# Introduction

The U.S. Department of Energy's Hydrogen and Fuel Cells Program (the Program) focuses on early stage research and development (R&D) activities and works with stakeholders to enable the widespread market acceptance 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 (FE), Nuclear Energy (NE), Science (SC), and Advanced Research Projects Agency–Energy (ARPA-E). Every year, FCTO publishes an Annual Progress Report documenting progress, accomplishments, and technology status with respect to performance metrics. This report includes several hundred 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 subprogram introductions, subsequent project reports, and in the corresponding 2018 Annual Merit Review and Peer Evaluation Report.

In Fiscal Year (FY) 2018, Congress appropriated approximately $115 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, $2 million, and $19 million, respectively. This represents a total DOE budget for FY 2018 of approximately $185 million related to hydrogen and fuel cell technologies.[1] 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

In FY 2018, the Program's primary efforts focused on increasing its emphasis on Hydrogen at Scale (H2@Scale).[2] H2@Scale is a DOE initiative that brings together stakeholders to advance affordable hydrogen production, transport, storage, and utilization to increase revenue opportunities and impact in multiple energy sectors. Figure 1 depicts the H2@Scale conceptual vision with hydrogen as an energy carrier that enables new value-added applications. The premise of H2@Scale is that hydrogen can be generated and used in various industries by leveraging low-cost sources of energy that are intermittently available throughout the year (such as solar or wind) *as well as* baseload power (such as nuclear) from generators that are being economically challenged by ongoing changes in the energy sector. By optimizing the use of otherwise-curtailed energy, as well as energy sources that cannot be turned down rapidly enough to compensate for intermittent renewables, H2@Scale offers innovative ways to enable energy security, energy storage, resilience, and economic value. R&D efforts include scalable concepts for dispatchable hydrogen production, delivery, and storage, including hydrogen carriers, liquefaction, materials development, and systems integration across diverse generation sources and end uses.

[1] Historical budgets are available at https://www.hydrogen.energy.gov/budget.html.
[2] For more information, see https://energy.gov/eere/fuelcells/h2-scale.

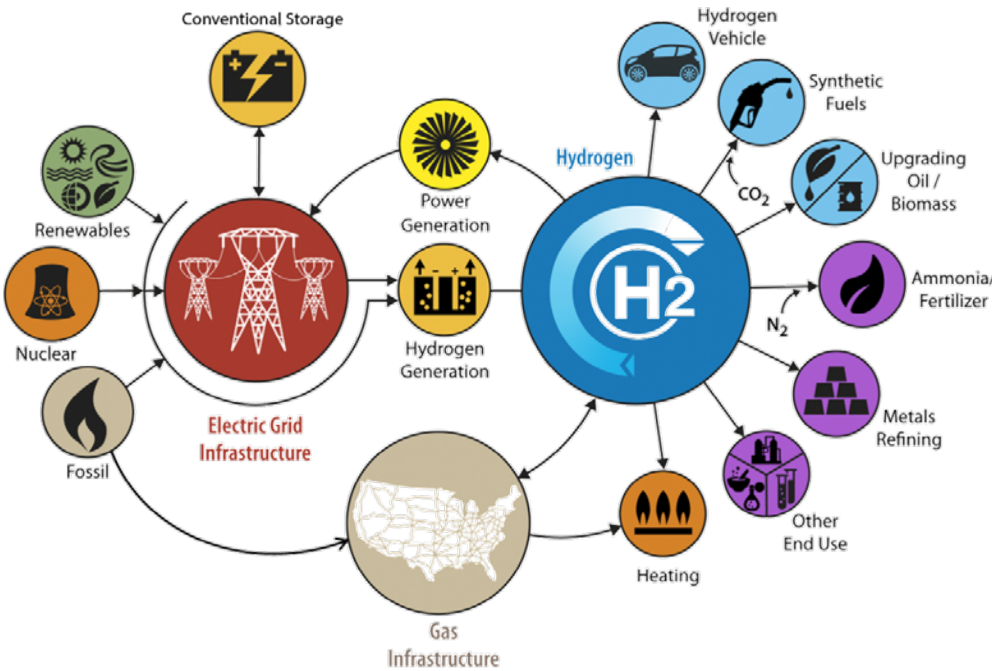


Figure 1. Schematic of H2@Scale

The H2@Scale initiative also provides a framework in which national laboratories and industry can work together through government co-funded projects to accelerate the early-stage research, development, and demonstration of applicable hydrogen technologies.

