U.S. DEPARTMENT OF ENERGY

Hydrogen and Fuel Cell Activities, Progress and Plans: September 2016 to August 2019

Fifth Report to Congress
January 2020

United States Department of Energy
Washington, DC 20585

Message from the Secretary

This report, *Hydrogen and Fuel Cell Activities, Progress and Plans*, is the fifth in a series[1] and covers the period from September 2016 to August 2019. The first report covered the period from the start of the Hydrogen Fuel Initiative in 2004 through July 2008. The second report covered August 2008 to August 2010, the third from September 2010 to August 2013, and the fourth from September 2013 to August 2016.

This report is being provided to the following Members of Congress:

The Honorable Michael R. Pence
President of the Senate

The Honorable Nancy Pelosi
Speaker of the House of Representatives

The Honorable Lisa Murkowski
Chairman, Senate Committee on Energy and Natural Resources

The Honorable Joe Manchin
Ranking Member, Senate Committee on Energy and Natural Resources

The Honorable Frank Pallone, Jr.
Chairman, House Committee on Energy and Commerce

The Honorable Greg Walden
Ranking Member, House Committee on Energy and Commerce

The Honorable Eddie Bernice Johnson
Chairwoman, House Committee on Science, Space, and Technology

The Honorable Frank Lucas
Ranking Member, House Committee on Science, Space, and Technology

[1] Required by section 811(a) of the Energy Policy Act of 2005 (EPACT), P.L. 109-58, enacted in August 2005.

If you have any questions or need additional information, please contact me or Mr. Shawn Affolter, Deputy Assistant Secretary for Senate Affairs, or Mr. Christopher Morris, Deputy Assistant Secretary for House Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Dan Brouillette

Executive Summary

This report documents the activities of the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) that fulfill the provisions of Title VIII of the Energy Policy Act of 2005 (EPACT).

Over the period covered by this report (fiscal year [FY] 2016 to FY 2019) the DOE's Hydrogen and Fuel Cells Program (Program), continued to make progress in addressing the barriers to hydrogen and fuel cell technologies, aligned with EPACT. DOE coordinates activities across relevant offices, including Energy Efficiency and Renewable Energy (EERE), Nuclear Energy (NE), Fossil Energy (FE), Science (SC), and Advanced Research Projects Agency-Energy (ARPA-E) to leverage synergies, avoid duplication, and ensure the most effective use of taxpayer investment.

Efforts by the EERE Fuel Cell Technologies Offices (FCTO) have led to more than 960 hydrogen and fuel cell related patents (over 90 patents awarded since 2016), more than 30 commercial technologies, and about 65 technologies projected to be commercialized within three to five years.[2] In addition, EERE has successfully stimulated early markets for fuel cells through strategically targeted deployments that are cost-shared with industry partners. For example, deployments of more than 1,600 fuel cells in key early U.S. markets have led to approximately 25,000 additional orders for fuel cell forklifts by industry worldwide, with no additional DOE funding.[3] More than 7,000 of these purchases were made since 2016, a 39 percent increase over the last three years.

During FY 2016 – 2019, approximately $515 million in DOE funding was put toward hydrogen and fuel cell research and development (R&D) activities in EERE, NE, and SC. The Program's primary focus is funding R&D to enable affordability, along with performance, durability, and reliability of hydrogen production, delivery, storage, and fuel cell technologies. The Program also conducts R&D to enable safety, as well as development of the necessary codes and standards by industry, informed by FCTO's foundational research. To accelerate innovation and increase industry's access to the capabilities and expertise at the National Labs, the Program established four new R&D consortia – ElectroCat , HyMARC, HydroGEN, and H-Mat – and continues to leverage the Fuel Cell Consortium for Performance and Durability.[4] These consortia coordinate National Laboratory R&D activities and serve as a resource for universities and industry. Partners on competitively selected projects are able to work through the consortia to leverage National Laboratory state-of-the-art capabilities, such as advanced computational and experimental tools and state-of-the-art imaging technologies, to accelerate materials breakthroughs and innovations in early-stage R&D.

[2] U.S. Department of Energy, Fuel Cell Technologies Office Market Analysis Reports. Accessed July 22, 2019. https://www.energy.gov/eere/fuelcells/market-analysis-reports#mkt-program.

[3] Plug Power, Plug Power Reports Breakthrough Fourth Quarter of 2018. Accessed July 22, 2019. https://s21.q4cdn.com/824959975/files/doc_financials/2018/q4/Q4-2018-earnings-letter-FINAL-W.-UPDATED-TABLES.pdf. (Plug Power's GenDrive fuel cell forklifts are sold commercially with no DOE cost share or funding.)

[4] U.S. Department of Energy, Fuel Cell Technologies Office, Consortia. Accessed July 22, 2019. https://www.energy.gov/eere/fuelcells/fuel-cell-technologies-office-consortia.

These R&D priorities and activities support H2@Scale,[5] a key new element of DOE's strategy launched in FY 2017 to enable affordable and reliable large-scale hydrogen generation, transport, storage, and utilization throughout the energy system in the United States. The key to achieving such scale is diversifying and increasing the use of hydrogen across sectors and applications, as an energy carrier, commodity feedstock, energy storage medium, or fuel. As a low-cost energy carrier, hydrogen can couple nuclear, fossil fuels, and renewable power to enhance the economics of both baseload plants and intermittent renewables on the grid, enabling resiliency and avoiding curtailment.

The Program's accomplishments are thoroughly documented in its *Annual Progress Report;*[6] a summary of major accomplishments is provided in both this report and in the "Accomplishments and Progress" page of the Fuel Cell Technologies Office website.[7]

Key FY 2016 – 2019 R&D accomplishments are listed below and additional highlights are provided in Section 7 of this report.

- Launched H2@Scale in 2017, bringing together diverse stakeholders from industry, universities and the National Labs to facilitate the widespread adoption of hydrogen and fuel cell technologies across multiple sectors, including transportation, power generation and chemicals production.
- Demonstrated fuel cell hybrid parcel delivery trucks with double the driving range of baseline battery electric trucks.
- Demonstrated the world's first hydrogen fuel cell for shore-to-ship power in Hawaii, replacing diesel generators.
- Awarded the H2 Refuel H-Prize in 2017 for a small-scale hydrogen refueling appliance that uses only water and electricity to produce and dispense one-kilogram fills to hydrogen fuel cell cars in less than 15 minutes. The award-winning start-up company SimpleFuel® is now exporting units to Japan.
- Completed experimental validation of an innovative pressure consolidation strategy for hydrogen fueling stations supplied by tube trailers, which can lower the capital cost for hydrogen compression at the station by up to 40 percent.
- Developed first-of-a-kind high-temperature electrolyzer test facility to enable highly-efficient hybrid energy systems based on hydrogen integration with nuclear or solar power.
- Leveraged capabilities and expertise at the R&D consortia to develop state-of-the-art computational methods and tools (including machine learning techniques) for accelerated discovery and development of next generation materials for hydrogen production, storage and utilization.

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[5] U.S. Department of Energy, Fuel Cell Technologies Office. Accessed July 22, 2019. https://www.energy.gov/eere/fuelcells/h2-scale

[6] U.S. Department of Energy, Hydrogen and Fuel Cells Program, Annual Progress Reports. Accessed July 22, 2019. https://www.hydrogen.energy.gov/annual_progress.html.

[7] U.S. Department of Energy, Fuel Cells Technologies Office, Fuel Cells Technologies Office Accomplishments and Progress. Accessed November 4, 2019. https://www.energy.gov/eere/fuelcells/fuel-cell-technologies-office-accomplishments-and-progress.

HYDROGEN AND FUEL CELL ACTIVITIES, PROGRESS AND PLANS: SEPTEMBER 2016 TO AUGUST 2019

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I. Legislative Language

This report addresses subsection 811(a) of Public Law 109-58, also known as the Energy Policy Act of 2005 (EPACT). Subsection 811(a) states:

. . . not later than 2 years after the date of enactment of this Act, and triennially thereafter, the Secretary shall submit to Congress a report describing--

(1) activities carried out by the Department under this title, for hydrogen and fuel cell technology;

(2) measures the Secretary has taken during the preceding 3 years to support the transition of primary industry (or a related industry) to a fully commercialized hydrogen economy;

(3) any change made to the strategy relating to hydrogen and fuel cell technology to reflect the results of learning demonstrations;

(4) progress, including progress in infrastructure, made toward achieving the goal of producing and deploying not less than--

(A) 100,000 hydrogen-fueled vehicles in the United States by 2010; and

(B) 2,500,000 hydrogen-fueled vehicles in the United States by 2020;

(5) progress made toward achieving the goal of supplying hydrogen at a sufficient number of fueling stations in the United States by 2010 including by integrating--

(A) hydrogen activities; and

(B) associated targets and timetables for the development of hydrogen technologies;

(6) any problem relating to the design, execution, or funding of a program under this title;

(7) progress made toward and goals achieved in carrying out this title and updates to the developmental roadmap, including the results of the reviews conducted by the National Academy of Sciences under subsection (b) for the fiscal years covered by the report; and

(8) any updates to strategic plans that are necessary to meet the goals described in paragraph (4).

II. Department of Energy Hydrogen and Fuel Cells Program—Activities under EPACT Title VIII

Response to EPACT section 811(a)(1)

The U.S. Department of Energy's (DOE) Hydrogen and Fuel Cells Program (the Program) focuses on research, development, and innovation to advance hydrogen and fuel cells technologies for transportation as well as for other diverse applications across multiple sectors. Over the period covered by this report, the Program conducted early-stage and applied research, technology development, and demonstrations to advance hydrogen and fuel cell technologies. The Program also leverages the private sector and other activities to support the market success of these technologies and helps transition laboratory advances to commercial use aligned with the goals of EPACT.

The Program coordinates activities across DOE, including the Office of Energy Efficiency and Renewable Energy (EERE), led by the Fuel Cell Technologies Office (FCTO), and the offices of Nuclear Energy (NE), Fossil Energy (FE), and Science (SC) to leverage synergies and avoid duplication.[8] In addition, the Program coordinates with the Advanced Research Projects Agency–Energy (ARPA-E) to communicate research priorities and share results of relevant projects. The DOE offices also foster collaboration and coordination with other agencies, including the U.S. Department of Transportation (DOT), U.S. Department of Defense (DOD), and National Aeronautics and Space Administration (NASA), among others. In addition, global collaborations allow the Program to stay abreast of the latest advances to help maintain domestic competitiveness and harmonize codes and standards to enable a global supply chain in emerging hydrogen and fuel cell technologies.

