I.0 Introduction

The U.S. Department of Energy's Hydrogen and Fuel Cells Program (the Program) focuses primarily on early-stage research and development (R&D) activities and works with stakeholders to enable the widespread commercialization of hydrogen and fuel cell technologies across diverse applications. The Program is coordinated across the U.S. Department of Energy (DOE), incorporating activities in the offices of Energy Efficiency and Renewable Energy (EERE)—led through the Fuel Cell Technologies Office (FCTO)—Fossil Energy, Nuclear Energy (NE), Science, and Advanced Research Projects Agency – Energy (ARPA-E). Every year, the FCTO publishes an Annual Progress Report documenting progress, accomplishments, and technology status with respect to performance metrics. This report includes over 700 pages of accomplishments achieved by DOE-funded projects in the last year. The following summary includes only a few examples. More details can be found in the individual sub-program introductions, subsequent project reports, and in the corresponding 2017 Annual Merit Review and Peer Evaluation Report.[1]

In Fiscal Year (FY) 2017, Congress appropriated approximately $101 million for EERE's FCTO hydrogen and fuel cell activities and approximately $30 million for the Office of Fossil Energy's solid oxide fuel cell activities. In addition, funding within ARPA-E, NE, and the Office of Science relevant to hydrogen and fuel cell activities amounted to approximately $47 million, $2 million, and $22 million, respectively. This represents a total DOE budget for FY 2017 of approximately $202 million related to hydrogen and fuel cell technologies.[2] While FCTO is the primary office responsible for hydrogen and fuel cell activities, 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. While the specific project summaries in this report focus on FCTO activities, examples of progress within other offices are also provided below.

In FY 2017, the Program's primary efforts focused on early-stage R&D work with three new consortia (ElectroCat [Electrocatalysis Consortium], HydroGEN [HydroGEN Advanced Water Splitting Materials consortium], and HyMARC [Hydrogen Materials—Advanced Research Consortium]), which aim to make unique, world-class expertise and capabilities of national labs more accessible and available to university and industry partners across the country. This approach creates a collaborative foundation for an innovation ecosystem that can bring in a steady influx of competitively selected projects to tackle the most pressing technical challenges in the field. Under the umbrella of DOE's Energy Materials Network, these efforts aim to use state-of-the-art computational, high-throughput/combinatorial synthesis and characterization tools; data management such as machine learning; and other approaches to accelerate progress through a multi-disciplinary team approach.

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 650 hydrogen and fuel cell patents, with approximately 40% coming from the national labs, and more than 30 technologies entering today's market, with potential for another 75 to be commercialized within the next few years.[3] Some of these include catalysts for fuel cells, high-pressure hydrogen tanks, electrolyzers for hydrogen production, and fuel cell system components. DOE-funded research has also cut the cost of automotive fuel cells by 60% in the last decade,[4] quadrupled durability to over 120,000 miles,[5] and cut electrolyzer stack costs by 80% since 2002.[6]

[1] https://www.hydrogen.energy.gov/annual_review17_report.html
[2] Hydrogen and Fuel Cells Program budgets—https://www.hydrogen.energy.gov/budget.html, https://www.hydrogen.energy.gov/pdfs/htac_feb18_01_satyapal.pdf—and subsequent awards by ARPA-E
[3] Pathways to Commercial Success: Technologies and Innovations Enabled by the U.S. Department of Energy Fuel Cell Technologies Office, https://energy.gov/eere/fuelcells/downloads/pathways-commercial-success-technologies-and-innovations-enabled-us
[4] *Fuel Cell System Cost–2016*, Program Record (Hydrogen and Fuel Cells Program) 16020, U.S. Department of Energy, 2016. https://www.hydrogen.energy.gov/pdfs/16020_fuel_cell_system_cost_2016.pdf
[5] *On-Road Fuel Cell Stack Durability–2016*, Program Record (Hydrogen and Fuel Cell Technologies Program) 16019, U.S. Department of Energy, 2016. https://www.hydrogen.energy.gov/pdfs/16019_fuel_cell_stack_durability_2016.pdf
[6] *Hydrogen Production Cost From PEM Electrolysis*, Program Record (Hydrogen and Fuel Cells Program) 14004, U.S. Department of Energy, 2014. https://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf

PROGRESS AND ACCOMPLISHMENTS BY KEY ACTIVITY

Fuel Cells

One of the most important metrics used to guide the Fuel Cells sub-program's R&D efforts is the projected high-volume manufacturing cost for automotive fuel cells, which is tracked on an annual basis. The sub-program is targeting an interim cost of \$40/kW and durability of 5,000 hours. Long-term competitiveness with alternative powertrains is expected to require further cost reduction to \$30/kW and durability of 8,000 hours, which represent the sub-program's ultimate targets. This year, the preliminary cost projection for an 80-kW_{net} automotive polymer electrolyte membrane (PEM) fuel cell system based on next-generation laboratory technology and operating on direct hydrogen is \$50/kW_{net} when manufactured at 100,000 units/yr and \$45/kW_{net} when manufactured at a volume of 500,000 units/yr.[7]

In FY 2017, the core group of national laboratories in the ElectroCat consortium (led by Los Alamos National Laboratory and Argonne National Laboratory [ANL]) established a list of capabilities and evaluated their value to the community in accelerating progress towards developing completely platinum-group-metal (PGM)-free catalysts for fuel cells. Major improvements to fuel cell catalysts included an atomically dispersed (AD) Fe-N-C catalyst, developed to create single atomic Fe sites on the catalyst surface (no nanoparticles, minimal Fe clustering), as seen in microscopy images. More details and examples are provided in this report.

