboratories. EERE's three core priorities of energy affordability, integration, and storage guide H2@Scale research and development (R&D) activities.

The overall vision of H2@Scale (Figure 1) recognizes hydrogen's versatility as a flexible energy carrier. H2@Scale enables—rather than competes with—energy pathways across many industrial sectors. Hydrogen can be produced from a variety of domestic sources and used in numerous industrial and consumer applications. While much of the hydrogen used in the United States today comes from low-cost natural gas, adding other production sources can make industries more resilient to potential price volatility. Ongoing R&D efforts include production scale-up, affordability, durability, and reliability, which are key to jumpstarting new markets for hydrogen, including heavy-duty applications, new industrial uses, and grid integration.

In FY 2019, FCTO focused on expanding its efforts beyond light-duty vehicles to advance the H2@Scale vision. The Office announced more than $40 million in funding for 29 projects.[1] Among the projects selected, three will demonstrate integrated H2@Scale systems in Texas, Illinois, and Florida. An additional project, funded through DOE's NE, will provide more than $9 million in funding for a first-of-a-kind demonstration incorporating hydrogen production with a nuclear power plant to supply regional demands for hydrogen, such as steelmaking or fleet fuel cell vehicles.

[1] https://www.energy.gov/articles/department-energy-announces-40-million-funding-29-projects-advance-h2scale

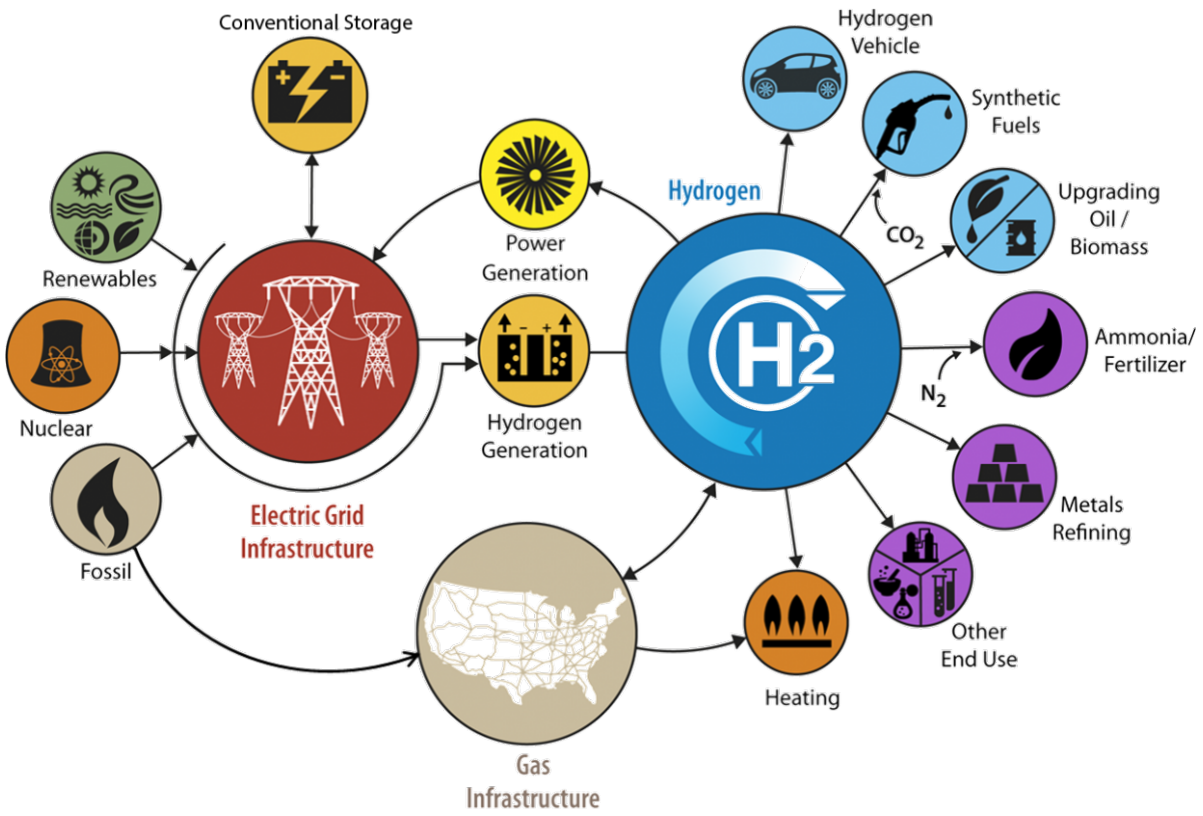

Figure 1. Schematic of H2@Scale

More than 20 H2@Scale Cooperative Research and Development Agreement projects are under way as part of the H2@Scale consortium, involving industry and National Lab partners. These projects are developing technologies for integrated energy systems, electrolyzers, hydrogen compression, and vehicle fueling with external funding to complement FCTO funds.

FCTO-funded projects made progress on efforts to demonstrate the potential for hydrogen and fuel cells to support grid services, including integrated nuclear-hydrogen energy systems. Examples include:

- Developed a first-of-a-kind high-temperature electrolyzer test facility to enable hybrid energy systems involving hydrogen integration with nuclear power plants.
- Conducted hardware-in-the-loop testing to establish, for the first time, that electrolyzers can respond to fluctuations in grid signals within sub-seconds, meeting the performance requirements of grid services.