In FY 2018, the Program held a kickoff meeting for more than 20 H2@Scale cooperative research and development agreement (CRADA) projects that were selected in late FY 2017. H2@Scale CRADA projects are being funded at the national laboratories by industry and nonprofit organizations, with cost match from FCTO. Project focus areas include integrating hydrogen production with electricity generation and transmission; reducing the cost of hydrogen production technologies; and lowering the cost, reducing footprint, and improving reliability of hydrogen fueling infrastructure. The H2@Scale "consortium" refers to the group of national laboratory and private sector partners that have ongoing CRADA projects. In FY 2018, the Program revised the original structure of the thematic areas within H2@Scale from a project-oriented format into four working group themes: "Make," "Move," "Use," and "Store" hydrogen. Subsequent to the August 2018 kickoff meeting, members of project teams related to hydrogen production and grid integration held the first Make working group meeting in December 2018. These working group meetings occur monthly to facilitate collaboration in specific areas.

Through a collaboration between FCTO and NE, a team of national laboratory researchers led by the National Renewable Energy Laboratory (NREL), and including Argonne National Laboratory (ANL), Idaho National Laboratory, and others, conducted a comprehensive analysis of the technical and economic potential of the H2@Scale vision in the United States. The analysis is currently under DOE review. Preliminary results characterize the maximum potential demand for hydrogen in the United States as roughly 150 million metric tonnes per year (MMTY) and the economic potential demand as 22–45 MMTY; for reference, U.S. hydrogen demand is currently approximately 10 MMTY. Analysis also indicates that ample, diverse energy resources (e.g., solar power, wind power, nuclear power, and natural gas) are available throughout the United States to satisfy the maximum potential demand for hydrogen.

Also in FY 2018, the Program competitively selected four new projects to demonstrate first-of-a-kind hydrogen-focused integrated renewable energy production, storage, and transportation fuel distribution/retailing systems. These projects will demonstrate use of electrolyzers to supply grid services at a solar farm, autonomous hydrogen fueling technologies, electrolysis of wastewater, and synthesis of methanol and dimethyl ether from streams of hydrogen and carbon dioxide. The Program also selected four new projects to enable cost-competitive manufacturing of megawatt-scale electrolyzers. Electrolyzers at megawatt scales are expected to be required in emerging applications, such as the provision of grid services or hydrogen production at fueling stations.

Lastly, the Program released two H2@Scale-related Requests for Information (RFIs) in FY 2018 to gather information from stakeholders. In August 2018, in collaboration with eight other DOE offices, the Program released a comprehensive H2@Scale RFI. This RFI aimed to identify and quantify domestic resources compatible with large-scale hydrogen production, and to identify pathways to enable effective near- and long-term leveraging of these resources in major industries requiring affordable, secure, domestic, and scalable hydrogen supplies. Information gathered from the RFI may guide H2@Scale projects and funding opportunities in FY 2019. In June 2018, the Program released an RFI to gather feedback on regulatory barriers to the development of hydrogen infrastructure. DOE will review the information gathered to identify priority R&D to reduce regulatory barriers affecting implementation of hydrogen technologies and potential courses of action to reduce deployment time and cost; share the information with relevant agencies with regulatory authority; and explore opportunities for interagency collaboration.

The Program also continued to prioritize early-stage R&D working through four consortia: Electrocatalysis Consortium (ElectroCAT), HydroGEN Advanced Water Splitting Materials Consortium (HydroGEN), Hydrogen Materials—Advanced Research Consortium (HyMARC), and the newly formed Hydrogen Materials Compatibility Consortium (H-Mat). These consortia 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 (EMN), these efforts 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 in energy materials R&D through a multi-disciplinary team approach.