While this report provides a concise summary, the in-depth, most recent results of the Hydrogen and Fuel Cells Program — with information on individual subprograms and projects — are found in the *DOE Hydrogen and Fuel Cells Program Annual Progress Report*,[9] and in the *Proceedings of the Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation* meetings.[10]

The Program conducted a wide range of activities between FY 2016 and FY 2019 to address the barriers to success. The primary effort is research and development (R&D) to enable affordability, along with performance, durability, and reliability of hydrogen production, delivery, storage, and fuel cell technologies. The Program also conducts hydrogen safety R&D to inform the development of necessary codes and standards by industry. These R&D priorities and activities

[8] U.S. Department of Energy, Hydrogen and Fuel Cells Program. Accessed July 22, 2019. https://www.hydrogen.energy.gov/index.html.

[9] U.S. Department of Energy, *DOE Hydrogen and Fuel Cells Program Annual Progress Report*. Accessed July 22, 2019. www.hydrogen.energy.gov/annual_progress.html.

[10] U.S. Department of Energy, Hydrogen and Fuel Cells Program Annual Merit Reviews. Accessed July 22, 2019. https://www.hydrogen.energy.gov/annual_review.html.

support the Department's H2@Scale vision for widespread hydrogen utilization throughout the energy system, to enable affordable, reliable, clean, and secure energy across sectors.

The following sections provide a summary of DOE's activities from FY 2016 to FY2019 under Title VIII of EPACT (*Progress and accomplishments by these activities are discussed in section 7 of this report*):

EERE

Hydrogen Fuel R&D focused on applied materials research and early-stage component and process development to reduce the cost and improve the reliability of technologies used to produce and store hydrogen from domestic energy resources. Hydrogen production R&D was focused on advanced water-splitting pathways, as well as innovative biological approaches and hybrid systems leveraging fossil, nuclear, and renewable resources. Hydrogen storage R&D included work to develop advanced materials-based hydrogen storage with potential for significantly improved energy density and performance.

Fuel Cell R&D focused on early-stage fuel cell component R&D to lower the cost and improve the performance and durability of fuel cells for transportation and crosscutting applications. This included work on materials and components such as platinum-free catalysts, membranes, and electrodes.

DOE's Office of Fossil Energy also conducted efforts in solid oxide fuel cells (SOFCs) from FY 2016 to FY 2019, which aimed to reduce the cost and improve the performance and reliability of SOFC-based power systems. FE's Solid Oxide Fuel Cell Program focuses on research, development, and demonstration activities to enable generation of highly efficient, cost-effective electricity from coal and natural gas with near-zero atmospheric emissions. The Hydrogen and Fuel Cells Program coordinates with the Office of Fossil Energy and keeps abreast of this program's progress in SOFCs as it relates to distributed energy generation.

Hydrogen Infrastructure R&D and Technology Acceleration included research and technology development, as well as demonstrations and enabling activities, to address the challenge of hydrogen infrastructure (hydrogen transport, bulk storage, compression, dispensing, etc.). Technology acceleration activities included manufacturing R&D to help transition laboratory successes to commercial viability, such as enabling processes for manufacturing advanced technologies at scale, and demonstrating first of a kind systems, such as integrating electrolyzers with renewables. Activities also include H2@Scale R&D to increase the security and resilience of the Nation's critical infrastructure, such as opportunities for hydrogen energy storage, materials compatibility R&D, and innovative hydrogen carriers.

Safety, Codes and Standards focused on R&D that enables safety as well as the development of codes and standards by industry, informed by FCTO's foundational research. The R&D provides a fundamental understanding of the relevant physics, critical data, and safety information used to develop and update technically sound and defensible codes and standards. Key examples includes development of quantitative risk assessment tools to ensure the safe use of hydrogen and R&D on hydrogen release under various scenarios to help reduce station footprint and use of hydrogen in enclosed spaces such as tunnels.

Systems Analysis focused on providing analysis to identify technology gaps, impacts, and future R&D needs and priorities.

SCIENCE

Basic Science Research addressing critical challenges related to hydrogen storage, production, and fuel cells is supported by the **Office of Basic Energy Sciences** (BES) within the DOE Office of Science. This fundamental scientific research, which includes work conducted by the Energy Frontier Research Centers (EFRCs), complements the technology specific R&D supported by other offices in the Program. Progress in any one area of basic science is likely to spill over to other areas and bring advances on more than one front as this research provides foundational knowledge that contributes to the vision of a secure and sustainable energy future.

In FY 2017, BES held a basic research needs workshop on catalysis science coordinated across EERE and other programs. Hydrogen and fuel cells were among the topics in the EFRC solicitation in 2018, and two EFRCs that have components focused on hydrogen production were awarded.[11] By maintaining close coordination between basic science research and applied R&D, the Program ensures that discoveries and related conceptual breakthroughs achieved in basic research programs will provide a foundation for the innovative design of materials and chemical processes.

FE and NE

The ***Office of Fossil Energy, Solid Oxide Fuel Cell Program*** has a mission to enable the generation of efficient, low-cost electricity with intrinsic carbon capture capabilities from natural gas or coal. The near-term goal is to develop natural gas-based 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. 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 SOFC system developers to address and resolve reliability issues, improve performance, and reduce the cost of SOFC power systems. The Solid Oxide Fuel Cell Program is emphasizing the resolution of design, operation, and performance at the system level and acquiring fabrication and operational experience on integrated prototype field tests. Cell development and core technology research continues and is well aligned with industry needs. In FY 2019, FE provided a report on the status of the Solid Oxide Fuel Cell Program in response to a request from Congress.

[11] Center for Biological Electron Transfer and Catalysis (https://science.osti.gov/bes/efrc/Centers/BETCy) and Center for Complex Materials from First Principles (https://science.osti.gov/bes/efrc/Centers/CCM).

The ***Office of Nuclear Energy*** is working with FCTO and industry partners to evaluate the potential demonstration of commercial-scale production of hydrogen using heat and electricity from nuclear energy systems. 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 (e.g., high-temperature electrolysis). These advanced reactors could provide the low-cost heat necessary for these processes to economically produce hydrogen. Hydrogen production at light-water reactors, including existing nuclear power plants, is also being assessed. In FY2017 through FY2019, NE provided funding for collaborative research with FCTO to analyze and develop technologies that use electricity and process heat from nuclear reactors to produce hydrogen.

ARPA-E

The ***Advanced Research Projects Agency-Energy*** has a mission 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. In FY 2016-2019, ARPA-E provided funding for fuel cells and electrolyzers through an open solicitation (2015 and 2018) and through focused programs including: the Duration Addition to electricitY Storage (DAYS), Reliable Electricity Based on ELectrochemical Systems (REBELS), Integration and Optimization of Novel Ion-Conducting Solids (IONICS), and Innovative Natural-Gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-Generation (INTEGRATE) programs.

Funding provided for these programs is shown in Section III of this report.

III. Measures Taken to Support the Transition of Primary Industry (or a Related Industry) to a Fully Commercialized Hydrogen Economy

Response to EPACT section 811(a)(2)

From FY 2016 to FY 2019, DOE pursued a strategically balanced portfolio of hydrogen and fuel cell activities, as summarized in Section II of this report. During this period, approximately $515 million in funding was put toward the Program's efforts (see fig. 3.1).[12]

A key element of the DOE strategy is to enable a steady transition from R&D to commercialization by balancing support for early market applications with efforts in longer-term, higher-impact areas. Therefore, DOE has maintained an inclusive, technology-neutral approach, pursuing advances for a wide range of applications, with varying time frames for commercial success.

	FY 2016	FY 2017	FY 2018	FY 2019	**TOTAL**
Fuel Cell R&D	33,962	30,832	30,832	28,905	124,531
Hydrogen Fuel R&D[13]	39,763	39,649	52,029	37,576	169,017
Technology Acceleration[14]	-	17,963	18,307	20,234	69,452
Manufacturing R&D[14]	2,948	-	-	-	-
Market Transformation[14]	3,000	-	-	-	-
Technology Validation[14]	7,000	-	-	-	-
Hydrogen Infrastructure R&D[15]	-	-	-	20,234	20,234
Systems Analysis	3,000	2,890	2,891	1,927	10,708
Safety, Codes & Standards	6,906	6,781	6,745	6,744	27,176
National Renewable Energy Laboratory (NREL) Site-Wide Facility Support	1,900	-	-	-	1,900
SBIR/STTR	2,471	2,885	4,196	4,380	13,932
EERE (FCTO) Hydrogen & Fuel Cells Total	**100,950**	**101,000**	**115,000**	**120,000**	**436,950**
Nuclear Energy[16]	0	2,000	2,000	2,000	6,000
Basic Energy Sciences	25,749	25,699	20,552	TBD	72,000
DOE Hydrogen & Fuel Cells Total	**126,699**	**128,699**	**137,552**	**122,000**	**514,950**
Fossil Energy Solid Oxide Fuel Cell	30,000	30,000	30,000	30,000	120,000
ARPA – E	39,300	47,0000	19,700	18,200	124,200
DOE Total	**195,999**	**205,699**	**187,252**	**170,200**	**759,150**

Figure 3.1. *Funding for DOE hydrogen and fuel cell activities FY 2016 – 2019 (as of June 2019).*

[12] This does not include funding for R&D of megawatt-scale, solid-oxide fuel cells under the Solid State Energy Conversion Alliance or ARPA-E, which are not part of the DOE Hydrogen and Fuel Cells Program.
[13] Hydrogen Fuel R&D includes Hydrogen Production R&D, Hydrogen Delivery R&D (FY 16 – 18 only) and Hydrogen Storage R&D.
[14] Technology Acceleration includes Manufacturing R&D, Technology Validation, and Market Transformation.
[15] Added in FY2019 to recognize the importance of research for hydrogen infrastructure; includes Hydrogen Delivery R&D, which was previously funded in the Hydrogen Fuel R&D line item.
[16] Includes funds appropriated for collaboration between NE and EERE. May not include all NE work relevant to hydrogen production.

The following activities were undertaken over the 2016-2019 timeframe to support the widespread market acceptance of hydrogen and fuel cell technologies across diverse applications.