In addition, FCTO, the Vehicle Technologies Office (VTO), and the Bioenergy Technologies Office issued a joint FY 2019 Funding Opportunity Announcement (FOA) on medium- and heavy-duty trucks that included fuel cell truck and hydrogen fueling applications. This FOA resulted in $18 million for 13 H2@Scale projects, including seven projects addressing advanced gaseous fuel storage, three on high-throughput fueling technologies for medium- and heavy-duty transportation, and three on high-durability, low-platinum membrane electrode assemblies (MEAs) for medium- and heavy-duty trucks.[2]

[2] $15 million from the Fuel Cell Technologies Office and $3 million from the Vehicle Technologies Office, https://www.energy.gov/articles/department-energy-announces-50-million-commercial-truck-road-vehicle-and-gaseous-fuels-0

Other FY 2019 Program highlights include:

- The Center for Hydrogen Safety, a partnership between Pacific Northwest National Laboratory and the American Institute of Chemical Engineers (AIChE), was launched to promote hydrogen safety and best practices worldwide. The Center will provide innovative tools and resources to address safety and coordination of standards in global deployment of hydrogen as an energy carrier, building upon competencies in AIChE's Center for Chemical Process Safety and worldwide partnering organizations that provide access to more than 60,000 stakeholders across 110 countries.
- The research community, government, and the private sector came together in various DOE workshops to identify gaps in RD&D and next steps to enable large-scale hydrogen use, including in the data center, rail, and maritime sectors.[3]
    - The Hydrogen and Fuel Cells for Data Center Applications Project Meeting was held March 20, 2019, in Seattle, Washington. Relevant research, industry, and government representatives gathered to discuss the status, RD&D challenges, and potential that hydrogen and fuel cell technologies have in meeting the power needs of data centers.
    - The H2@Rail Workshop, co-organized by FCTO and the U.S. Department of Transportation's Federal Railway Administration, was held March 26–27, 2019, in Lansing, Michigan. The workshop convened a diverse and international group of representatives from government agencies, academia, original equipment manufacturers, rail operators, and National Laboratories that are participating in hydrogen rail applications.
    - The H2@Ports Workshop, co-organized between FCTO, the U.S. Department of Transportation's Maritime Administration, and the European Commission's Fuel Cells and Hydrogen Joint Undertaking program, was held September 10–11, 2019, in San Francisco, California. It gathered close to 100 experts from government, ports, and the maritime industry to share information on the status of hydrogen and fuel cell technologies for maritime applications.
- In recognition of National Hydrogen and Fuel Cell Day (October 8, 2019), DOE announced a collaboration with the Department of Defense's U.S. Army Ground Vehicle Systems Center and the U.S. Army Corps of Engineers to develop and demonstrate "H2Rescue"—a hydrogen fuel cell-powered emergency relief truck capable of providing power, heat, and even potable water for 24–72 hours. This collaboration will enable increased resilience and clean energy capability for first responders conducting emergency relief and disaster management efforts.
- FCTO worked with VTO and industry stakeholders, including the 21st Century Truck Partnership, to develop technical targets for Class 8 long-haul tractor-trailer trucks powered by hydrogen and fuel cells. The targets, published in October 2019, will help guide early-stage R&D and serve as benchmarks for tracking technology.[4]
- FCTO completed an analysis of the current domestic and global market size for hydrogen. The Program Record,[5] published on October 1, 2019, estimates domestic hydrogen production at approximately 10 million metric tons and the global hydrogen production at 65–100 million metric tons per year. It also includes a discussion about the variability of production estimates based on which segments of hydrogen production are included in the market size calculation. These and other analysis efforts were coordinated with global stakeholders and peer reviewed by industry and other experts, including the International Energy Agency.

[3] For more information on these and other FCTO workshops, see https://www.energy.gov/eere/fuelcells/workshop-and-meeting-proceedings
[4] DOE Hydrogen and Fuel Cells Program Record 19006, Hydrogen Class 8 Long Haul Truck Targets, https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf
[5] DOE Hydrogen and Fuel Cells Program Record 19002, Current Hydrogen Market Size: Domestic and Global, https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf

Patents and Commercialized Technologies

Each year, FCTO tracks U.S. patents granted specifically as a result of its funding as just one indicator of cutting-edge innovation.

- Cumulatively, FCTO funding has led to more than 960 hydrogen and fuel cell patents, as shown in Figure 2, with approximately:
  - 37% of hydrogen and fuel cell patents coming from the National Labs[6]
  - More than 30 technologies commercialized
  - Over 65 technologies with potential to be commercial in the next few years
  - Over 1,000 patent applications resulting from FCTO-funded RD&D.
- FCTO funding has enabled a number of advances, including:
  - 60% decrease in the cost of automotive fuel cells in over a decade[7]
  - 4-fold improvement in durability for light-duty vehicles, to over 120,000 miles[8]
  - 80% decrease since 2002 in the cost of electrolyzer stacks[9]
  - 30% decrease in hydrogen carbon fiber composite storage tank cost since 2013.[10]