### 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, this funding has led to more than 730 hydrogen and fuel cell patents with approximately 35% coming from the national labs.[3] More than 30 technologies have been commercialized as a result of this research, including 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]

## EXAMPLES OF PROGRESS AND ACCOMPLISHMENTS BY KEY ACTIVITY

### Hydrogen Fuel R&D

The Hydrogen Fuel R&D subprogram focuses on early-stage 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 evaluates its project portfolio with respect to its potential to meet DOE's ultimate cost targets of

[3] 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
[4] DOE Hydrogen and Fuel Cells Program Record #16020, https://www.hydrogen.energy.gov/pdfs/16020_fuel_cell_system_cost_2016.pdf
[5] DOE Hydrogen and Fuel Cells Program Record #16019, https://www.hydrogen.energy.gov/pdfs/16019_fuel_cell_stack_durability_2016.pdf
[6] DOE Hydrogen and Fuel Cells Program Record #14004, https://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf

<$2/kg for hydrogen production, and $8/kWh for hydrogen storage system cost while achieving 2.2 kWh/kg and 1.7 kWh/L for hydrogen storage system gravimetric and volumetric energy densities, respectively.

FY 2018 activities focused primarily on early-stage R&D funded through the subprogram's two consortia:

1. HydroGEN to accelerate research, development, and deployment of advanced water splitting technologies for clean, sustainable hydrogen production.

2. HyMARC to accelerate the discovery of breakthrough hydrogen storage materials.

The Hydrogen Fuel R&D subprogram made significant progress on several fronts during FY 2018. Specific examples include the following.

- HydroGEN successfully engaged in an interagency collaboration with the National Science Foundation's (NSF) Designing Materials to Revolutionize and Engineer our Future (DMREF) program element, resulting in four NSF DMREF projects that will leverage HydroGEN's expertise and capabilities in three water splitting technologies—photoelectrochemical (PEC), low temperature electrolysis (LTE), and solar thermochemical (STCH).
- In PEC materials R&D, Rutgers achieved a solar-to-hydrogen efficiency of 11.5% with a platinum-group-metal (PGM)-free $Ni_5P_4$ hydrogen evolution catalyst integrated with a high-performing photoabsorber; this exceeds the target of 10% efficiency and is on par with conventional PtRu catalysts.
- In the areas of STCH materials R&D, the University of Colorado Boulder developed machine learning models for the discovery of efficient and stable STCH materials, identifying ~28,000 stable perovskite formulations from more than 1.1 million possible candidates with greater than 90% accuracy.
- Hydrogen storage R&D accomplishments included the demonstration of lower-cost polyacrylonitrile (PAN) feedstock material fiber spinning and conversion to high strength carbon fiber, resulting in 14% cost reduction compared to the current PAN. The University of Kentucky also demonstrated efficient solvent recovery and reduced fresh water use.
- A HyMARC seedling project conducted by the University of Hawaii demonstrated hydrogenation of $MgB_2$ to $Mg(BH_4)_2$ at 25% lower temperature and 22% lower pressure than prior state of the art.

### Fuel Cell R&D

One of the most important metrics used to guide the Fuel Cell R&D subprogram's R&D efforts is the projected high-volume manufacturing cost for automotive fuel cells, which is tracked periodically. The subprogram is targeting an interim cost of $40/kW and durability of 5,000 hours by 2025. Long-term competitiveness with alternative powertrains is expected to require further cost reduction to $30/kW and 8,000 hours durability, which represent the subprogram's ultimate targets. The industry peer-reviewed cost projection for an 80-$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/year and $45/$kW_{net}$ when manufactured at 500,000 units/year.[7] However, this status does not quite meet the durability targets of 5,000 hours by 2025 and further analysis is underway to update the cost projections.

[7] Hydrogen and Fuel Cells Program Record #16020, https://www.hydrogen.energy.gov/pdfs/16020_fuel_cell_system_cost_2016.pdf

In FY 2018, the ElectroCat and Fuel Cell Consortium for Performance and Durability (FC-PAD) made significant progress in R&D of PGM-free and low-PGM catalysts and electrodes, respectively. Highlights include the following.