- **H2@Scale:** A key new element of DOE's strategy focuses on advancing the H2@Scale[17] concept, which was launched in FY 2017 to enable affordable and reliable large scale hydrogen generation, transport, storage, and utilization in the United States. By achieving economies of scale, one can further reduce cost, foster the development of a hydrogen infrastructure (including the required supply chain, codes, and standards), and accelerate user acceptance. The key to achieving such scale is diversifying and increasing the use of hydrogen across sectors and applications, as shown in Figure 3.2. In addition, the initiative will enable hydrogen as a low-cost energy carrier, coupling nuclear, fossil fuels, and renewable power to enhance the economics of both baseload plants and intermittent renewables on the grid, enabling resiliency, and avoiding curtailment. Led by FCTO, H2@Scale coordinates and integrates relevant DOE (and other Federal agency) activities, both within and outside of the Hydrogen and Fuel Cells Program.

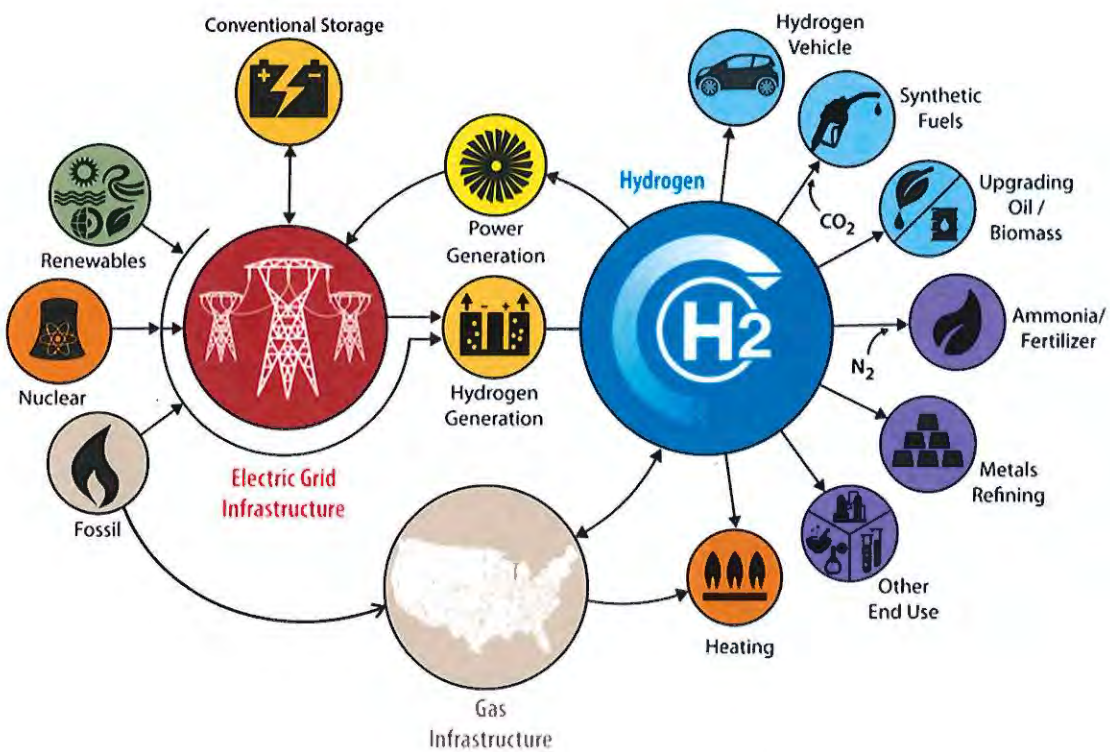

Figure 3.2 *H2@Scale impacts multiple technology sectors*

[17] U.S. Department of Energy, Fuel Cell Technologies Office, H2@Scale. Accessed July 22, 2019. https://www.energy.gov/eere/fuelcells/h2-scale

- **R&D Focus Areas:** The major challenges to enabling hydrogen use across sectors include reducing the cost of hydrogen delivery, storage and production, as well as lowering the cost and improving the durability of fuel cells. To address these and other challenges, the Program continues to support early-stage research, development, and innovation. This R&D is accomplished through competitively selected projects that also leverage National Laboratory state-of-the-art capabilities, such as advanced computational and experimental tools, to accelerate materials breakthroughs and innovations in early-stage R&D. Through four consortia that include National Labs, industry, and universities, research is conducted in the following focus areas:
    - **ElectroCat** for platinum group metal-free fuel cell catalysts;
    - **HydroGEN** for advanced water-splitting;
    - **HyMARC** for advanced hydrogen storage materials research; and
    - **H-Mat** for hydrogen materials compatibility R&D.

  In addition, an **H2@Scale** consortium leverages the private sector through Cooperative Research and Development Agreement (CRADA) projects, on an ongoing basis, with National Labs. All these consortia are 'virtual' in the sense that capabilities are utilized at the various partner sites, rather than duplicating facilities.

  As shown in Figure 3.3, the Program's R&D funding has successfully fostered a large number of patents, a strong indicator of technical impact.

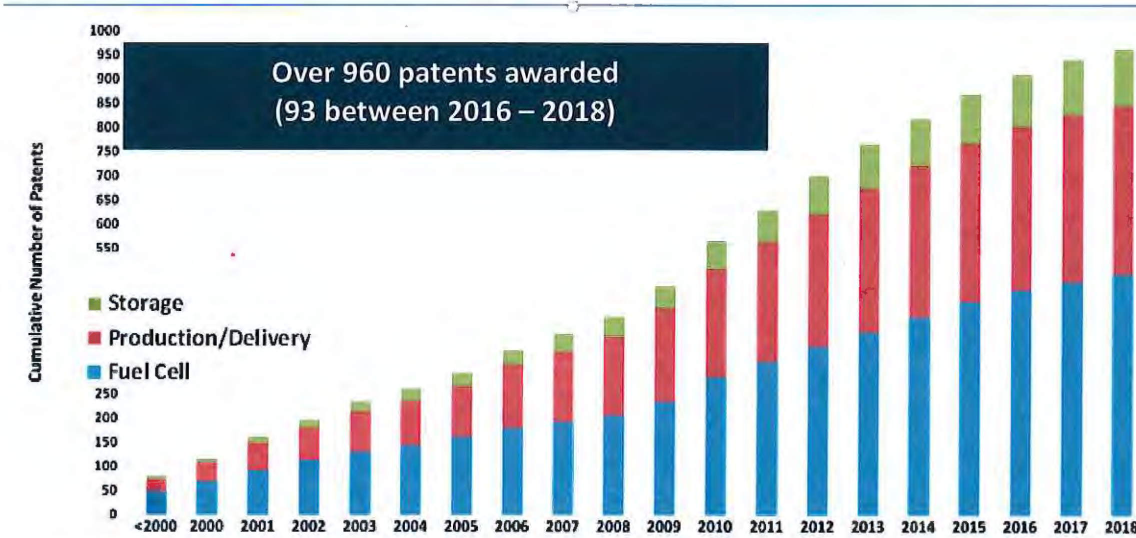

Figure 3.3. *Cumulative number of patent awards resulting from FCTO funding (1980 – 2018)*
Source: Pacific Northwest National Laboratory, *2018 FCTO Patent Update, https://www.energy.gov/eere/fuelcells/market-analysis-reports#mkt-program*

- **Solicitations for Research, Development and Demonstrations:** FCTO provided funding for a number of solicitations for competitively selected projects involving National Labs, industry, university, and other stakeholders.
    - An FY 2017 FCTO funding opportunity announcement (FOA) resulted in 30 awards to industry, universities, and National Labs totaling nearly $34 million in

DOE funding aimed at the discovery and development of novel, low-cost materials necessary for hydrogen production and storage and for fuel cells onboard light-duty vehicles. This included projects in the following 4 topic areas: 1) ElectroCat (platinum group metal-free catalyst and electrode R&D), 2) HydroGen (advanced water splitting materials), 3) HyMARC (hydrogen storage materials discovery), and 4) precursor development for low-cost, high-strength carbon fiber.

- The FY 2018 FCTO FOA made 28 awards to industry, universities, and National Labs. More than $38 million was provided for projects in 3 topic areas: 1) ElectroCat, 2) H2@Scale, and 3) Innovative Concepts. Five awards under the Innovative Concepts topic will provide almost $5 million for early-stage R&D on components for unitized reversible fuel cells that store energy and generate power, in support of DOE's Advanced Energy Storage Initiative (formerly known as Beyond Batteries).
- Between FY 2017, 2018 and 2019, 27 new projects were initiated as part of the H2@Scale consortium, through a CRADA-call for projects involving industry and National Lab partners, with external funding to complement FCTO funds. Funding to date includes $6.3M from FCTO with an additional $5.5M from industry, state, and non-profit (e.g., university) partners. These projects address topics central to the H2@Scale concept, such as hydrogen integration with energy generation (e.g., nuclear power plants and renewable energy technologies); innovative hydrogen distribution and dispensing R&D (e.g., station components and hydrogen carriers); quantitative performance analysis and operation R&D (e.g., risk modeling); and, advanced hydrogen production concepts R&D (e.g., high-performance electrolyzers). Applications are accepted on a rolling-basis to continue industry and National Lab partnerships in support of H2@Scale.
- In March 2019 FCTO issued a FOA to advance the H2@Scale concept, which will provide up to $31 million for competitively selected R&D projects in the following topic areas: 1) advanced hydrogen storage and infrastructure R&D; 2) innovative concepts for hydrogen production and utilization; and 3) pilot projects for integrated hydrogen production, storage, and fueling systems. More than 375 concept papers were received in response to the solicitation, which aims to award as many as 30 projects by the end of FY 2019.
- Finally, a joint FY 2019 FOA with FCTO, the Vehicle Technologies Office, and Bioenergy Technologies Office made available $51 million in funding for medium- and heavy-duty trucks, off-road vehicles, and the fueling equipment to power them. FCTO will provide up to $18 million to fund hydrogen and fuel cell projects from this solicitation in the topic areas of advanced storage for gaseous fuels, high throughput fueling, and durable fuel cells with low PGM content (all in truck applications).

- **Industry Access to the National Laboratories**: The Program increased its focus on building bridges between National Labs and industry to make the R&D outputs, expertise, and capabilities of the labs more accessible to industry. In addition to the early-stage R&D consortia, H2@Scale consortium, and CRADA projects already mentioned, the Program 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, a 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.