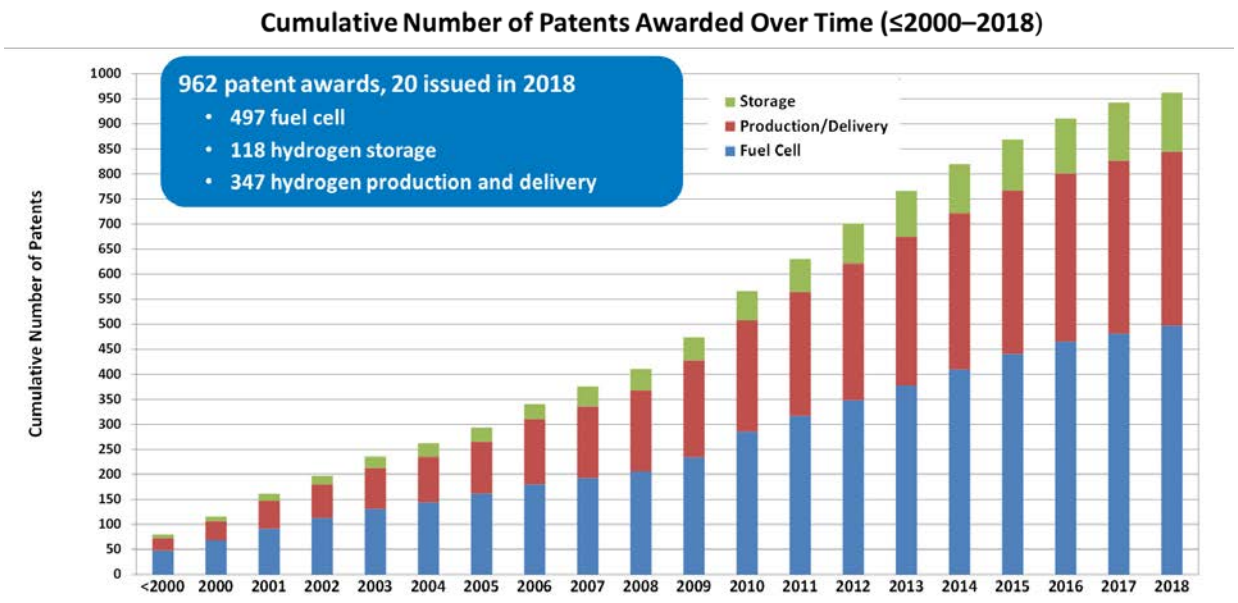

Figure 2. Patent awards by subprogram

EXAMPLES OF PROGRESS AND ACCOMPLISHMENTS BY KEY ACTIVITY

FCTO's activities were organized into four focus areas in FY 2019: Hydrogen Fuel R&D, Fuel Cell R&D, Infrastructure and Systems R&D, and Safety, Codes and Standards. FCTO coordinates with relevant offices to avoid duplication and leverage resources. The summaries in Figure 3 provide examples of focus areas and progress in key programs related to hydrogen and fuel cells. The subprogram sections of this report provide more details on the objectives, accomplishments, and projects in each area. The Program also funds Small Business Innovative Research Program projects each year; the projects funded in FY 2019 are listed in an appendix.

[6] Pathways to Success: Innovations Enabled by the U.S. Department of Energy Fuel Cell Technologies Office, https://www.energy.gov/sites/prod/files/2018/11/f57/fcto_2017_pathways_commercial_success.pdf
[7] DOE Hydrogen and Fuel Cells Program Record #16020, https://www.hydrogen.energy.gov/pdfs/16020_fuel_cell_system_cost_2016.pdf
[8] DOE Hydrogen and Fuel Cells Program Record #16019, https://www.hydrogen.energy.gov/pdfs/16019_fuel_cell_stack_durability_2016.pdf
[9] DOE Hydrogen and Fuel Cells Program Record #14004, https://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf
[10] DOE Hydrogen and Fuel Cells Program Record #19008, https://www.hydrogen.energy.gov/pdfs/19008_onboard_storage_cost_performance_status.pdf

Hydrogen Fuel R&D

The Hydrogen Fuel R&D subprogram focuses on R&D to reduce the cost and improve the reliability of technologies used to produce and store hydrogen from diverse domestic energy resources. The subprogram addresses technical challenges through a portfolio of projects in two R&D areas:

- **Hydrogen production** addresses low-cost, highly efficient hydrogen production technologies that utilize diverse domestic sources of energy for both centralized and distributed production applications. R&D activities continued to focus on advanced water splitting and innovative concepts to enable the ultimate DOE target of $2/kg for hydrogen.
- **Hydrogen storage** addresses cost-effective onboard and offboard hydrogen storage technologies with improved energy density and lower costs. R&D activities include high-pressure compressed storage, materials-based storage, and hydrogen carriers. While targets will be developed for specific applications, the current onboard targets are 1.7 kWh/L, 2.2 kWh/kg, and $8/kWh for the complete hydrogen storage system (including any materials, tank, balance-of-plant, etc.).

Fuel Cell R&D

The Fuel Cell R&D subprogram supports R&D of fuel cell technologies for transportation, stationary, and cross-cutting applications. The subprogram mainly focuses on reducing cost and improving durability and efficiency to allow for fuel cells to compete with incumbent and advanced alternative technologies.

The subprogram has expanded its focus to heavy-duty applications, which have more stringent durability requirements compared to light-duty vehicle applications. Stationary applications include the development of fuel cells for distributed power generation, including combined heat and power for residential and commercial applications. Existing early markets and near-term markets generating market traction for adoption of fuel cell electric vehicles include primary/backup power for critical infrastructure such as data centers, auxiliary power units, and specialty applications such as material handling equipment. Fuel cell research areas include catalysts, membranes, and fuel cell performance and durability.

While targets are being developed for various applications (e.g., rail, marine), a key accomplishment in FY 2019 was development of targets for heavy-duty vehicles, which include $60/kW for the fuel cell system and 30,000 hour durability.