- FC-PAD continued to conduct foundational R&D on low-PGM catalysts and electrodes that is critical to decreasing cost and improving performance and durability of PEMFCs. For example, FC-PAD researchers conducted extensive characterization and electrochemical testing of stack materials to benchmark on-road commercial fuel cell technology.
- ElectroCat made a number of breakthroughs in PGM-free catalysts. The consortium made key insights into the structure and density of active sites by counting with molecular probes, backed up by electrochemical, spectroscopic, and computational tools.
    - The core consortium improved catalyst performance in membrane electrode assemblies by more than 50% compared to the 2016 baseline. In one example, PGM-free catalysts achieved 27 mA/cm$^2$ compared to the 2016 baseline of 16 (mA/cm$^2$), a more than 65% improvement.
    - The consortium also began working with new industry and academic partners to improve PGM-free catalysts, resulting in record performance for Co- and Mn-based catalysts.
- A project led by Los Alamos National Laboratory (LANL) has developed novel membranes and electrode ionomers to enable fuel cells operating over a temperature range of 80°– 220°C, with demonstrated power density of nearly 1.5 W/cm$^2$ at 200°C. In this project, a highly conductive phosphonated ionomer and a phosphoric-acid-doped, ion-pair-coordinated quaternary ammonium hydrocarbon-based polymer membrane increased low-temperature performance and water tolerance with significantly decreased phosphoric acid leaching. This project will be continued through a grant recently awarded by ARPA-E, demonstrating effective cross-office coordination.

### Technology Acceleration and Hydrogen Infrastructure R&D

Technology Acceleration and Hydrogen Infrastructure R&D activities help accelerate the transition of early-stage hydrogen and fuel cell research to subsequent stages of development and leverage the private sector to enable deployment. This includes R&D to integrate hydrogen production technologies with the electricity grid, advance technologies that can be used in hybrid energy systems, lower the cost of manufacturing hydrogen and fuel cell technologies, reduce the cost of hydrogen transport and distribution, reduce the cost and improve reliability of hydrogen fueling stations, and support the infrastructure component supply chain. In FY 2018, hydrogen delivery R&D was moved into a new Hydrogen Infrastructure R&D budget line item in the FY 2019 budget request, emphasizing the importance of hydrogen delivery R&D in the context of hydrogen infrastructure.

In FY 2018, Technology Acceleration and Hydrogen Infrastructure R&D made significant progress to advance cost-competitive hydrogen technologies and establish the viability of hydrogen in emerging applications. R&D is aimed at achieving the Program's objective of $5/kg for hydrogen delivery and dispensing by 2025 ($2/kg ultimate target) and supporting the Program's H2@Scale initiative.

Examples of key accomplishments in FY 2018 include the following.

- In collaboration with the Safety, Codes and Standards subprogram and the hydrogen storage activity within the Hydrogen Fuel R&D subprogram, Technology Acceleration and Hydrogen Infrastructure R&D initiated activities to launch the Hydrogen Materials Compatibility (H-Mat) national laboratory consortium. H-Mat will conduct materials research to reduce the costs and enhance the durability of steels and polymers in hydrogen service.

- One of the 27 fuel cell electric buses undergoing performance evaluation by NREL exceeded DOE's ultimate target for fuel cell durability of 25,000 hours. Twelve buses have exceeded 19,000 hours to date. NREL continued to collect data on bus maintenance costs and hydrogen consumption and completed its annual report on status versus targets.

- GVD Corporation determined that its novel coatings for hydrogen compressor seals can reduce seal erosion by 70%. GVD's coatings comprise polymeric and inorganic layers that enhance seal flexibility and lubricity, and they are expected to reduce hydrogen permeation by 10-fold.

- Giner ELX achieved one of the highest known efficiencies to date for 350-bar electrochemical hydrogen compression—4 kWh/kg at an inlet pressure of 100 bar and outlet pressure of 350 bar. Giner's compressor concept relies on novel aromatic membranes that achieve 30% less drag than conventional perfluorosulfonic acid membranes and 50% less back diffusion.

- Ivys Energy Solutions established that its approach to wireless communication between vehicles and fueling stations, using digital short range communication, can exceed the requirements of the SAE International J2799 standard. Ivys also established that its novel metering technology, based on Coriolis meters, can achieve an accuracy of at least 2%. The accuracy of 2% exceeds the current hydrogen meter accuracy requirement of 5% specified in the National Institute of Standards and Technology Handbook 44.

- NREL and Gore scanned rolls of fuel cell membrane material on a web-line optical research apparatus at NREL to obtain a two-dimensional thickness map (at ~1 mm spatial resolution). This map can be easily be analyzed to locate where thickness is above or below defined thresholds for quality control. In-line mapping of thickness will help enable high-volume manufacturing and cost reduction of membranes for fuel cells and electrolyzers.

- ANL completed performance evaluation of the Toyota Mirai under varying conditions, including outside temperature (-7°C to 35°C). Systems engineering solutions have enabled excellent durability.