The Program also launched the L'Innovator (coined for "Lab Innovator") pilot program, which bundles national lab intellectual property to increase its value and mitigate risk (for example catalyst from one lab, membrane from another, and electrode fabrication intellectual property from another). This intellectual property is offered to the private sector for commercialization. In FY 2017, the first company was selected for potential licensing, contingent on industry/investor cost share.

Hydrogen Production

Significant progress was made by the Hydrogen Production sub-program on several important fronts in FY 2017. In January 2017, DOE announced SimpleFuel as the winner of the \$1 million H2 Refuel H-Prize Competition. Launched in October 2014, the H2 Refuel H-Prize Competition challenged America's innovators to deploy an on-site hydrogen generation system, using electricity or natural gas, that can be used in homes, community centers, small businesses, or similar locations to fuel hydrogen vehicles. During the competition, SimpleFuel demonstrated that its home-scale refueling appliance can provide a 1-kilogram fill to vehicles in 15 minutes or less at 700 bar using hydrogen produced via electrolysis, with a cost-effective design that minimizes setback distances and reduces the physical footprint of the system.

The HydroGEN advanced water splitting materials consortium, comprised of six core national laboratories (National Renewable Energy Laboratory [NREL], Sandia National Laboratories [SNL], Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Idaho National Laboratory, and Savanna River National Laboratory), launched its expanded website featuring an advanced search engine to facilitate access to the consortium's more than 80 unique world-class research capabilities.[8] HydroGEN also launched its data portal aligned with DOE's Energy Materials Network guidelines and requirements. Nineteen new projects were competitively selected in areas of advanced water splitting materials R&D, which leverage the HydroGEN Consortium's core capabilities. HydroGEN's photoelectrochemical team at NREL published three high-impact journal articles in *Nature Energy* related to the synthesis innovations, rigorous characterization, and benchmark validation of their recent world-record photoelectrochemical device. NREL's ground-breaking device incorporating an inverted metamorphic multijunction structure of III–V semiconductors has achieved photoelectrochemical solar-to-hydrogen conversion efficiencies greater than 16%, exceeding previous records closer to 10%. Besides photoelectrochemical research, the sub-program's R&D supports collaboration between FCTO and NE by enabling integrated energy systems using high- and low-temperature electrolyzers, as well as thermochemical approaches that can use high-temperature solar, nuclear, or other heat sources for hydrogen production.

[7] *Fuel Cell System Cost–2016*, Program Record (Hydrogen and Fuel Cells Program) 16020, U.S. Department of Energy, 2016. https://www.hydrogen.energy.gov/pdfs/16020_fuel_cell_system_cost_2016.pdf
[8] https://energy.gov/eere/fuelcells/hydrogen-advanced-water-splitting-materials-consortium

In addition, based on appropriations guidance, the Program allocated $3 million from FY 2017 funding for R&D on hydrogen production using new chemical synthesis methods that break apart natural gas to solid carbon and hydrogen. A report[9] was prepared on the status of these technologies, and a call for innovative concepts was issued in conjunction with the Office of Fossil Energy's National Energy Technology Laboratory. FCTO and the National Energy Technology Laboratory will report on the outcomes once projects are initiated.

Hydrogen Delivery

Hydrogen delivery, including transport, bulk storage, and dispensing, is increasingly being seen as critical to the rollout of hydrogen infrastructure. In FY 2017, ANL's innovative tube trailer consolidation approach, which is expected to lower hydrogen fueling cost by 40%, received widespread interest by industry, and a patent was issued.[10] The strategy involves using a fueling station's compressor to pressurize the hydrogen in the tube trailer during off-peak hours. As a result, the compressor has high-pressure hydrogen available during peak hours and is able to achieve higher flow rates than otherwise possible. In this way, a station can satisfy its daily demand with a compressor that costs 60% less than under normal operation.[11] The strategy is being evaluated experimentally at NREL through the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project and is also being demonstrated by industry. H2FIRST is just one example of efforts aligned with appropriations guidance to engage national laboratories to pursue novel advanced demonstrations, and it provides feedback to early-stage R&D activities.

In FY 2017, materials R&D funded by DOE and the U.S. Department of Transportation was used in the modification of the ASME B31.12 Code for Hydrogen Piping and Pipelines. Evaluations of the performance of high-strength steel and fiber-reinforced polymer in high-pressure hydrogen service over the past decade have led to Code modifications that (1) allow for the use of fiber-reinforced pipeline in 170-bar hydrogen service and (2) remove thickness penalties on X70 steel used in 100-bar hydrogen service. Each of these modifications can independently lower the installation costs (material and labor) of hydrogen pipelines by 25%.[12] Such examples show how early-stage R&D can impact codes and standards, enabling industry to benefit from core capabilities at the national labs.