Infrastructure and Systems R&D

The Infrastructure and Systems R&D subprogram aims to address technology barriers, systems and systems-integration challenges, and other cross-cutting activities to reduce the cost of hydrogen production, storage, use, and transport and enable H2@Scale. In FY 2019, the subprogram included three project categories: Hydrogen Infrastructure R&D, Technology Acceleration, and Systems Analysis. R&D focus areas included (1) low-cost, high-efficiency liquefaction, pipelines, chemical carriers, and tube trailers; (2) low-cost and reliable compressors, pumps, dispensers, and stationary storage; (3) grid integration of electrolyzers; (4) novel methods of manufacturing and quality control, applicable to scale; and (5) systems analysis to inform R&D priorities, assess supply and demand opportunities for hydrogen, and determine program impact.

Safety, Codes and Standards

The Safety, Codes and Standards subprogram identifies and performs R&D to provide a fundamental understanding of the relevant physics, critical data, and safety information used to develop and revise technically sound and defensible codes and standards. These codes and standards provide the technical basis to facilitate and enable the safe deployment and commercialization of hydrogen and fuel cell technologies in multiple applications. The subprogram identifies and evaluates safety and risk management measures that can be used to define requirements and close the gaps in codes and standards in a timely manner. Additionally, the subprogram promotes collaboration among government, industry, codes and standards development organizations, universities, and national laboratories in an effort to harmonize regulations, codes, and standards both internationally and domestically.

Example FCTO FY 2019 R&D Progress and Accomplishments

Fuel Cell R&D

- ✓ Completed preliminary modeling of cost and performance of fuel cell heavy-duty trucks, providing key strategic analysis to guide target development and R&D approaches for heavy-duty fuel cells to be competitive in the marketplace.
- ✓ Achieved 85% improvement in platinum group metal (PGM)-free catalyst activity over the 2016 baseline of 16 mA/cm^2. The MEA performance with this PGM-free cathode in an H_2-O_2 fuel cell was 29.6 mA/cm^2 (at 0.90 V iR-corrected, 1.0 bar partial pressure of O_2, and cell temperature 80°C), exceeding the 2019 target of 29 mA/cm^2.
- ✓ Finalized and disseminated PGM-free fuel cell catalyst test protocols through ElectroCat, harmonizing testing and best practices—critical to ensure consistency in reporting results across the research community.

Hydrogen Fuel R&D

Hydrogen Production

- ✓ The HydroGEN consortium added 11 new projects through the FY 2019 FOA and continued supporting 20 active projects, resulting in the exchange of more than 100 material samples, two Materials Research Society Symposia, 30 published papers, 104 presentations, and one patent with two provisional applications filed.
- ✓ Convened the first Advanced Water Splitting Benchmarking Workshop in conjunction with HydroGEN, with 80 experts representing 40 institutions, to establish consistent performance and durability testing protocols and benchmarks.
- ✓ Achieved a 24% increase in the rate of hydrogen production using an engineered strain (versus a non-engineered strain) of *Clostridium thermocellum* fermenting pretreated biomass, demonstrated in a batch reactor.
- ✓ Demonstrated high anion exchange membrane electrolyzer performance (using PGM-free H_2 evolution catalysts).
- ✓ Developed machine-learning methods to screen more than 10^{10} descriptors to support perovskite materials selection for low-cost hydrogen production pathways.

Hydrogen Storage

- ✓ Initiated 11 new competitively selected HyMARC seedling projects: seven on hydrogen and/or natural gas storage materials development and four on hydrogen carrier development.
- ✓ Demonstrated light-activated hydrogen desorption at ambient temperature from two material systems (TiN/MgH_2 and $TiOx/Mg(BH_4)_2$) using LED light.
- ✓ Completed characterization of a metal organic framework material demonstrating a binding enthalpy in the range predicted to enable significant room-temperature hydrogen adsorption.
- ✓ In support of lower cost carbon fiber precursors, demonstrated fiber spinning of hollow polyacrylonitrile multifilament fiber tows; demonstrated melt-spinning of polyacrylonitrile plasticized with ionic liquids; and demonstrated a new class of polyethylene-g-pitch copolymers with greater than 70% mass yield on carbonization.

Infrastructure and Systems R&D

Hydrogen Infrastructure

- ✓ Added more than 10 partners to the Hydrogen Materials Compatibility (H-Mat) National Laboratory consortium to address materials compatibility issues with hydrogen infrastructure and components. Partners will collaborate with H-Mat on six new FOA projects focused on development of novel metals and polymers for use in hydrogen infrastructure and development of accelerated test methods.

Technology Acceleration

- ✓ Initiated tests with the newly developed 25-kW high temperature electrolyzer test facility to: (1) demonstrate response rate to support the grid, (2) analyze real-time stack degradation, and (3) characterize performance under dynamic grid conditions.
- ✓ Validated the fuel cell durability of 29 fuel cell buses, of which 12 exceeded 20,000 hours, six exceeded 25,000 hours, and one exceeded 30,000 hours.
- ✓ Validated two (New York and California) first-of-a-kind prototype fuel cell hybrid electric parcel delivery vans, one of which (New York) demonstrated a range of up to 150 miles and logged over 15,000 miles in service.
- ✓ Designed and developed an advanced hydrogen mobile fueler capable of fueling approximately 20–40 fuel cell vehicles per day up to 70 MPa with -40°C cooling.