- **User Tools and Resources**: The Program continued to support the development of tools for the user community, for example:
  - **Hydrogen Station Equipment Performance device (HyStEP)**[18]: This mobile device, funded by FCTO and developed by Sandia National Laboratories (SNL), NREL, and Powertech Labs, was developed in 2016 and used by certification agencies to verify hydrogen fueling station performance and compliance with hydrogen fueling standards, dramatically reducing the time and cost for station commissioning. The device design has been made available so companies can replicate it for commercial use.
  - **Hydrogen Financial Analysis Scenario Tool (H2FAST)**[19]: H2FAST is a standard financial accounting framework applied to DOE's hydrogen cost analysis models. This tool can be used to inform investment decisions by providing end-users a tool to explore financial aspects of scenarios such as one hydrogen station or multiple or building a broader hydrogen infrastructure network.
  - **Hydrogen Tools Portal (H2Tools)**[20]: H2Tools provides resources to support implementation of the practices and procedures that will ensure safety in the handling and use of hydrogen in a variety of fuel cell applications.
  - **Center for Hydrogen Safety (CHS)**[21]: Formally launched in early 2019 as a partnership between AIChE and the Pacific Northwest National Laboratory, the CHS provides the hydrogen and fuel cell industries with resources, hydrogen safety guidelines, global conferences, and access to the Hydrogen Safety Panel for independent safety evaluation of projects and facilities.

- **Strategic Partnerships and International Activities**: DOE leveraged other established strategic partnerships by:
  - Collaborating with members of the **U.S. DRIVE Partnership**[22] to evaluate research results and establish technical requirements; and
  - Leading the **Hydrogen and Fuel Cell Interagency Task Force and Interagency Working Group** to focus efforts on Federal leadership of early adoption of hydrogen and fuel

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[18] Hydrogen Tools Portal, HyStEP (Hydrogen Station Equipment Performance) Device. Accessed July 22, 2019. https://h2tools.org/h2first/HyStEp.
[19] National Renewable Energy Laboratory, Hydrogen and Fuel Cells, H2FAST: Hydrogen Financial Analysis Scenario Tool. Accessed July 22, 2019. https://www.nrel.gov/hydrogen/h2fast.html.
[20] Hydrogen Tools Portal. Accessed July 22, 2019. https://h2tools.org.
[21] Center for Hydrogen Safety. Accessed July 22, 2019. https://www.aiche.org/CHS.
[22] Other members of the U.S. Drive partnership include automakers, energy companies, and electric utilities. Accessed November 4, 2019. https://www.energy.gov/eere/vehicles/us-drive.

cell technologies. Over the FY 2016 – 2019 timeframe, the Program strengthened partnerships with a number of Federal and state agencies in an effort to coordinate and leverage funding for hydrogen and fuel cells in multiple applications. Key accomplishments included:

  - Memoranda of Understanding were established to conduct mission-oriented work with the Army Ground Vehicle Systems Center (formerly known as the Tank Automotive Research and Development Center, or TARDEC), Department of Transportation (DOT) Federal Railroad Administration, DOT Maritime Administration, and Michigan Economic Development Corporation.
  - In FY 2017, the United States Postal Service installed approximately 90 fuel-cell-powered material handling equipment units at their Washington, DC, Network Distribution Center.
  - In FY 2016 DOE and the National Park Service (NPS) worked together to open a hydrogen refueling demonstration station at the NPS Maintenance Facility in the Brentwood neighborhood of Washington, DC. The station was operational from 2016 – fall 2019.

- Collaborating with international partners, representing several leading economies, through the International Partnership for **Hydrogen and Fuel Cells in the Economy (IPHE).**[23] In May 2018, the U.S. was elected as Chair of IPHE. IPHE includes members from 19 nations and the European Commission who work to:
  - Accelerate the market penetration and early adoption of hydrogen and fuel cell technologies and their supporting infrastructure;
  - Share information, lessons learned and best practices among member countries on initiatives, programs, policies, and regulatory actions - including safety, codes and standards, to enable affordable and sustainable widespread deployment across sectors;
  - Provide accurate factual and unbiased information to policy-makers, including government officials at the Federal, regional and state level, as well as to the public, students, industry and non-governmental associations; and
  - Monitor technology developments worldwide to help inform future government research, development, demonstration, and analysis activities.

DOE also participated in the first Hydrogen Energy Ministerial in more than 15 years. Held in Japan in October 2018, the Ministerial was attended by representatives from 20 countries including the Deputy Secretary of Energy.

- **Stakeholder Feedback**: DOE gathered feedback from stakeholders (researchers, technology developers and users, potential investors, etc.) through a variety of mechanisms. The Program continued to conduct its annual peer reviews (the 2017, 2018, and 2019 *Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meetings)*. These reviews convened technical experts from industry, academia, and National Laboratories to evaluate the progress

[23] International Partnership for Hydrogen and Fuel Cells in the Economy. Accessed July 22, 2019. www.iphe.net.

and provide valuable feedback to principal investigators and DOE managers.[24] In 2018 and 2019, the AMR also included a one-day track of presentations featuring hydrogen and fuel cell related activities being conducted by other Federal, state, and regional agencies. More information on external reviews is provided in Section VIII.

Several Requests for Information (RFI) and stakeholder workshops were also held in the FY 2016 – 2019 timeframe to gather feedback on specific topic areas, including:

- Two RFIs were released: (1) a June 2018 RFI gathered input on regulatory barriers to the development of hydrogen infrastructure, and (2) an August 2018 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.
- A number of workshops[25] were held convening diverse groups of representatives from industry, academia, National Labs, government agencies, trade groups, and others. These workshops explored emerging opportunities for hydrogen and fuel cells, including in railroad, marine, data centers and heavy- and medium-duty trucks. Workshops included: (1) a joint workshop with the U.S. Army's Tank Automotive Research, Development and Engineering Center (TARDEC) to evaluate hydrogen refueling infrastructure pathways for tactical vehicles; (2) DOE Physical-Based Hydrogen Storage Workshop: Identifying Potential Pathways for Lower Cost 700 Bar Storage Vessels; (3) International Hydrogen Infrastructure Workshop; (4) 2017 Ohio Fuel Cell Symposium and Balance of Plant Workshop; (5) Hydrogen and Fuel Cells for Data Center Applications Project Meeting,; (6) Fuel Cell Truck Powertrain R&D Activities and Target Review; (7) H2@Rail Workshop to discuss hydrogen railroad applications; and (8) several workshops to explore challenges and R&D needs related to H2@Scale.

[24] U.S. Department of Energy Hydrogen and Fuel Cells Program Annual Merit Reviews. Accessed July 22, 2019. www.hydrogen.energy.gov/annual_review.html.

[25] U.S. Department of Energy, Fuel Cell Technologies Office, Workshop and Meetings Proceedings. Accessed July 22, 2019. https://www.energy.gov/eere/fuelcells/workshop-and-meeting-proceedings.

IV. Changes Made to the Strategy Reflecting Results of Learning Demonstrations

Response to EPACT section 811(a)(3)

Each application of hydrogen and fuel cells has different cost and performance targets to enable the technologies to be competitive with incumbent or other emerging technologies. These targets will continue to be developed and updated with input from industry as the vision of H2@Scale continues to evolve and more end use applications for hydrogen continue to be developed. The Program uses the results of technology validation, technoeconomic analysis, and various stakeholder engagement activities to assess status vs. targets, and to inform and guide program strategies and R&D priorities.

The Program's demonstration efforts have played an essential role in assessing the status of the technologies, providing feedback to R&D efforts, and ultimately demonstrating commercial readiness to establish business cases for potential industry investors. NREL continues to collect and validate data on fuel cell electric vehicles (FCEVs -- cars and buses) and hydrogen fueling stations at the National Fuel Cell Technology Evaluation Center (NFCTEC), with support from industry partners and DOE. NREL aggregates individual system, fleet, and site analysis results into public results called composite data products (CDPs) that show the status and progress of the technology without identifying individual companies or revealing proprietary information. As of the end of FY 2019, these efforts will have developed and released to the public more than 560 CDPs, which are available on the NFCTEC website.[26]

The results from these technology validation efforts, as well as DOE's detailed technoeconomic analysis, have led the Program to place a greater emphasis on improved and novel hydrogen fueling infrastructure materials and systems. As shown in Figure 4.1, hydrogen compressors and dispensers are key cost factors. The major change over the past three years, as reflected in the FOA projects discussed in the previous section, is an increased emphasis on hydrogen delivery and station related technologies, including component technologies (e.g., compressors), and the creation of the H-Mat consortium to address materials reliability and durability issues.

In addition, to complement large scale stations and provide an alternate option for reliable hydrogen availability, the Program awarded the $1 million H-Prize for the H2 Refuel competition, which challenged America's innovators to develop and deploy a compact on-site hydrogen generation system that can be used to fill hydrogen vehicles in homes, community centers, small businesses, or other locations. The award-winning SimpleFuel® hydrogen refueling appliance, has already initiated commercial deployments with its first export to Japan. The small-scale device provides a 1-kg fill—enough fuel to travel approximately 60-70 miles—in 15 minutes or less at 700 bar using hydrogen produced via electrolysis.

[26] NREL, Hydrogen and Fuel Cells, National Fuel Cell Technology Evaluation Center. Accessed July 22, 2019. https://www.nrel.gov/hydrogen/nfctec.html.