Hydrogen Storage

FY 2017 marked the second full year of efforts within HyMARC, the Energy Materials Network consortium on hydrogen storage. The work of the core team of national laboratory partners (SNL–lead, Lawrence Livermore National Laboratory, and Lawrence Berkeley National Laboratory) made a great deal of progress as it continued to address scientific gaps impeding the advancement of materials-based storage. For example, an experimental investigation involving several advanced characterization techniques showed that titanium is not present on the surface during hydrogen desorption from Ti-doped $NaAlH_4$, supporting the "zipper" mechanism and invalidating several other published mechanisms. This study demonstrates the power of bringing together these laboratory capabilities under the umbrella of HyMARC, as it utilized low energy ion scattering at SNL, X-ray adsorption spectroscopy at SNL, and scanning transmission X-ray microscopy as part of the Advanced Light Source project at Lawrence Berkeley National Laboratory. HyMARC researchers also continued to develop extensive theoretical modeling capabilities to complement these experimental tools. Modeling work at Lawrence Livermore National Laboratory on $Mg(BH_4)_2$, a promising material with over 14 wt.% theoretical capacity and favorable thermodynamics, and its absorption/desorption reaction pathways continues to assist other HyMARC core efforts.

In FY 2017, NREL completed the multi-laboratory round robin study on volumetric uptake in sorbents, including national laboratory, university, industrial, and international partners, and analyzed the results to identify sources of error in volumetric uptake measurements. These results are being prepared for dissemination to the hydrogen storage community.

[9] https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26726.pdf
[10] Elgowainy, A. (2017). U.S. Patent No. 9,739,418. Washington, D.C.: U.S. Patent and Trademark Office.
[11] Elgowainy, A., Reddi, K., Sutherland, E., and Joseck, F. "Tube-trailer consolidation strategy for reducing hydrogen refueling station costs." International Journal of Hydrogen Energy (2014). http://www.sciencedirect.com/science/article/pii/S036031991402833X
[12] Cost assessment for fiber-reinforced pipeline has been based on consultation with members of industry. Cost assessment for steel is published in: Fekete, J., Sowards, J.W., and Amaro, R.L. "Economic impact of applying high strength steels in hydrogen gas pipelines." International Journal of Hydrogen Energy (2015). <http://www.sciencedirect.com/science/article/pii/S036031991501575X?via%3Dihub>

Manufacturing R&D

GLWN completed an analysis of the global fuel cell and hydrogen supply chain to determine opportunities, as well as in-depth analysis of the supply chain for five key components (bipolar plates, membranes, gas diffusion layers, catalysts, and hydrogen storage vessels) at different manufacturing volumes.

The Program also continued its efforts on quality control R&D for roll-to-roll manufacturing. For example, NREL identified and tested defective samples of membrane electrode assemblies. Preliminary results indicated that defects less than 10 µm have no immediate effect on performance, but defects larger than 300 µm decrease performance. NREL also demonstrated real-time imaging of membrane thickness. Another success is the partnership of the small company, Mainstream Engineering, with NREL to develop a device to monitor defects; the device should be available in early 2019.

Technology Validation

In FY 2017, fuel cell bus durability exceeding the ultimate DOE–U.S. Department of Transportation target of 25,000 hours was validated based on one bus fuel cell power plant; seven additional fuel cell systems have surpassed the 2016 target of 18,000 hours. More R&D will be required to meet both cost and durability targets simultaneously, but these durability results through use in real-world passenger service (by AC Transit) show tremendous progress and opportunity.

The Program also continued to collect and utilize valuable data through partnership with state and industry activities. For example, using the data reported to NREL from 26 retail hydrogen stations and nine non-retail stations in FY 2017, analyses were conducted on several categories including deployment, performance, reliability, utilization, safety, energy use, and hydrogen quality. Current analysis shows that max daily utilization is beginning to approach station capacity at a few stations, which implies a need for larger and/or more stations to meet the upcoming vehicle demand. An increase in the amount of hydrogen dispensed each quarter results from more stations being built and more fuel cell electric vehicles (FCEVs) on the road. In 2016, over 107,000 kg of hydrogen were dispensed from retail stations. A further deep dive into maintenance by equipment type shows that hydrogen dispensers are now the primary items needing maintenance both in terms of number of events and labor hours. These examples show how technology validation activities help feed back information to guide future early-stage R&D within the Program.

Market Transformation

Examples of progress in market transformation activities include first-of-their-kind prototypes for airport cargo delivery, medium-duty truck parcel delivery, and maritime applications for pier-side power and ultimately ship-board auxiliary power. For airport baggage tow tractors, an initial design has been completed and units have been assembled and tested in field operations. The stacks were redesigned after a root cause failure analysis, new stacks replaced the originals, and testing in the field is underway.

The Maritime Fuel Cell Generator Project, with funding leveraged by the Maritime Administration, is testing a first-of-its-kind hydrogen fuel cell power generator. Initial operation testing at a pier-side site was completed, with results confirming substantial energy efficiency improvements compared to diesel engines. Balance-of-plant components have been redesigned and replaced.