Systems Analysis

- ✓ Assessed economic potential of hydrogen in nine different sectors and integrated with estimates of hydrogen supply potential from water splitting, natural gas reforming, and coal gasification in support of H2@Scale.
- ✓ Initiated comprehensive market segmentation analysis evaluating total cost of ownership of fuel cell, battery, compressed natural gas, and diesel powertrains in Class 4 and Class 8 trucks.

Safety, Codes and Standards

- ✓ Issued an open-source license for Sandia's Hydrogen Risk Assessment Model (HyRAM 2.0) and released installer and source code to the public, allowing users and researchers to avoid a lengthy licensing process, view and verify models, and contribute improvements to HyRAM.
- ✓ Developed and demonstrated a novel laser diagnostic in the laboratory that can measure cryogenic hydrogen concentrations from a standoff distance of 40 feet, which could be applied to vent stack releases and large pooling and vaporization scenarios; this diagnostic is critical for the reduction of setback distances.
- ✓ Performed and validated quantitative characterization of the behavior of indoor hydrogen releases through computational fluid dynamic models.
- ✓ Demonstrated successful field operation of Los Alamos National Laboratory's hydrogen contaminant detector technology with an external humidification system.
- ✓ Partnered with AIChE to establish the Center for Hydrogen Safety, thus enabling long-term sustainability and broader impact of the Hydrogen Safety Panel, first responder training, and safety knowledge resources.

Figure 3. FCTO FY 2019 R&D progress and accomplishments—examples

OTHER FY 2019 PROGRAM ACTIVITIES AND HIGHLIGHTS

Office of Fossil Energy, Solid Oxide Fuel Cell Program

The Solid Oxide Fuel Cell (SOFC) Program within FE had an enacted budget of $30 million in FY 2019. The SOFC Program's mission is to enable the generation of efficient, low-cost electricity from natural gas or coal. The near-term goal is to develop natural-gas-fueled distributed generation and small-scale, modular coal-fueled systems, with a long-term goal of coal and natural gas utility-scale applications with carbon capture and sequestration. Drivers include cost and efficiency benefits to coal and natural gas power systems and the development of near-term natural gas distributed generation applications. The Program maintains a portfolio of approximately 50 projects that focus on cell and core technology and systems development. Researchers from academia, National Laboratories, research institutions, and small businesses collaborate with SOFC developers to address and resolve reliability issues, improve performance, and reduce the cost of SOFC power systems.

Office of Nuclear Energy

NE is working with partners in EERE and industry to evaluate the potential demonstration of commercial-scale hydrogen production using heat and electricity from a nuclear energy system. In addition to the emissions-free electricity currently produced by nuclear reactors, some advanced nuclear reactor designs will operate at very high temperatures, making them well suited for promising new thermally driven hydrogen production processes. These advanced reactors, now being developed by NE, could provide the low-cost heat necessary for these processes to economically produce hydrogen. Hydrogen production is also being assessed for light-water reactor (LWR) technologies (currently operating and new builds), although these systems will likely be operated at somewhat lower efficiency than advanced high-temperature reactors.

In FY 2019, NE provided funding to analyze the economic and technical aspects of using nuclear reactors to produce hydrogen. Two key studies were completed in collaboration with industry, each of which are documented in publicly available reports:

- *Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest* (INL/EXT-19-55090).[11]
- *Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest* (INL/EXT-19-55395).[12]

These studies provided the foundation for two LWR-hydrogen demonstration projects at existing nuclear power plants.

- In September 2019, NE selected Energy Harbor (formerly FirstEnergy Solutions) for a cost-shared project to develop an LWR hybrid energy system. The project, selected under NE's U.S. Industry Opportunities for Advanced Nuclear Technology Development FOA, aims to award up to $9.2 million in NE funding to install a low-temperature electrolysis (LTE) unit at Davis-Besse Nuclear Power Station. Major interfaces required for LWR hybrid operations (e.g., dynamic controls to apportion power output between the electrical grid and LTE unit) will be addressed. A final report describing outcomes and business case opportunities will be shared with partners and third parties interested in LWR hybrid energy systems.
- NE is providing $2 million in cost share for an FY 2019 EERE FOA award to demonstrate hydrogen electrolysis at an Exelon nuclear plant. This project will install a 1–2 MWe electrolysis skid that will produce hydrogen for use at the nuclear power plant and will demonstrate cycling of the electrolysis unit as power is dispatched from the nuclear plant to either the grid or the electrolysis plant. Results of this demonstration will be used to model a system that is scaled up to demonstrate the benefits to grid services.

[11] https://www.osti.gov/biblio/1559965-evaluation-non-electric-market-options-light-water-reactor-midwest
[12] https://www.osti.gov/biblio/1569271-evaluation-hydrogen-production-feasibility-light-water-reactor-midwest

FY 2019 NE funding also supported final design for an electrically heated thermal energy distribution system that can support testing and demonstration of a thermal-energy-driven high-temperature electrolysis system. This thermal energy input can be controlled in a manner that emulates the integration with an LWR. It is anticipated that this thermal system will be constructed in FY 2020 to support future nuclear system demonstration.

Office of Science, Basic Energy Sciences

The Basic Energy Sciences program within the Office of Science had a cross-cut spending level of approximately $20.5 million in FY 2019. Hydrogen and fuel cells were among the topics in the Energy Frontier Research Center solicitation in FY 2018, and two Energy Frontier Research Centers were awarded that have components focused on hydrogen production. Specific accomplishments include the following:

- Strong electronic interactions between carbon supports and molecular catalysts based on cobalt porphyrins were revealed to directly increase the rate of electrocatalytic oxygen reduction. The results offer the possibility of incorporating tunable molecular active sites onto a conductive solid as a platform for controlling electrocatalytic properties at the molecular level.
- A 15-carbon molecular wire was used to tether Photosystem I from photosynthetic bacteria to an FeFe hydrogenase enzyme from a soil bacterium. With addition of appropriate electron donors and mediators, this construct generated 50 micromoles of hydrogen per milligram Photosystem I chlorophyll per hour and provided new insights into the design of self-assembling biological systems for light-driven hydrogen production.