### Safety, Codes and Standards

The Safety, Codes and Standards subprogram focuses on R&D that enables safety as well as the development of codes and standards by industry, informed by FCTO's foundational research. The subprogram identifies and performs early-stage R&D that provides a fundamental understanding of the relevant physics, critical data, and safety information used to develop and revise technically sound and defensible codes and standards.

FY 2018 accomplishments include the following.

- Sandia National Laboratories (SNL) published a report documenting a "Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study" that provided a scientific basis for allowing fuel cell electric vehicles (FCEVs) in tunnels. The report is intended to enable the adoption of FCEVs in the northeast region of the United States.

- Pacific Northwest National Laboratory (PNNL) partnered with the American Institute of Chemical Engineers to establish the Center for Hydrogen Safety, enabling long-term sustainability and broader impact of the Hydrogen Safety Panel and its safety knowledge resources.

- LANLcompleted the planning and installation of an in-line fuel analyzer in the field (with H2Frontier) and conducted on-site baseline measurements while adding wireless capabilities for remote testing.

- SNL developed and proposed design curves for pressure-vessel steels—applicable to both Cr-Mo and Ni-Cr-Mo steels—to the ASME (the American Society of Mechanical Engineers) Pressure Vessel Committee as the basis for a code case that will allow pressure vessel design for high-pressure hydrogen without additional testing burden.

### Systems Analysis

Systems Analysis activities are foundational to the Program and help identify technology gaps, impacts, and future R&D needs. Systems Analysis also supports H2@Scale activities as demonstrated by the results reported above.

Two separate projects evaluated the cost impacts of FCTO-funded R&D. A comparative total cost of ownership analysis was completed for five different truck powertrain technologies (diesel, diesel hybrid-electric, compressed natural gas, battery electric, and fuel cell electric) in three different truck applications (Class 8 long haul, Class 8 short haul, and Class 4 parcel delivery) for three time periods reflecting different technology status levels (2018, 2020, and 2040). The study found fuel cell powertrain trucks to have the lowest total cost of ownership of the various powertrains by 2020, if FCTO program cost and performance targets are met.

The second study evaluated the potential of reducing fueling station costs by integrating advanced onboard storage systems with hydrogen delivery technology. The analysis concluded that the hydrogen delivery and refueling cost is strongly impacted by the pressure and temperature requirements of an FCEV's onboard storage systems. Low-pressure and near-ambient-temperature dispensing can significantly reduce hydrogen dispensing cost to FCEV customers. These onboard storage options, including their respective boundary conditions, will be integrated with hydrogen delivery technologies to evaluate the cost impact on the hydrogen pathways. The inputs and assumptions used in these analysis efforts are the result of collaboration with EERE's Vehicle Technologies Office and Bioenergy Technologies Office.

## OTHER PROGRAM ACTIVITIES AND HIGHLIGHTS FROM FY 2017–2018

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

ARPA-E's FY 2018 funding for fuel cells and electrolyzers for energy conversion and storage activities was approximately $20 million, which was applied to focused programs as well as projects within the more general OPEN 2015 solicitation. In FY 2019, ARPA-E anticipates a budget of approximately $15 million in related selected projects from the recent OPEN 2018 solicitation. The mission of the 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, commercial, and industrial power customers across the economy, resulting in increased energy efficiency and security, significant fuel and energy savings, and reduced emissions. The drivers are growth of intermittent renewable energy and cheap and abundant natural gas, the need for increased energy efficiency throughout the whole economy, an increased demand for clean/electrified transportation, and the growth of microgrids and distributed energy generation.

#### *Duration Addition to electricitY Storage*

The mission of the Duration Addition to electricitY Storage (DAYS) program is to develop energy storage systems that provide power to the electric grid for durations of 10 hours to up to 100 hours, opening significant new opportunities to increase grid resilience and performance. The extended discharge times of DAYS projects will enable a new set of grid applications including long-lasting backup power and greater integration of domestic, renewable energy resources. Project teams will develop storage systems that are deployable in almost any location and charge and discharge electricity at a target fixed cost per cycle. The FY 2018 budget for projects related to chemical storage is approximately $12 million with projects commencing in FY 2019.