The Fuel Cell Hybrid Electric Medium-Duty Truck Project is developing a design for a battery electric powertrain system hybridized with fuel cell power to improve drive performance and range on a medium-duty cargo truck. The project has completed a prototype design, and vehicle testing is being initiated.

Safety, Codes and Standards

This sub-program focuses on foundational R&D that enables safety and informs the development of codes and standards by industry. In FY 2017, the sub-program collaborated with the National Institute for Standards and Technology, specifically on the standard for hydrogen metering accuracy. Previously, the standard was unachievable with available technology; however, as a result of collaborations between NREL and the National Institute for Standards and Technology and through support from the State of California, a modified hydrogen metrology standard of 5% was accepted in FY 2017, which now permits hydrogen to be sold at retail stations.

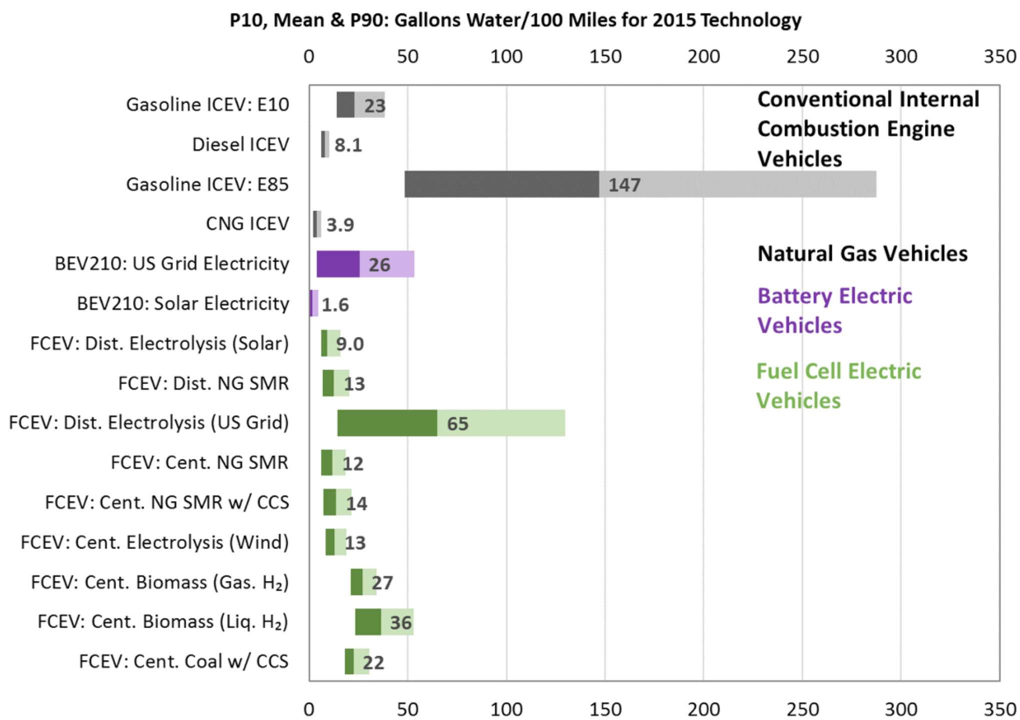
Also in FY 2017, the sub-program built on results from the previous year and released the Hydrogen Risk Assessment Model (HyRAM) Version 1.1 for public use. HyRAM, developed by SNL, enables quantitative risk assessment and performance-based design while also incorporating the sub-program's hydrogen behavior models.

In addition, model development and validation began for cryogenic hydrogen releases in the newly built cryogenic laboratory to help inform separation distances for liquid hydrogen. These unique national lab capabilities provide support on key infrastructure needs such as reducing station setback distances. Finally, the use of risk assessment was applied to real-world scenarios for the use of FCEVs in tunnels. Global stakeholders across industry and relevant code organizations provided significant positive feedback on the value of such tools, and further work to support such efforts is underway.

Systems Analysis

Systems Analysis activities are foundational to the Program and help identify technology gaps, impacts, and future R&D needs. ANL's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model was expanded to assess lifecycle petroleum use and air emissions of medium- and heavy-duty vehicles compared to baseline diesel. Simulation results show that medium- and heavy-duty FCEVs generally achieve 1.7 times better fuel economy (miles per diesel gallon equivalent) compared to conventional diesel vehicles.

ANL also analyzed the lifecycle freshwater consumption associated with various transportation fuels for light-duty vehicles in the United States using the water module of the GREET model. The results show the lifecycle water consumption for FCEVs can be comparable to that of conventional gasoline vehicles for certain fuel pathways, as illustrated in Figure 1. These efforts were coordinated across FCTO, EERE's Vehicle Technologies Office, and EERE's Bioenergy Technology Office to ensure consistency in assumptions across fuel and vehicle pathways.