Advanced Research Projects Agency–Energy

ARPA-E's FY 2019 funding for fuel cells and electrolyzers for energy conversion and storage activities was approximately $20.0 million, which includes approximately $14.5 million for projects in the more general OPEN 2018 program and approximately $5.5 million in additional funds allocated to focused programs. In FY 2020, ARPA-E anticipates potential spending of up to $45 million on fuel cell and hybrid systems through the current Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH) program solicitation and anticipated Phase II awards within the existing Innovative Natural-Gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-Generation (INTEGRATE) program.

A summary of relevant focused programs follows:

- The Duration Addition to electricitY Storage (DAYS) program seeks to develop energy storage systems that provide power to the electric grid for durations of 10 hours to up to 100 hours. There was no additional funding during FY 2019.
- The INTEGRATE program seeks to reduce the cost and increase the primary energy efficiency associated with the conversion of a range of fuels to electric power for stationary and transportation applications. There was no additional funding during FY 2019. However, $25 million of FY 2020 funds are expected to be invested in Phase II system sub-scale prototypes.
- The Integration and Optimization of Novel Ion-Conducting Solids (IONICS) program seeks to create components for electrochemical cells using solid ion conductors. The FY 2019 budget for Categories 2 and 3 was approximately $2.9 million.
- The Reliable Electricity Based on ELectrochemical Systems (REBELS) program seeks to develop transformational electrochemical fuel cells operating at intermediate temperatures. There was no additional funding during FY 2019.
- The Renewable Energy to Fuels through Utilization of Energy-dense Liquids (REFUEL) program seeks to enable the use of existing infrastructure to deliver electricity or hydrogen to customers at a competitive price. The FY 2019 budget was approximately $2.6 million.

- The REEACH solicitation seeks to develop highly efficient fuel-to-electric-power conversion systems operating on carbon-neutral liquid fuel for commercial aviation. Up to $20 million of FY 2020 funds are expected to be invested in fuel cell and/or hybrid system technologies.

INTERNATIONAL ACTIVITIES

With increased global interest in hydrogen and fuel cell technologies, international activities and partnerships to share lessons learned and exchange information received increased attention in FY 2019, pushing global progress forward. FCTO has been engaged with all the key international partnerships for a number of years and developed a document that describes these various entities and their roles and responsibilities. Figure 4 depicts key international initiatives related to hydrogen and fuel cells, where those in blue denote a focus solely on hydrogen and fuel cell technologies. In some cases, hydrogen and fuel cells are included within a broader initiative or organization. A key accomplishment involved coordination across the various partners to avoid duplication, leverage resources, and maximize effectiveness.

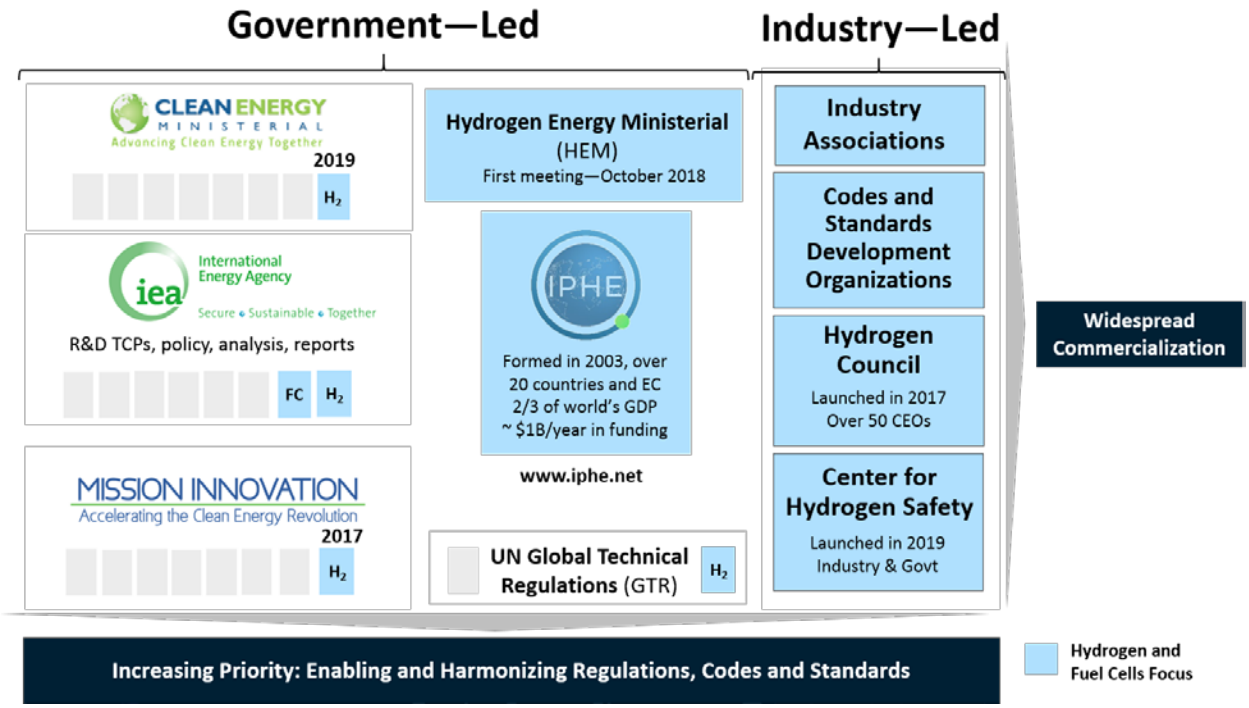

Figure 4. Key international initiatives related to hydrogen and fuel cells

Highlights for the government-led global initiatives that the Program engaged with more closely during 2019 include the following:

International Partnership for Hydrogen and Fuel Cells in the Economy

The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), established in 2003, brings together governments at the working level to advance worldwide progress in hydrogen and fuel cell technologies. Chaired by the United States and co-chaired by Japan, IPHE includes 19 member countries (Australia, Austria, Brazil, Canada, China, Costa Rica, France, Germany, Iceland, India, Italy, Japan, the Netherlands, Norway, the Republic of Korea, the Russian Federation, South Africa, the United Kingdom, and the United States) and the European Commission. IPHE held two steering committee meetings and policy forums in 2019—one in Vienna, Austria, in April, and one in Seoul, Republic of Korea, in October.

The IPHE began work on key actions identified as a result of discussions during this meeting, including:

- The creation of a task force to develop a methodology for assessing hydrogen production pathways and approaches to "certificates" of origin. This would facilitate the trade of hydrogen across international borders and was voted the highest priority at the IPHE Steering Committee meeting in October 2019.
- A tool that maps out IPHE's role in supporting the Global Action Agenda and tracks IPHE progress from its Education and Outreach and Regulations, Codes, Standards and Safety Working Groups. The working groups are directly addressing areas outlined in the Global Action Agenda, as described in the following section.
- A revamp of the website. International members posted several country webinars and developed a number of social media platforms to increase visibility.

Other Government-Led International Partnerships and Initiatives

- **G20 Summit:** In June 2019, the G20 Summit was held in Kuruizawa, Japan, and hydrogen was among the number of topics raised, along with the release of a comprehensive report by the International Energy Agency. FCTO served on the advisory board for the development and review of this report.
- **Hydrogen Energy Ministerial Meeting (HEM):** The HEM was initiated by Japan in October 2018 as a platform to encourage countries worldwide to promote global utilization of hydrogen and to engage Ministerial-level participation. The United States, through DOE's participation, has been engaged with HEM since its first meeting. The second HEM in October 2019 in Tokyo resulted in the release of the Global Action Agenda[13] calling for an aspirational goal of "Ten, ten, ten": 10 million hydrogen powered systems and 10 thousand hydrogen refueling stations in 10 years, to help mobilize the private sector and investment community. The Global Action Agenda followed on from the Tokyo Statement[14] released at the first HEM in 2018, which outlined key areas for countries to collaborate on and to enable a hydrogen economy.
- **Clean Energy Ministerial Hydrogen Initiative:** Canada spearheaded the launch of the New Hydrogen Initiative as part of the Clean Energy Ministerial in May 2019. Under Secretary Menezes attended on behalf of the United States and DOE. The Netherlands, United States, Japan, and the European Commission are supporting as co-leads. As a co-lead, the United States is ensuring resources are leveraged to avoid duplication of efforts already covered under other initiatives, including IPHE.
- **Mission Innovation on Hydrogen (IC-8) Challenge:** Australia took the lead to establish a specific Mission Innovation Challenge (IC-8) on Hydrogen in 2018 with the European Commission and Germany as co-leads. The distinguishing feature of IC-8 is the focus on "hydrogen valleys" covering regional clusters for deployment of hydrogen and fuel cell applications. DOE participated in two IC-8 workshops in 2019, focusing on hydrogen valleys in Antwerp and on hydrogen materials compatibility in Berlin. The United States also supported a joint Mission Innovation IC-8-IPHE workshop in the United Kingdom on hydrogen blending in natural gas.
- **International Energy Agency:** The United States engages with the International Energy Agency's Advanced Fuel Cells Technology Collaboration Programme. This Technology Collaboration Programme, which met twice in 2019, provides a mechanism for member countries to share the results of pre-competitive R&D and analysis related to fuel cell and electrolyzer technologies through Executive Committee and annex meetings, topical and outreach meetings, publications from the annexes and other groups, newsletters, and other forms of exchange.

[13] https://h2em2019.go.jp/summary/summary_en.pdf
[14] https://www.meti.go.jp/press/2018/10/20181023011/20181023011-5.pdf

EXTERNAL COORDINATION, INPUT, AND ASSESSMENTS

Hydrogen and Fuel Cells Technical Advisory Committee

The Hydrogen and Fuel Cells Technical Advisory Committee (HTAC), a congressionally mandated committee to advise the Secretary of Energy, formally convened twice in FY 2019. HTAC submitted its eleventh annual report to DOE, which summarizes progress in hydrogen and fuel cell technologies, domestic and international RD&D, and commercialization activities, and offers recommendations on DOE's hydrogen-related R&D activities and initiatives. HTAC also published outputs from two subcommittees: (1) one tasked with creating outreach modules for a general audience providing basic information on key hydrogen and fuel cell topics, and (2) one to explore the global competitiveness of the U.S. hydrogen and fuel cell industry and any steps DOE could take to help improve the U.S. position. The reports from these subcommittees are available on the HTAC website.[15]