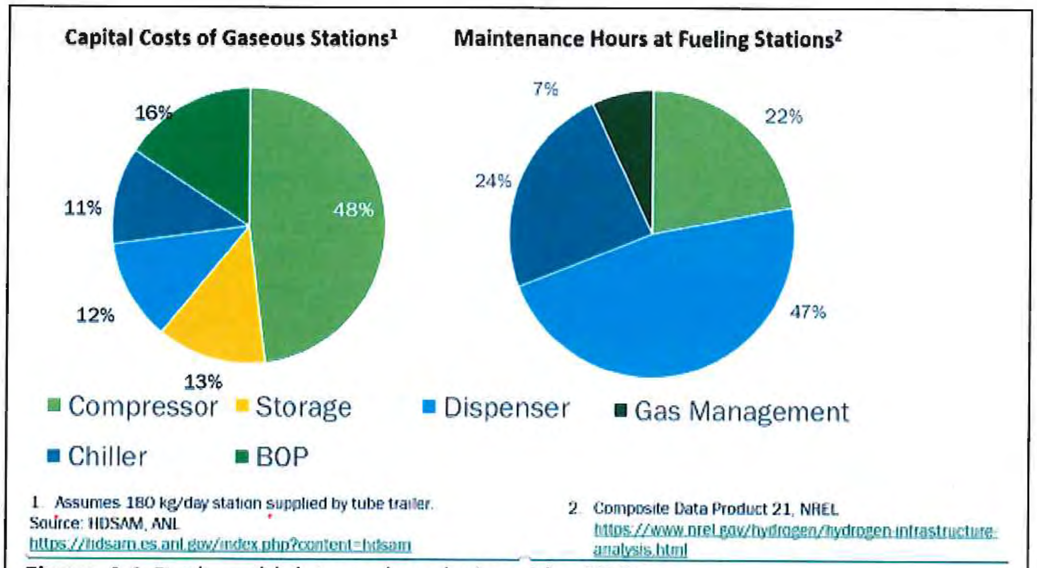

Figure 4.1 *Real-world data and analysis guides R&D*

DOE has also put into place a number of activities and resources that address hydrogen and fuel cell competitiveness and demand. For example, **H2@Scale** is exploring opportunities that could increase U.S. demand for hydrogen across multiple sectors, including the potential for bundling demand to supply regionally based industry, transportation, and power generation needs.

Safety, including the cost and reliability of hydrogen station safety systems, also continues to be identified as a major Program priority. This is especially true as the use of hydrogen and fuel cell technologies becomes more widespread in the U.S. and around the world. In FY 2018, partly in response to the Program's Federal advisory committee recommendations, the Pacific Northwest National Laboratory (PNNL) and the American Institute of Chemical Engineers (AIChE) established the **Center for Hydrogen Safety** (CHS).[27] The CHS is a global-oriented non-profit dedicated to promoting hydrogen safety and best practices worldwide with access to 60,000 members in 110 countries. It will provide access to DOE-developed knowledge tools (including the Hydrogen Tools Portal[28]) and provide a mechanism to continue independent safety evaluations of projects by the Hydrogen Safety Panel.[29] By establishing the CHS with AIChE, DOE aims to ensure the long-term sustainability and broader impact of the hydrogen safety activities and tools initiated with DOE funding.

The Program has also built on its success in catalyzing early market applications for material handling equipment and back-up power, which are now achieving commercial success. The Program is currently funding new limited demonstration projects in fuel cell range extenders for battery-powered parcel delivery vans, airport ground support equipment, and marine applications, and is exploring opportunities for hydrogen and fuel cells in other early-market applications, such as data centers.

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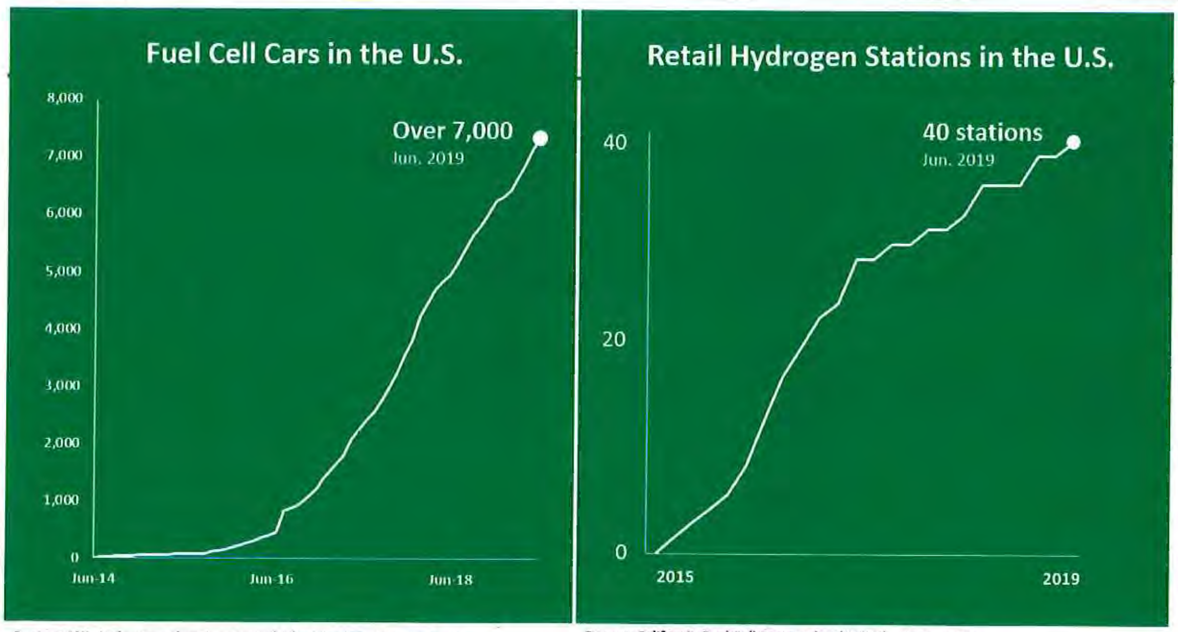
[27] Center for Hydrogen Safety. Accessed July 22, 2019. https://www.aiche.org/CHS. The CHS was formed through a partnership between PNNL and AIChE. The partnership was formalized in a June 2018 Memorandum of Understanding between the two organizations.
[28] Hydrogen Tools Portal. Accessed July 22, 2019. https://h2tools.org.
[29] Hydrogen Safety Panel. Accessed July 22, 2019. https://h2tools.org/hsp.

V. Progress toward Vehicle Deployment and Hydrogen Infrastructure Goals in EPACT Title VIII

Response to EPACT sections 811(a)(4) and 811(a)(5)

Section 7 of this report discusses the progress that DOE made toward its technology development goals between FY 2016 and FY 2019. This progress has gone a long way toward enabling increased commercialization of FCEVs and availability of hydrogen, including major cost reductions and improvements in the performance and durability of fuel cell systems, and reductions in the cost of producing and delivering hydrogen.

Evidence of how far fuel cell technologies have progressed is seen in the announcements of FCEV rollout plans by major automakers; the partnerships announced among these companies to support FCEV commercialization; and the major government-industry partnerships that have been established around the world to support FCEV rollout plans. Since November 2014, when Hyundai first started leasing its Tucson FCEV in the U.S., two other car companies (Toyota and Honda) have started offering FCEVs in the U.S. Today, there are more FCEVs on the road in the U.S. than in any other country. As shown in Figure 5.1, the number of vehicle and stations has grown rapidly over the past three years; as of June 2019, there were over 7,000 FCEVs[30] and 40



Source: ANL, Light Duty Electric Drive Vehicles Monthly Sales Updates. https://www.anl.gov/es/light-duty-electric-drive-vehicles-monthly-sales-updates

Source: California Fuel Cell Partnership (CaFCP), Stations Map. https://cafcp.org/stationmap

Figure 5.1. *Fuel cell vehicle and hydrogen infrastructure status as of June 2019*

[30] Light Duty Electric Drive Vehicles Monthly Sales Updates, Argonne National Laboratory. Accessed July 22, 2019. https://www.anl.gov/es/light-duty-electric-drive-vehicles-monthly-sales-updates.

hydrogen stations[31] in the U.S. This compares to over 3,025 FCEVs and 103 stations in Japan and 505 FCEVs and 64 stations in Germany.[32] While still a very small share of total vehicle sales (over the same time period from June 2014 – June 2019 more than 33 million cars were sold in the U.S.), the acceleration in FCEV sales in recent years is encouraging.

To support growth, FCTO has invested in R&D to lower the cost and improve the performance, durability, and safety of hydrogen and fuel cell technologies. While progress has been substantial and DOE's efforts have produced technologies that meet key technology-readiness targets, we did not meet the deployment goal specified in EPACT Section 811(a)(4) of 100,000 hydrogen-fueled vehicles by 2010 and will not meet the goal of 2.5 million FCEVs by 2020. Achieving those volumes would require significant investment in the buildout of cost-effective hydrogen infrastructure across the U.S., as well as lower vehicle cost and fuel cost to the end consumer. Manufacturers and public purchase incentives currently subsidize the vehicle purchase cost of FCEVs as well as the higher fuel cost to operate the vehicles, thereby limiting their availability and current market penetration. Some of these are factors outside the scope of DOE R&D. DOE will continue to conduct R&D that focuses on the next steps towards reducing the cost of FCEVs, lowering the cost and increasing the widespread availability of hydrogen, and enabling higher manufacturing volumes of hydrogen and fuel cell components and systems. The volume and number of models of vehicles are likely to remain limited until costs can be reduced for both vehicles and fuel.

Although FCEV and station costs are still high, the deployment plans of California, Japan, Western Europe, and China are likely to result in cost reduction associated with higher production and more robust supply chains. There is also growing international recognition of hydrogen's value as an energy carrier for multiple sectors, and DOE's H2@Scale initiative seeks to advance affordable, largescale hydrogen production, transport, storage, and utilization by lowering infrastructure costs and increasing revenue opportunities and benefits across sectors.

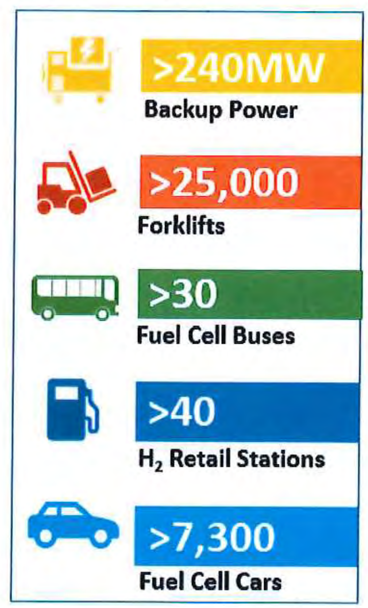


Figure 5.2. *U.S. fuel cell deployment status as of June 2019*

The majority of current FCEV and hydrogen station deployments in the U.S. are in California, supported by the state's strong incentives for zero emission vehicles and alternative fuels. Over the last three years, other states and regions have also started to gain momentum and are supporting hydrogen and fuel cells for a variety of reasons, including emissions reduction, efficient and

[31] California Air Resources Board, *2019 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development*. July 2019. https://ww2.arb.ca.gov/sites/default/files/2019-07/AB8_report_2019_Final.pdf.