ICEV – internal combustion engine vehicle; E10 – a fuel blend consisting of 90% gasoline and 10% ethanol; E85 – a fuel blend consisting of 15% gasoline and 85% ethanol; CNG – compressed natural gas; BEV210 – battery electric vehicle with 210 miles all-electric range; NG – natural gas; Dist. – distributed; Cent. – central; SMR – steam methane reforming; CCS – carbon capture and sequestration; Gas. – gaseous; Liq. - liquid

FIGURE 1. Lifecycle water consumption per 100 miles driven (ANL). See DOE program record.[13]

Two separate projects evaluated the impacts of FCTO-funded R&D. One analysis showed that if the ultimate fuel cell and hydrogen storage R&D targets are both met, cost reduction could reach approximately $4,000 per FCEV. The second analysis concluded that successful deployment of FCTO-funded technologies in FCEVs could improve the fuel economy of the light-duty vehicle stock by 25% to 30% and reduce projected petroleum consumption by 0.3 million to approximately 1 million barrels per day.

[13] *Water Consumption for Light-Duty Vehicles' Transportation Fuels*, Program Record (EERE Offices of Fuel Cell, Vehicle, and Bioenergy Technologies) 17005, U.S. Department of Energy, 2017. https://www.hydrogen.energy.gov/pdfs/17005_water_consumption_ldv_fuels.pdf

OTHER PROGRAM ACTIVITIES AND HIGHLIGHTS FROM FY 2016–2017

ARPA-E Programs in Fuel Cells/Electrolyzers for Energy Conversion and Storage

The ARPA-E FY 2017 funding for fuel cells/electrolyzers for energy conversion and storage activities was approximately $47 million. The mission of the ARPA-E program is to develop new disruptive technologies for efficient, cost-effective electrical storage and generation systems using renewable energy and natural gas, with applications for transportation and for commercial and industrial power customers across the economy, resulting in increased energy efficiency and security, significant fuel and energy savings, and emissions reduction. The drivers are growth of intermittent renewable energy and cheap and abundant natural gas, the need for increased efficiency throughout the whole economy, an increased demand for clean/electrified transportation, and the growth of microgrids and distributed energy generation.

Renewable Energy to Fuels through Utilization of Energy-dense Liquids

The Renewable Energy to Fuels through Utilization of Energy-dense Liquids mission is to reduce transportation and storage costs of energy from remote renewable intermittent sources to consumers and to enable the use of existing infrastructure to deliver electricity or hydrogen at the end point. The budget in FY 2017 was $23 million. Specific program goals include the following.

- Develop catalytic or electrochemical fuel cracking to deliver hydrogen at 30 bar at a cost <$4.5/kg, enabling hydrogen fueling stations.
- Develop fuel cell technologies for conversion of fuels to electricity with source-to-use cost <$0.30/kWh.

Reliable Electricity Based on Electrochemical Systems

With an FY 2017 budget of approximately $3 million, the Reliable Electricity Based on Electrochemical Systems mission is to develop transformational electrochemical fuel cell technologies for distributed power generation to improve grid stability, increase energy security, and balance intermittent renewable technologies while reducing CO_2 emissions associated with current distributed generation systems. Specific accomplishments include the following.

- The Colorado School of Mines achieved 150 mW/cm^2 power density at 500°C on direct methane fuel and showed stability for thousands of hours. The project is now scaling up to larger prototypes.
- Georgia Institute of Technology achieved 200 mW/cm^2 power density at 500°C on 97% methane fuel.

Integration and Optimization of Novel Ion-Conducting Solids

Funded in FY 2016, the Integration and Optimization of Novel Ion-Conducting Solids mission is to create components for electrochemical cells using solid ion conductors to enable transformational performance and cost improvements. Specific accomplishments include the following.

- Increased the energy content of Li battery packs by >30% while reducing the cost of energy storage.
- Developed flow batteries with a fully installed cost of $150/kWh for a 5-h duration.
- Created alkaline-conducting membranes that open a path to fuel cells and electrolyzers without expensive, rare elements like Pt.

Innovative Natural-Gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-Generation

With an FY 2017 budget of $20 million that will be expended in FY 2018, FY 2019, and FY 2020, the mission of Innovative Natural-Gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-Generation is to reduce the cost and increase the primary energy efficiency associated with the provision of electric power to commercial and industrial customers. The approach taken is to support the development of natural-gas-fueled distributed generation systems (<1 MW) with electric efficiencies of ≥70% and installed costs of ≤$1,800/kW and to focus on engine–solid oxide fuel cell hybrid systems to leverage available thermo-economic synergies.

Office of Science, Basic Energy Sciences

The Basic Energy Sciences program within the Office of Science had a cross-cut spending level of $22 million in FY 2017. Hydrogen and fuel cells were among the topics in the Energy Frontier Research Center solicitation for which awards will be made in FY 2018. In FY 2017, Basic Energy Sciences held a basic research needs workshop on catalysis science coordinated across EERE and other programs.

Specific accomplishments include the following.