Federal Interagency Coordination

FCTO coordinates DOE Hydrogen and Fuel Cells Program R&D activities with other federal agencies, as mandated by the Energy Policy Act of 2005. FCTO convenes monthly meetings with an Interagency Working Group to share information, which in FY 2019 included webinars covering a variety of topics, such as the Department of Transportation Federal Transit Administration's fuel cell buses and Lo-No emissions vehicles projects, a briefing from the Center for Hydrogen Safety, and the Roadmap for Hydrogen and Fuel Cell Deployment in the U.S. Northeast. In addition, the 2019 Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting included a one-day track of presentations from other federal, state, and regional agencies. These oral and poster sessions included briefings on hydrogen- and fuel cells-related activities being conducted by other DOE offices, the Department of Defense (DoD), NASA, Department of Transportation, United States Postal Services (USPS), National Park Service, and Environmental Protection Agency, among others. The session also included several panels with representatives from state and regional organizations to discuss progress on regional hydrogen infrastructure and state-funded hydrogen and fuel cell activities.

This year, a new interagency collaboration was started with the U.S. Department of Transportation's Maritime Administration to evaluate a hydrogen fuel cell system for cold ironing applications at the National Oceanic and Atmospheric Administration's Scripps Institution of Oceanography in San Diego, California. The fuel cell system is expected to supply power to the research vessel Robert Gordon Sproul while at berth.

Industry and Association Roadmap Analysis

The Program fostered collaboration among diverse industry groups, including utilities, fuel cell developers, hydrogen suppliers, and various end users, to enable an industry-led roadmap to be developed that quantified the potential and the benefits of hydrogen technologies in the U.S. market. National Laboratory experts engaged in the review of assumptions and analysis, and the Executive Summary was published in November 2019.[16]

FY 2019 Annual Merit Review and Peer Evaluation

The Program's Annual Merit Review and Peer Evaluation Meeting (AMR) took place April 29–May 1, 2019, in Crystal City, Virginia, and provided an opportunity for the Program to obtain expert peer reviews of the projects it supports and to report its accomplishments and progress. Approximately 840 participants attended, and 200 experts peer reviewed 129 of the Program's projects. The AMR included, for the second year, a full 2.5-day track of oral and poster presentations from DOE-FE's SOFC Program, as well as a one-day track of sessions on other federal and state agency activities. The report summarizing the results and comments from the 2019 AMR reviews is available on DOE's website.[17] The AMR is a key part of the Program's comprehensive approach toward active management of its projects. Careful assessment of project portfolios—

[15] HTAC Reports and Other Publications, https://www.hydrogen.energy.gov/htac_reports.html
[16] Roadmap to a US Hydrogen Economy: Reducing Emissions and Driving Growth across the Nation, March 2020, http://www.fchea.org/us-hydrogen-study
[17] 2019 Annual Merit Review and Peer Evaluation Report, https://www.hydrogen.energy.gov/annual_review19_report.html

through the AMR and other go/no-go decision-making activities (with criteria defined in the project scope of work)—helped the Program save and redirect approximately $5.19 million of funding in FY 2019.

IN CLOSING…

This year marked an important period in the Program's history with the broadening of the Program's activities and project portfolio to address new and emerging applications beyond light-duty vehicles, in alignment with the H2@Scale vision. The Program carried out workshops on data centers, ports, and rail; engaged with other countries through partnerships like IPHE and global initiatives such as the Clean Energy Ministerial, HEM, and Mission Innovation; engaged with local stakeholders through regional coalition events and other meetings; collaborated with other DOE programs and federal agencies to pool resources while maximizing impact; and released R&D funding opportunities that are critical to advance technological progress. To continue momentum with the H2@Scale initiative, the Program launched new demonstration projects—in Texas, Florida, Ohio, and Illinois—and the first nuclear-to-hydrogen projects in the United States.

Signs of progress on the domestic and international front are visible. The hydrogen and fuel cell market is robust with 71,000 fuel cell units totaling over 1 gigawatt of fuel cell power shipped worldwide in 2019.[18] Just in the United States, more than 500 MW of stationary fuel cell power has been installed to support telephone towers and other critical load facilities, more than 30,000 hydrogen fuel cell forklifts are helping move merchandise at warehouses, and more than 20 million hydrogen refuelings have taken place to support these forklift operations in just the last few years. In addition, more than 8,300 fuel cell cars and more than 30 fuel cell buses travel the roads, with 45 retail public stations open.

On the global landscape, hydrogen keeps gaining momentum with multiple countries developing national energy strategies and roadmaps around hydrogen. Large-scale hydrogen use applications are also gaining attention with the rollout of the first hydrogen trains in Germany, several European port and shipping activities, and the first liquid hydrogen export project from Australia to Japan.

The progress is encouraging but important work remains to be done on multiple fronts: cost needs to be reduced in several areas—without compromising performance—for technologies to be competitive, infrastructure needs to be addressed, and scaling up is key. The next few years will be critical to move the needle toward a full incorporation of hydrogen in the broader energy system. The DOE Hydrogen and Fuel Cells Program will continue to work in close collaboration with key stakeholders and will continue its strong commitment to effective stewardship of taxpayer dollars in support of its mission to enable the energy, environmental, and economic security of the nation. In support of these efforts, the following nearly 1,000 pages document the results and impacts of the Program in the last year.

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[18] E4tech, The Fuel Cell Industry Review 2019, http://www.fuelcellindustryreview.com/