[32] International Partnership for Hydrogen and Fuel Cells in the Economy, Summary Country Updates for Japan and Germany April 2019. Accessed July 22, 2019. https://www.iphe.net/japan and https://www.iphe.net/germany.

reliable power generation, resilience to emergencies, and business development. This has led to vehicle, station, and other fuel cell deployments around the country. As shown in Figure 5.2, this includes deployment of more than 25,000 fuel cell forklifts for commercial material handling and distribution centers, over 240 MW of backup power, and more than 30 fuel cell buses operated by multiple state transit agencies.

Both Federal and state policies have included initiatives on hydrogen and fuel cells to encourage more widespread use. The Bipartisan Budget Act of 2018 (P.L. 115-123) reinstated Section 48 and Section 25D of the Investment Tax Credit (ITC) for fuel cells for businesses and residential installations. The reinstatement established a tiered phase-out of the credit through 2023, based on when construction commences, allowing owners of stationary and material handling fuel cell systems to claim up to 30 percent of total system equipment and installation costs.[33] Notable new state policies, programs, and activities in the 2016 – 2018 timeframe include:

- In May 2018, New Jersey joined 8 other states (California, Connecticut, Maryland, Massachusetts, New York, Oregon, Rhode Island, and Vermont) in a Zero-Emission Vehicles (ZEV) memorandum of Understanding (MOU)[34] that sets a collective target to have at least 3.3 million ZEVs on the road in their states by 2025 and to work together to establish a fueling infrastructure that will adequately support this number of vehicles
- In early 2019, Colorado introduced an executive order[35] to adopt a ZEV mandate that would increase the percentage of ZEVs, including fuel cell cars, sold in the state.
- On January 18, 2019, DOE announced the signing of an MOU with the Michigan Economic Development Corporation (MEDC) to enhance collaboration on hydrogen and fuel cell R&D with the state of Michigan to promote private investment and domestic job creation.
- In early 2018, California Governor Jerry Brown signed an executive order[36] to further increase ZEVs and charging/refueling stations in the state. The initiative set a goal for 5 million ZEVs on the road by 2030, with up to $2.5 billion in funding for 250,000 vehicle charging stations and 200 hydrogen fueling stations.
- Also in 2018, the California Air Resources Board increased the carbon intensity reduction requirement under its Low Carbon Fuel Standard[37] to 20 percent (versus 10 percent) by 2030. Hydrogen qualifies as a low-carbon fuel.
- California is ramping up efforts to address emissions from medium- and heavy-duty vehicles through projects and programs to demonstrate and deploy fuel cell cargo trucks and fueling infrastructure and to increase the deployment of fuel cell buses.

[33] Section 1336 of the Energy Policy Act of 2005, as amended by the Bipartisan Budget Act of 2018, 26 U.S.C. § 48 (a)(2) and (a)(7).
[34] Multi-State ZEV Task Force. Accessed November 21, 2019. https://www.zevstates.us/.
[35] Colorado Executive Order B 2019 002, January 17, 2019, Governor Jared Polis, Supporting a Transition to Zero Emission Vehicles. Accessed November 21, 2019. https://www.colorado.gov/governor/sites/default/files/inline-files/b_2019-002_supporting_a_transition_to_zero_emissions_vehicles.pdf.
[36] California Executive Order B-48-18, January 26, 2018, Governor Edmund G. Brown. Accessed November 21, 2019. https://www.ca.gov/archive/gov39/2018/01/26/governor-brown-takes-action-to-increase-zero-emission-vehicles-fund-new-climate-investments/index.html.
[37] California Air Resources Board. Low Carbon Fuel Standard. Accessed November 21, 2019. https://ww3.arb.ca.gov/fuels/lcfs/lcfs.htm.

- In January 2018, regulators at the Arizona Corporation Commission proposed to pursue 80 percent clean energy by 2050 and 3,000 MW of energy storage by 2030.
- FCTO has demonstration projects underway in various states, including fuel cell powered baggage tow tractors (with FedEx in Memphis, Tennessee and Albany, New York), hybrid fuel cell parcel delivery vans (with UPS in Sacramento, California and FedEx in Albany, New York), and fuel cell auxiliary power systems for use on ships and in port to replace diesel generators (Hawaii).
- FCTO is also working with the Idaho National Laboratory to establish a nuclear hybrid energy test system in Idaho Falls which integrates grid simulation, nuclear reactor simulation, and high-temperature hydrogen generation systems.

VI. Problems Relating to Design, Execution, or Funding of Activities under EPACT Title VIII

Response to EPACT section 811(a)(6)

Section 8 of this report covers reviews of the Program from September 2016 to July 2019. These reviews have provided extensive and valuable recommendations and have not identified any significant problems relating to the design or execution of Program's activities in this period. The need for increased focus on hydrogen infrastructure related technologies (especially compressors, dispensers, storage tanks, and liquefaction) has been a common theme, and DOE is addressing this by increasing R&D resources directed towards the H2@Scale initiative and components and systems for hydrogen fueling stations, transport, and grid integration.

One issue that may impact widespread, nationwide hydrogen use is the challenge of meeting regulatory and permit requirements for hydrogen installations. As current and near-term technologies are deployed (i.e., light, medium, and heavy duty vehicles) and as hydrogen technologies are more widely adopted, existing issues within the codes and standards and permitting community begin to have a greater impact. Similar problems may occur with large-scale hydrogen storage (i.e., greater than 1,000 kilograms stored or used per day). These large-scale needs are frequently beyond the scope of existing codes and would likely necessitate new courses of action prior to their deployment.

To address these challenges, DOE released a Request for Information in 2018 to solicit feedback and gain insight into the technical and economic barriers associated with these production pathways and is currently developing plans to address this feedback. FCTO will continue to work with states, code development organizations, and regional authorities to address regulatory challenges such as setback distances, tunnel safety, hydrogen metering, and various equipment testing and safety design issues.

The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) noted the need for sustained efforts to maintain domestic competitiveness. In a March 2019 briefing to DOE, they stressed the increasing threat of foreign competition, particularly from China, Japan, and Europe. The HTAC asserts that the U.S. is at a "tipping point" for key decisions to secure its long-term competitive technical and commercial position in this industry and urged action to tip the scales back in favor of domestic investment and manufacturing. DOE continues to work with multiple stakeholders to identify key R&D priorities to stay at the cutting edge of innovation as this industry is an important potential source of sustainable domestic job growth, future innovation, and energy leadership.

VII. Progress toward Program Goals

Response to EPACT section 811(a)(7)

The Program made significant progress towards its goals as shown in Figure 7.1. The knowledge and innovations enabled by the Program have translated into commercial and emerging hydrogen and fuel cell technologies including electrolyzers, catalysts, membranes, high-pressure gas storage tanks as well as hydrogen detection and manufacturing techniques — all of which are paving the way for a robust fuel cell and hydrogen market.

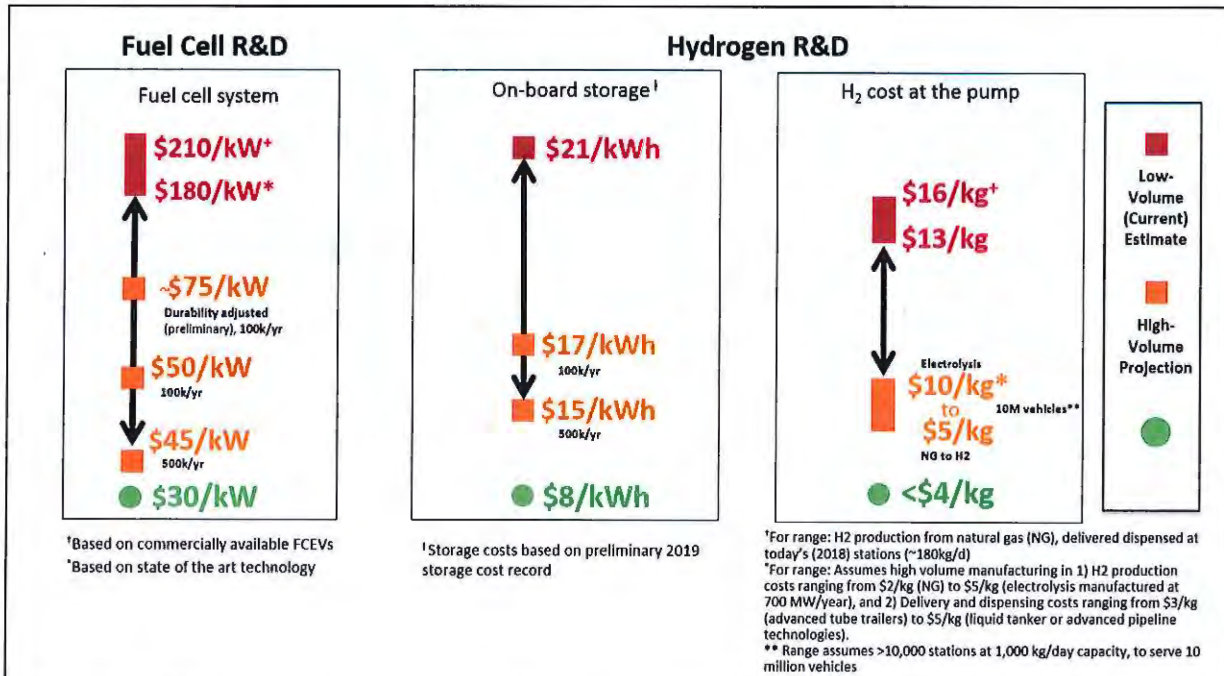


Figure 7.1 *DOE Fuel Cell Technologies Office - cost targets and status as of May 2019*

In addition, DOE has successfully stimulated early markets for fuel cells through strategically targeted deployments of fuel cells for back-up power and material handling, cost-shared with industry partners.

The Program's accomplishments are thoroughly documented every year in the *Annual Progress Report*. Over the last three years, these included more than 300 detailed reports from individual R&D projects. A summary of the Program's major accomplishments (including citations) is shown on the "Accomplishments and Progress" page of the Fuel Cell Technologies Office's website (http://energy.gov/eere/fuelcells/fuel-cell-technologies-office-accomplishments-and-progress).

Figure 7.2 presents highlights of Program accomplishments in the 2016 – 2019 timeframe. Figures 7.3 and 7.4 present the cost breakdowns for individual technology areas; these analyses are used to help focus R&D on the highest cost components.