- New functional materials have been synthesized using metal-organic clusters as pore-partitioning agent inside nanoporous channels. With diverse and unprecedented compositions and functionalities, both on the framework and within the channel, these new materials have a number of potential applications such as catalysis, fuel storage, and chemical separation.
- In systems involving interfaces between catalytic surfaces and proton exchange membranes, reactive molecular dynamics, at least 1,000 times faster than ab initio molecular dynamics, has shown how the hydrophilicity of the surface affects the membrane structure, water network formation, and proton transport. Hydrophilic surfaces were found to promote robust water layer formation at the interface. Additionally, decreasing interaction between charged sulfonate groups and hydronium molecules increases diffusion.
- Post-exposure of metal organic framework materials to ethylenediamine forms a monolayer cap, which allows the trapping of small molecules, even when they are only weakly bound. The ability to create a molecular surface barrier layer on metal organic framework external surfaces constitutes an entirely new paradigm for trapping weakly adsorbing molecules within metal organic frameworks, with importance for gas storage and sequestration applications.

Office of Fossil Energy, Solid Oxide Fuel Cell Program

The Solid Oxide Fuel Cell Program within the Office of Fossil Energy had an enacted budget of $30 million in FY 2017. The 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 Solid Oxide Fuel Cell 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 solid oxide fuel cell developers to address and resolve reliability issues, improve performance, and reduce the cost of solid oxide fuel cell power systems. Based on progressively larger natural-gas-fueled validation tests, MWe-class distributed generation solid oxide fuel cell power systems that are cost-competitive with existing distributed generation technologies are envisioned circa 2020.

Specific FY 2017 accomplishments include the following.

- Operated 50 kWe proof-of-concept system.
- Operated 200 kWe pressurized proof-of-concept system.
- Awarded contracts for two 250 kWe-class prototype system field tests.
- Developed multiple approaches to mitigate chromium-assisted system degradation.

Office of Nuclear Energy

NE is working with partners in EERE and industry to evaluate the potential demonstration of commercial-scale production of hydrogen using heat from a nuclear energy system. In addition to producing emissions-free electricity, some advanced nuclear reactor designs now under development by NE, which operate at very high temperatures, will be well suited for providing the low-cost heat necessary to economically produce hydrogen using promising new thermally-driven hydrogen production processes.

In FY 2017, NE provided $2 million in collaborative research funding to analyze, via advanced modeling and simulation tools, and develop the following technologies that use nuclear reactors to produce hydrogen, in collaboration with EERE's FCTO.

- High-temperature electrolysis (HTE): HTE uses electricity to produce hydrogen from steam instead of liquid water. This method promises higher efficiencies than standard electrolysis, which is employed commercially today. The new high-temperature design involves many technical challenges, including the development of high-temperature materials and membranes. FY 2017 research indicates the potential to use steam produced via current light water reactor technologies, in addition to advanced reactor designs, to support HTE.
- Reactor/hydrogen production process interface: The interface between the nuclear reactor and the hydrogen production system involves potentially long heat transfer paths at elevated temperatures, heat exchangers that are subject to both elevated temperature and corrosive chemical environments, new safety and regulatory issues, and supporting systems for chemical processes and hydrogen and oxygen storage. FY 2017 research under NE focused on developing high-fidelity, dynamic modeling and simulation tools that can be applied to determine optimal system design and operation for use of light water reactor technologies to support hydrogen production via HTE.
- Thermochemical water-splitting cycles: Previous research indicated strong potential for the use of thermochemical water splitting processes to produce hydrogen. Thermochemical cycles are a series of chemical reactions that convert water to hydrogen and oxygen using chemical catalysts at high temperatures. These processes offer the potential for high-efficiency hydrogen production at large-scale production rates, but the technology is relatively immature.

INTERNATIONAL ACTIVITIES

International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)

IPHE includes 18 member countries (Australia, Austria, Brazil, Canada, China, 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 is a forum for governments to work together to advance worldwide progress in hydrogen and fuel cell technologies. IPHE also offers a mechanism for international R&D managers, researchers, and policy makers to share program strategies, early-stage R&D, and the status of demonstrations and various assessments. IPHE members embarked upon a second 10-year term in November 2013. An independent secretariat was established in 2015, and France is currently the Chair. The United States continues its strong role as Vice Chair. In FY 2017, the IPHE Steering Committee met in Gwangju, Republic of Korea (November 2016), and in Hanover, Germany (April 2017), to share progress and plans related to hydrogen and fuel cells.

International Energy Agency

The United States is also involved in international collaboration on hydrogen and fuel cell R&D through the International Energy Agency's Technology Collaboration Program on Advanced Fuel Cells. This Technology Collaboration Program provides a mechanism for member countries to share the results of pre-competitive R&D and analysis activities related to innovative fuel cell and electrolyzer technologies. In FY 2017, the Advanced Fuel Cells Technology Collaboration Program ramped up efforts. Outreach events and topical meetings will be included in future plans in addition to publication of new materials such as journal articles and books. The Executive Committee will explore standardization of measurement and reporting procedures in electrolysis to help facilitate R&D of different electrolyzer technologies.