### *Renewable Energy to Fuels through Utilization of Energy-dense Liquids*

The Renewable Energy to Fuels through Utilization of Energy-dense Liquids (REFUEL) program mission is to reduce transportation and storage costs of energy from remote renewable intermittent sources to consumers and enable the use of existing infrastructure to deliver electricity or hydrogen at the end point. Specific program goals are to:

- 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*

The Reliable Electricity Based on ELectrochemical Systems (REBELS) 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 Tech 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 (IONICS) mission is to create components for electrochemical cells using solid ion conductors to enable transformational performance and cost improvements. The FY 2018 budget was approximately $7 million. Specific accomplishments include the following:

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

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

Funded in FY 2017 with projects commencing in FY 2018, the mission of the Innovative Natural-Gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-Generation (INTEGRATE) program 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 focus on engine/solid oxide fuel cell (SOFC) 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 approximately $20 million in FY 2018. 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:

- Increases in catalytic reactivity were realized by tailoring the oxide surfaces at the atomic level. Layer-by-layer synthesis of perovskite oxide catalysts was utilized to precisely locate the reactive dopant atoms and increase catalytic activity while avoiding surface poisoning reactions.
- A single-site water oxidation catalyst was designed that increased the reaction rate more than 100 times at low pH. By utilizing computational insights, a catalyst was designed to more easily accommodate the water molecule and lower the barriers to oxidation, thereby substantially increasing the rate of hydrogen production.
- New insights into hydrogen bonding in a metal-organic framework material are allowing selective diffusion of gases through the material. Hydrogen-containing molecules such as $NH_3$ and $H_2O$ can displace other molecules in the metal-organic framework crystallite via a hydrogen bond and then block molecules such as $CO_2$, while allowing hydrocarbons to pass through.

### Office of Fossil Energy, Solid Oxide Fuel Cell Program

The SOFC Program within FE had an enacted budget of $30 million in FY 2018. 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 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. Based on progressively larger natural-gas-fueled validation tests, MWe-class distributed generation SOFC power systems that are cost competitive with existing distributed generation technologies are envisioned circa 2020.

Specific FY 2018 accomplishments include the following:

- Field tested a 250 kWe pressurized prototype system.
- Factory tested a 200 kWe prototype system.
- Awarded two projects to initiate conceptual design and conduct techno-economic evaluation of a distributed generation, natural-gas-fueled MWe-class SOFC power system.

### 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 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 technologies (currently operating and new builds), although these systems will likely be operated at somewhat lower efficiency than advanced high-temperature reactors.

In FY 2018, NE provided funding for collaborative research to analyze (via advanced modeling and simulation tools) and develop the following technologies that use nuclear reactors to produce hydrogen, in collaboration with 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 2018 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 2018 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.

FY 2018 NE funding also supported development of a detailed engineering 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 a light water reactor. It is anticipated that this thermal system will be constructed in FY 2019 to support future nuclear system demonstration.

## INTERNATIONAL ACTIVITIES

### International Partnership for Hydrogen and Fuel Cells in the Economy

The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is a forum for governments to work together to advance worldwide progress in hydrogen and fuel cell technologies. It 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. Additional countries expressed interest in 2018 as well. The United States was elected as chair at the May 2018 Steering Committee meeting in Japan and subsequently chaired the Steering Committee meeting in South Africa. In October Japan hosted the first Hydrogen Energy Ministerial in more than 15 years, attended by representatives from 20 countries including Deputy Secretary of Energy Dan Brouillette. IPHE agreed to rename its Regulations, Codes and Standards (RCS) Working Group to RCSS by adding an emphasis on safety. Sharing safety information, harmonizing codes and standards, and ensuring a global market for the growing supply chain are examples of focus areas within IPHE.

### International Energy Agency

The United States is involved in international collaboration on clean energy technologies through the International Energy Agency's Technology Collaboration Programme (TCP) on Advanced Fuel Cells. This TCP 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 2018, the TCP on Advanced Fuel Cells held an outreach event at its Executive Committee meeting in cooperation with the Austrian Energy Agency. The event was targeted toward Austrian stakeholders and addressed the market readiness of fuel cells. The TCP voted to set up a subtask on heavy duty vehicles in the Polymer Electrolyte Fuel Cells Annex and it is considering a new subtask on maritime application. The focus of the topical meeting in 2020 will be on heavy-duty transportation with onboard storage opportunities. 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 (HTAC), a congressionally mandated committee to advise the Secretary of Energy, formally convened twice in FY 2018. In December 2018, HTAC submitted its tenth 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 convened 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.