Figure 7.2. *Progress and accomplishments FY 2016 – 2019 - key examples*

Fuel Cell R&D

- ✓ Demonstrated record high activity for potentially inexpensive platinum (Pt)-free catalysts (containing iron, nitrogen, and carbon) in 2018, a greater than 65 percent improvement over the 2016 baseline.
- ✓ Increased the power generated by a fuel cell with a low platinum group metal (PGM) catalyst by more than 50 percent, surpassing the target of 8 kilowatts per gram PGM. This catalyst's performance is higher than the performance of a catalyst used in commercial FCEVs despite having less than 20 percent of the platinum loading.
- ✓ Developed ordered platinum-cobalt (Pt-Co) fuel cell catalysts that meet DOE targets for both catalyst activity and durability at the same time. These catalysts hold onto Co 40 percent better than random Pt-Co alloys during durability tests.
- ✓ Through a consortium dedicated to Fuel Cell Performance and Durability, tested, modeled, and characterized Pt catalysts and provided guidance to the stakeholder community for developing more stable catalysts and operating conditions that will extend catalyst lifetime.
- ✓ Through the PGM-free electrocatalysis consortium ElectroCat, used high-throughput methods and machine learning to screen over 125 catalyst samples and guide future PGM-free catalyst synthesis, achieving a 45 percent improvement in catalyst activity over the highest activity observed in an initial sample set.
- ✓ Developed alkaline membranes for fuel cells with 4x less (areal) resistance and 5x greater power than current alkaline membrane fuel cells.
- ✓ Developed a novel fuel cell membrane that operates at temperatures of 160-200°C with a peak power density 45 percent higher than commercial state-of-the-art high temperature fuel cells.

Hydrogen Fuel R&D

Hydrogen Production

- ✓ Awarded the H2 Refuel H-Prize in 2017 for a small-scale hydrogen refueling appliance that uses only water and electricity to produce and dispense 1 kilogram fills to hydrogen fuel cell cars in less than 15 minutes. The award-winning start-up company SimpleFuel® is now exporting units to Japan.
- ✓ Developed a novel hybrid Reformer-Electrolyzer-Purifier (REP) technology for distributed production of low-cost hydrogen generated simultaneously from natural gas reforming and high-temperature electrolysis while incorporating electrochemical purification to remove CO_2 in situ. The project team demonstrated 100 kg H_2/day stack with a path to a 2000 kg H_2/day and modeled costs of \$3.10/kg H_2.
- ✓ Broke a standing 18 year world record, demonstrating 16.2 percent solar-to-hydrogen (STH) efficiency over the previous 12 percent STH as a result of innovations in materials synthesis and characterization for photoelectrochemical (PEC) water splitting. This demonstrates the long-term potential for low-cost solar hydrogen production.
- ✓ Published a Program Record projecting hydrogen production cost from high-temperature solid oxide electrolysis cells (SOEC) at ~\$2.80 to ~\$5.80/kg H_2 at high volume (untaxed, excluding delivery and dispensing). SOECs can be integrated with industrial systems or nuclear reactors, to take advantage of process heat for improved electrical efficiencies compared to low temperature electrolysis.
- ✓ Utilized machine learning models coupled with ab initio thermodynamic and kinetic screening to aid in the discovery of efficient and stable solar thermochemical materials, identifying ~27,000 stable perovskite formulations from more than 1.1 million possible candidates with greater than 90 percent accuracy.

Hydrogen Storage

- ✓ Through the Hydrogen Materials - Advanced Research Consortium (HyMARC) and associated projects, demonstrated hydrogenation of MgB2 to Mg(BH4)2 at 25 percent lower temperature and 22 percent lower pressure than prior state-of-the-art technologies, as well as a factor of 10 improvement in dehydrogenation kinetics for Mg(BH4)2 compared to the bulk material.
- ✓ Identified over 69,000 real and hypothetical metal-organic framework (MOF) structures with the potential to outperform the current state-of-the-art material through computational machine learning techniques.
- ✓ Made progress towards the goal to develop an alternative precursor material for high-strength carbon fiber with equivalent properties to Toray T700S, but with a 50 percent lower cost. Developed four novel polyolefin materials that are less capital intensive, have a higher mass yield on carbonization, and can be produced via melt spinning, a lower cost process compared to solution spinning required for PAN precursors.
- ✓ By utilizing several unique and complementary capabilities across HyMARC, researchers were able to increase the hydrogenation and dehydrogenation rates of Li3N by a factor of two; high-performance computing simulations were Code Case that will allow pressure vessel design for high-pressure hydrogen without additional testing burden.

Figure 7.2. *Progress and accomplishments FY 2016 – 2019 - key examples (continued)*

Hydrogen Infrastructure and Systems R&D

Hydrogen Infrastructure

- ✓ Set a world record by using magnets to reach a 100-K temperature drop in layers of magnetocaloric materials. These materials were subsequently used to liquefy propane gas from room temperature, for the first time ever. This concept has potential to improve the efficiency of hydrogen liquefaction by 50 percent.
- ✓ Developed a design for an 875 bar hydrogen storage vessel that has been independently estimated to cost 50 percent less than those currently on the market. The design is based on wrapping autofrettaged liners with high-strength steel wire.
- ✓ Completed experimental validation of an innovative pressure consolidation strategy for hydrogen fueling stations supplied by tube trailers, which can lower the capital cost for hydrogen compression at the station by up to 40 percent.
- ✓ In collaboration with the U.S. Department of Transportation, enabled a revision to the American Society of Mechanical Engineers (ASME) B31.12 Code for Hydrogen Piping and Pipelines that approves the use of lower cost polymeric materials and steel alloys for hydrogen service. These changes can lower the installation costs (material and labor) of hydrogen pipelines by up to 30 percent.
- ✓ Published a rigorous analysis identifying a pathway to achieve an early-market hydrogen production and delivery cost target of $7/kg by 2025.
- ✓ Developed novel coatings that reduce erosion of hydrogen compressor seals by 70 percent.
- ✓ Achieved the highest known efficiency for 350-bar electrochemical hydrogen compression using a new technology that relies on novel aromatic membranes. The concept has achieved an efficiency of 2 kWh/kg, double the efficiency previously known to be feasible under the same inlet and outlet pressure conditions.
- ✓ Developed a novel metering technology that achieves an accuracy of at least 2 percent, exceeding the current standards in the National Institute of Standards and Technology (NIST's) Handbook 44.
- ✓

Technology Acceleration

- ✓ Developed 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.
- ✓ Developed a first-of-its-kind zero-emissions maritime auxiliary power system showing an increase in energy efficiency of 30 percent relative to a comparable diesel generator. The 100-kW generator with 72 kg of hydrogen storage was designed and tested in collaboration with the DOT U.S. Maritime Administration for 10 months powering refrigerated containers at a port facility. Safety and regulatory reviews by the Hydrogen Safety Panel, US Coast Guard, and American Bureau of Shipping identified technical challenges for hydrogen and fuel cell use in the maritime shipping industry.
- ✓ Validated that a single fuel cell bus system passed 29,000 hours of real-world public transit operation without major repair or cell replacement, surpassing the DOE and Federal Transit Administration ultimate performance target of 25,000. Of the 27 fuel cell power plants included in the fuel cell electric bus data set, 12 (44 percent) have surpassed 20,000 hours of operation and five have surpassed 25,000 hours.
- ✓ Developed and demonstrated manufacturing quality control technology, detecting defects at web line speeds of up to 100 feet per minute and now transferring technique to commercialization partner.

Systems Analysis

- ✓ Completed annual analyses of patent awards and applications as a result of FCTO funding. This measure of program impact found that FCTO's efforts have led to the award of more than 960 patents, more than 90 in the 2016-1018 timeframe.
- ✓ Examined areas of early stage R&D to support hydrogen demand for multiple industries such as ammonia, metals refining, transportation and synthetic fuels by identifying the hydrogen supply needed for the respective industries and the renewable resources such as wind, solar and nuclear required for hydrogen production.
- ✓ Developed a comprehensive assessment of domestic resources including wind, solar, nuclear, natural gas and coal required to produce hydrogen supply to meet the demand of several light duty transportation scenarios in comparison to current resource consumption rates and projected resource availability.

Safety, Codes & Standards

- ✓ Performed extensive modeling based on hydrogen behavior validation R&D to inform regional authorities as they seek to allow FCEVs in tunnels. This work was documented in the Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study, published by Sandia National Laboratories in October 2017, which provides a scientific basis for allowing FCEVs in tunnels.
- ✓ Developed and proposed design curves for ASME pressure vessel steels (applicable to both Cr-Mo and Ni-Cr-Mo steels) to the ASME Pressure Vessel Committee as the basis for a Code Case that will allow pressure vessel design for high-pressure hydrogen without additional testing burden.
- ✓ As a result of R&D and collaborations between NREL and the National Institute for Standards and Technology (NIST) and with support from the State of California, a modified NIST hydrogen metrology standard of 5% was accepted in FY 2017, which enables hydrogen to be sold at retail stations.