EXTERNAL COORDINATION, INPUT, AND ASSESSMENTS

Hydrogen and Fuel Cells Technical Advisory Committee

The Hydrogen and Fuel Cells Technical Advisory Committee, a congressionally mandated committee to advise the Secretary of Energy, formally convened once in FY 2017. In July 2017, the Committee submitted its ninth annual report to DOE, which summarizes progress in hydrogen and fuel cell technologies, domestic and international R&D and demonstrations, and commercialization activities, and offers recommendations on the Department's hydrogen-related R&D activities and initiatives. Also in 2017, the Hydrogen Safety and Event Response Plan subcommittee completed its work to review and assess current resources such as safety plans; event response plans; current federal, state, and local requirements; and case studies to identify gaps and potential actions to address current and projected needs. The Committee submitted a report to the Energy Secretary summarizing the findings of the subcommittee, including recommendations to address the identified gaps.

Federal Inter-Agency Coordination

The Hydrogen and Fuel Cell Interagency Task Force, mandated by the Energy Policy Act of 2005, includes senior representatives from federal agencies supporting hydrogen and fuel cell activities, with DOE serving as the chair. One example of interagency collaboration was the development of a federal fleet strategy for early adoption of FCEVs to drive initial demand and lead by example. Four separate federal agencies—Veterans Affairs, Department of Defense, DOE, and National Aeronautics and Space Administration—each expressed interest in leasing FCEVs in California following DOE and task force input, to make use of and help grow the nascent hydrogen infrastructure there.

Another example involves DOE and the United States Postal Service. In FY 2017, the United States Postal Service installed approximately 90 fuel-cell-powered material handling equipment units at their Washington, D.C., Network Distribution Center. The Hydrogen and Fuel Cell Interagency Working Group held a webinar on the results of previous fuel cell forklift deployments within the Department of Defense and DOE, which led the United States Postal Service to move forward on its first deployment of fuel cell material handling equipment at its Capitol Heights (Maryland) Network Distribution Center. In addition, the Interagency Working Group continued to meet monthly, led by FCTO, to coordinate hydrogen and fuel cell activities across all relevant agencies.

FY 2017 Annual Merit Review and Peer Evaluation (AMR)

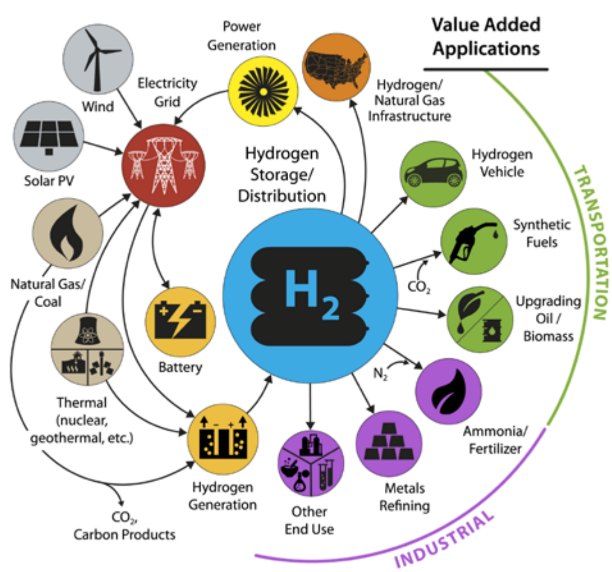
The Program's AMR took place June 5–9, 2017, in Washington, D.C., and provided an opportunity for the Program to obtain expert peer reviews of the projects it supports and to report its accomplishments and progress. This year, approximately 1,800 participants attended, and more than 380 experts peer-reviewed 150 of the Program's projects. The report summarizing the results and comments from these reviews is available on DOE's website.[14] The 2018 AMR will be held June 13–15 in Washington, D.C. For the first time, the AMR will include presentations from other federal agencies and state activities and will be preceded by a National Hydrogen and Fuel Cell Forum, showcasing industry progress, exhibits of technologies, and opportunities.

Funds Saved through Active Project Management

The AMR is a key part of the Program's comprehensive approach toward active management of its projects. Termination of underperforming projects—identified through the AMR as well as through go/no-go decisions (with criteria defined in the project scope of work)—helped the Program redirect approximately $3.3 million in funding in FY 2017, $2.4 million in funding in FY 2016, $1.6 million in funding in FY 2015, and over $42 million since FY 2010. In addition, the Program implements EERE's robust Active Project Management requirements to identify and resolve issues early and to mitigate risks in impactful ways, helping underperforming projects get back on track.

Hydrogen at Scale (H2@Scale) Activities

Finally, a cornerstone of the Program's activities and future plans is the H2@Scale concept. Numerous activities were conducted throughout FY 2017 in support of this effort.[15] H2@Scale is a DOE initiative to enable technology innovations that unlock revenue potential across multiple sectors. Figure 2 depicts the H2@Scale conceptual vision with hydrogen as an energy carrier, like electricity, but opening up many more value-added applications, in addition to enabling energy security, energy storage, and resilience. The premise of H2@Scale is that water-splitting technologies can be used to supply hydrogen to growing industries by leveraging low-cost sources of energy that are intermittently available throughout the year (such as solar or wind), and low-cost baseload power generation (such as nuclear), which are increasingly facing challenges as a higher proportion of renewables enter the market. R&D efforts include scalable concepts for dispatchable hydrogen production, delivery, and storage, including hydrogen carriers, liquefaction, materials development, and



PV – photovoltaic

FIGURE 2. Schematic of H2@Scale Concept

[14] https://www.hydrogen.energy.gov/annual_review17_report.html
[15] https://energy.gov/eere/fuelcells/h2-scale

integration with diverse generation sources. To gather feedback from external stakeholders, DOE held multiple workshops and distributed a request for information. The Program also completed a report on hydrogen infrastructure, which included a discussion of the Department's coordination with other relevant agencies.