### 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. In 2018 the Program convened, for the first time, a one-day track of presentations from other federal, state, and regional agencies at the Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation. 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 (DOT), United States Postal Services (USPS), National Park Service, and Environmental Protection Agency, among others. In addition, panels were held 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 DOT's Federal Railroad Administration to assess hydrogen and fuel cell technologies for rail applications. In another new interagency collaboration with DoD's Army Tank Automotive Research, Development and Engineering Center (TARDEC), a joint workshop was held to evaluate hydrogen refueling infrastructure pathways for tactical vehicles. DOE convenes monthly meetings with an Interagency Working Group to share information, which in FY 2018 included webinars covering a variety of topics such as NASA's Mars Mission, the TARDEC fuel cell programs, and the USPS's fuel cell lift truck operations results.

### FY 2018 Annual Merit Review and Peer Evaluation

The Program's Annual Merit Review and Peer Evaluation Meeting (AMR) took place June 13–15, 2018, 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. More than 850 participants attended, and more than 175 experts peer reviewed almost 120 of the Program's projects. For the first time, the AMR included participation of FE's SOFC Program (which ran a full 2.5-day track of oral and poster presentations) and activities from other federal and state agencies. The 2018 AMR was also preceded by a National Hydrogen and Fuel Cell Forum, showcasing industry progress, exhibits of technologies, and opportunities for industry. The report summarizing the results and comments from the AMR reviews is available on DOE's website.[8] The 2019 AMR is being held April 29–May 1, in Crystal City, Virginia, and will continue to involve the SOFC Program and other DOE offices and federal agencies.

### 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 other go/no-go decisions (with criteria defined in the project scope of work)—helped the Program redirect approximately $6.0 million in funding in FY 2018, $3.3 million in funding in FY 2017, $2.4 million in funding in FY 2016, and more than $48 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.

[8] https://www.hydrogen.energy.gov/annual_review.html

## IN CLOSING …

The hydrogen and fuel cell market is growing rapidly in the United States and the world beyond. In fact, 70,000 fuel cell units totaling 650 megawatts of fuel cell power were shipped worldwide in 2017, with several hydrogen and fuel cell companies reporting a collective $2 billion in revenue.

States have invested more than $180 million in hydrogen infrastructure within the past decade and there were more than 35 retail hydrogen stations in the United States, as of the end of 2018. California has more than 30 of those stations and has planned for a total of 200 stations in the coming years.

There were more than 5,600 commercial fuel cell cars on the road (either leased or sold) at the end of 2018. Along with the Toyota Mirai and the Hyundai Tucson, the new Hyundai NEXO with autonomous capability is now available to retail consumers in select U.S. locations.

At DOE, Deputy Secretary Dan Brouillette and Undersecretary for Energy Mark Menezes drove one of the brand-new Hyundai NEXOs. On loan from Hyundai and Toyota, DOE’s pair of fuel cell vehicles have been used for interagency, congressional, and community outreach across the Washington, D.C. area, in addition to getting real-world fueling data that will help guide future early stage R&D efforts.

But it’s not just about fuel cell cars. The status at the end of 2018 includes: 240 MW of backup power, more than 20,000 forklifts, and more than 30 fuel cell buses in the United States. Long-range, heavy-duty vehicles are emerging as key applications, and fuel cell delivery and parcel trucks are starting deliveries in California and New York. These early-market applications pave the way for expanding hydrogen infrastructure and contribute substantially to the widespread adoption of hydrogen and fuel cells.

Additional advancements in the hydrogen technologies are expected through DOE’s H2@Scale initiative by incentivizing the private sector and national laboratories to tackle key challenges together. Throughout FY 2018, hydrogen was increasingly being recognized as an energy carrier that can unite all our nation’s energy resources: natural gas, coal, nuclear, and renewables. The fact that several utilities joined the initiative is a testament to the increased interest. However, there are still a number of challenges, and a major focus is achieving continued cost reductions, performance improvements and economies of scale. H2@Scale offers the opportunity for technology scale up that can enable affordability and lead to viable, sustainable industries across sectors. It is the next-generation vision for hydrogen, beyond light-duty passenger vehicles, and the Program is committed to advancing this work.

This introduction provides only a few examples of activities conducted during FY 2018. The hundreds of pages 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 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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