To advance H2@Scale from a strategic perspective, national labs conducted scenario analyses to determine the potential for hydrogen production using domestic resources across the nation as well as market demand potential. The next steps are to determine where hydrogen utilization could be increased from a business case perspective and to couple this increase with the potential for hydrogen generation at scale. The technical potential for hydrogen was estimated to be 60 million metric tons per year; this preliminary analysis will be updated and an estimate for the economic potential will be developed.

In FY 2017, Idaho National Laboratory developed a world-class HTE laboratory and test capability that includes a flexible test station plus infrastructure support for up to 250 kW HTE turnkey systems, in collaboration with NREL. The Program conducted R&D for modular solid oxide electrolysis systems with potential for producing hydrogen at a cost of $2/kg or less (excluding delivery, compression, storage, and dispensing). The Program also demonstrated sub-second response times and real-time simulation of the grid through a first-of-a-kind capability linking Idaho National Laboratory and NREL. These efforts demonstrate the value of hydrogen not only for energy storage, but also for grid resiliency and ancillary services such as frequency regulation, as a result of the dynamic response capabilities of electrolyzers.

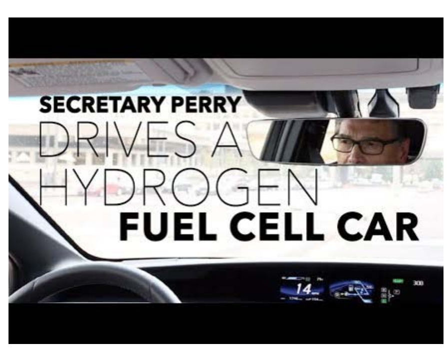
A major accomplishment in FY 2017 was leveraging the private sector and state funds by offering state-of-the-art national lab capabilities to address the key challenges in enabling the H2@Scale vision. A total of 25 projects were selected as part of a Cooperative Research and Development Agreement call for proposals focused on H2@Scale. Projects selected through this process include work in hydrogen component R&D, hydrogen integration as an energy carrier, station risk analysis and safety R&D, and hydrogen production R&D. The Program will focus on these activities along with working groups to address remaining challenges in the coming year.

IN CLOSING …

Now is an exciting time for the hydrogen and fuel cell industry. The fuel cell market has seen consistent growth in the last few years. In fact, more than 62,000 fuel cell systems and 500 MW in fuel cell power shipped in 2016, and on average, shipments of fuel cell systems are growing 30% annually worldwide.[16] More exciting yet, Toyota, Hyundai, and Honda all have commercially available fuel cell vehicle models, and growth capacity in the transportation sector nearly tripled in one year. This can be attributed to the introduction and expansion of fuel cell light-duty vehicles from Japan and Korea to new regions around the world, including the United States. In the United States, the stock of fuel cell electric vehicles has increased rapidly, especially in the past year. Research shows that there were nearly 3,500 fuel cell cars on the road, primarily in California, through the end of 2017. Automakers and hydrogen providers have made commitments for commercial deployments in the northeastern United States as well.

Another strong signal of the growing global interest in hydrogen and fuel cells is the launch of the Hydrogen Council in January 2017. The Hydrogen Council is a global initiative of chief executive officers in leading energy, transport, and industrial sectors. It includes major companies such as Toyota, General Motors, Honda, Hyundai, Shell, and others, who collectively represent total revenues of well over $1 trillion and have 1.7 million employees around the world. They have estimated the potential for over $2.5 trillion in revenues and 30 million jobs globally by 2050 as a result of hydrogen technologies worldwide across sectors.

At DOE, both Secretary of Energy Rick Perry and Daniel Simmons, Principal Deputy Assistant Secretary, were able to drive fuel cell electric vehicles that are part of the DOE fleet. Videos were created to commemorate both occasions and were posted online.[17] On loan from Toyota and Hyundai, DOE's fuel cell vehicles are used for interagency, congressional, and community outreach across the Washington, D.C., area, in addition to generating real-world fueling data that will help guide future early-stage R&D efforts.



This is a critical time for fuel cells and hydrogen, particularly in addressing the challenge of hydrogen infrastructure. This introduction provides only a few examples of activities conducted within FY 2017. The hundreds of pages

[16] https://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-market-report
[17] https://energy.gov/eere/fuelcells/secretary-perry-drives-hydrogen-fuel-cell-car

that follow provide more detail from project recipients, demonstrating the value and impact of DOE funds. 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, fostering early-stage R&D and innovation, and enabling the success of hydrogen and fuel cell technologies as one component of an "all of the above" energy strategy for the nation.

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