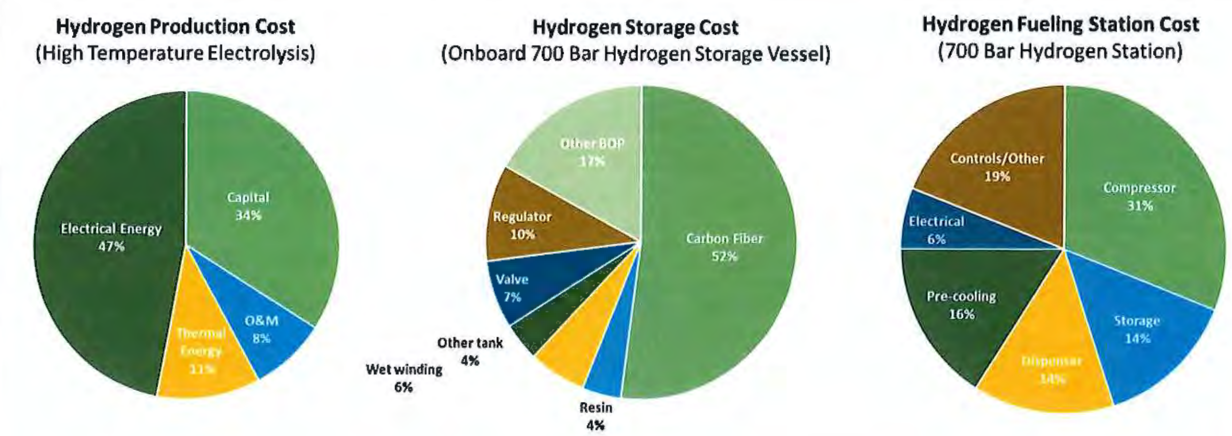


Figure 7.3. *Hydrogen fuel R&D cost breakdown by area (May 2019)*

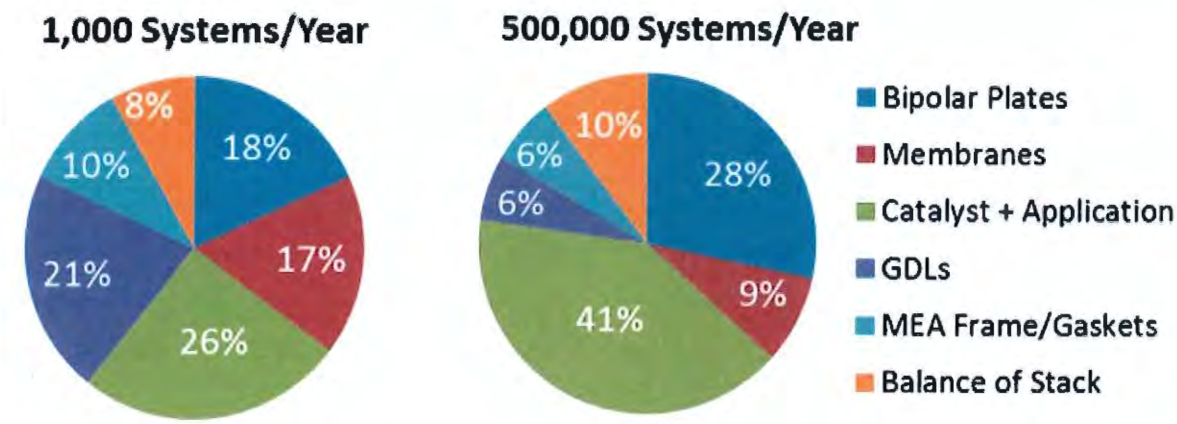


Figure 7.4. *Fuel cell R&D cost breakdown (May 2019)*

VIII. External Reviews and Updates to Developmental Roadmap and Strategic Plan

Response to EPACT section 811(a)(7) and 811(a)(8)

The Program used a number of mechanisms for obtaining external input, review, and evaluation. For example, the National Academy of Sciences (NAS) conducts reviews of DOE's R&D progress under the U.S. DRIVE Partnership (formerly the FreedomCAR and Fuel Partnership), and the Hydrogen and Fuel Cell Technical Advisory Committee provides technical and programmatic advice to the Secretary of Energy on hydrogen and fuel cells. In addition, the Program received feedback through its Annual Merit Review and Peer Evaluation Meetings,[38] which attract close to 1,000 participants, including close to 200 technical experts that reviewed the R&D program and over 120 individual RD&D projects every year. Feedback from Program stakeholders is also gathered through Requests for Information and workshops.

The Program periodically revises its planning documents, including the *Hydrogen and Fuel Cells Program Plan* (formerly the *Hydrogen Posture Plan)* and the Fuel Cell Technologies Office's *Multi-Year Research, Development, and Demonstration Plan* (*MYRD&D Plan*) to incorporate both the recommendations of these reviews and updates based on technological progress, programmatic changes, and policy decisions. The *Program Plan* is being updated with an expected release in calendar year 2019. The *MYRD&D Plan* is periodically updated to reflect changes in program targets and strategies.

NATIONAL ACADEMY'S REVIEW OF THE U.S. DRIVE PARTNERSHIP[39]

The U.S. DRIVE Partnership includes three automotive companies, five energy companies, two electric power companies, and the Electric Power Research Institute with the U.S. Department of Energy providing Federal leadership. It provides a forum to discuss precompetitive, technology specific R&D needs; identify possible solutions; and evaluate progress toward jointly developed technical goals. This process helps to inform DOE on the precompetitive R&D carried out by DOE's Vehicle Technologies Office and Fuel Cell Technologies Office. The NAS periodically reviews the effectiveness of the Partnership in meeting its mission, namely: "to accelerate the development of pre-competitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles, as well as related energy infrastructure."

Reviews by the NAS assess progress in each of the Partnership's research and program management areas as well as the responses of DOE program management to recommendations

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[38] For more information on the Annual Merit Review and Peer Evaluation Meeting, see: www.hydrogen.energy.gov/annual_review.html. Accessed July 22, 2019.

[39] U.S. DRIVE stands for "Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability"; the partnership was formerly known as the FreedomCAR and Fuel Partnership.

made in prior reports. Key comments and recommendations from the latest 2017 NAS review report[40] included:

- "...the Partnership is well-managed and has an increasingly robust consensus-building process for developing goals and targets and for providing guidance and input to DOE... and this process benefits greatly from the recent addition of overall systems analysis." (p. 41) In this regard, "the cradle-to-grave model should be continually updated and, where possible, tailored to improve its ability to support senior policy makers." (p. 204)

- "The Partnership provides a forum to discuss precompetitive, technology-specific R&D needs; identify possible solutions; and evaluate progress toward jointly developed technical goals. This process helps to inform the Department of Energy (DOE) on the precompetitive R&D that is carried out by DOE's Vehicle Technologies Office (VTO) and the Fuel Cell Technologies Office (FCTO)." (p. 2)

- "...lack of infrastructure is arguably the biggest challenge to the widespread deployment of hydrogen fuel cell vehicles, and continued emphasis by DOE on infrastructure enablers as well as an implementation plan is vital, whether within the Partnership or not." (p. 4) To support this effort "there remains a need for precompetitive work on technology enablers to reduce system cost, improve durability, and substantially lower the cost of delivered "green" hydrogen and electricity." (p. 217)

- "...the pathways (e.g., combinations of vehicles technologies and fuels) to achieve extremely aggressive greenhouse gas emission goals are very limited and would suggest that Partnership-related projects be increasingly focused on those few pathways that offer a realistic chance of success in meeting those goals." (p. 217)

- "The development and deployment of roadworthy fuel cell vehicles is a major accomplishment and one that will help to identify remaining technical, cost, manufacturing, and infrastructure challenges. Though the cars are still in the late stages of development, the fact that the cars have advanced to this point is due in part to R&D coordination by the Partnership and its prior organizations, as well as from decades of funding of pertinent research projects by the DOE and Partnership members." (p. viii)

- "Hydrogen production by natural gas reforming is currently a cost-effective option for near-term hydrogen requirements, and it also provides a pathway to reduced GHG emissions. To further reduce GHG emissions, the use of renewable sources of energy, such as biomass, wind, and solar, is required." (p. 11)

- "The [Parternship's] Executive Steering Group should address issues elated to hydrogen infrastructure and assess U.S. DRIVE's role to formulate an action plan to address the issues and barriers." (p. 146)

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[40] National Academies of Sciences, Engineering, and Medicine 2017. *Review of the Research Program of the U.S. DRIVE Partnership: Fifth Report.* Accessed July 22, 2019. https://doi.org/10.17226/24717.

REVIEW BY THE HYDROGEN AND FUEL CELL TECHNICAL ADVISORY COMMITTEE

EPACT section 807 required the establishment of the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) to advise the Secretary of Energy on programs and activities under Title VIII. EPACT states that the committee is to review and make recommendations to the Secretary on: (1) the implementation of programs and activities under Title VIII; (2) the safety, economical, and environmental consequences of technologies for the production, distribution, delivery, storage, or use of hydrogen energy and fuel cells; and (3) the plan called for by section 804 of EPACT, the *Hydrogen and Fuel Cells Program Plan* (formerly known as the *Hydrogen Posture Plan*).

During the period covered by this report, the HTAC met six times (once via webinar and five in-person meetings). They also delivered several reports[41] to the Secretary, including their 2016 and 2017 Annual Reports and a subcommittee report on hydrogen safety and event response (the 2018 HTAC Annual Report and a report from a subcommittee on U.S. competitiveness are currently being drafted by the Committee.) As stated in EPACT section 807(d)(2), the Secretary "shall transmit a biennial report to Congress describing any recommendations made by the Technical Advisory Committee since the previous report. The report shall include a description of how the Secretary has implemented or plans to implement the recommendations, or an explanation of the reasons that a recommendation will not be implemented." The Department has submitted six biennial reports outlining the recommendations by the Committee and the Department's responses. The report submitted to Congress in October 2016 covered recommendations made during fiscal years 2014 and 2015, and the report submitted in September 2018 covered FY 2016 to 2017.[42]

UPDATES TO STRATEGIC PLANS

The Program is currently updating its planning documents—including the *Hydrogen and Fuel Cells Program Plan* and the *MYRD&D Plan* — to reflect changes in the status of the technologies and the policy and market environment. These updates include changes to plans for fuel cell research, development, and demonstration activities, and they address recommendations from external reviews and audits.

The Program coordinated closely with industry and other partners to understand the needs and develop strategies for the development of hydrogen infrastructure and fuel cell technologies that will meet market requirements. The Program also stayed closely attuned to international activities and strategies for FCEVs and hydrogen. As previously mentioned, the U.S. was elected Chair of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and is

[41] U.S. Department of Energy, Hydrogen and Fuel Cells Program, HTAC Reports and Other Publications. Accessed July 22, 2019. https://www.hydrogen.energy.gov/htac_reports.html.

[42] U.S. Department of Energy, Fifth and Sixth Biennial Reports to Congress on "Response to Findings and Recommendations of the Hydrogen and Fuel Cell Technical Advisory Committee." Accessed July 22, 2019. https://www.hydrogen.energy.gov/pdfs/biennial_report_to_congress_2016.pdf and https://www.hydrogen.energy.gov/pdfs/sixth-biennial-report-to-congress-htac.pdf.

working with the other 18 member countries and the European Commission to increase information sharing and collaboration.[43] The Program closely monitors hydrogen infrastructure initiatives launched in these countries in order to apply lessons learned and best practices to strategies and activities in the U.S.

[43] International Partnership for Hydrogen and Fuel Cells in the Economy. Accessed July 22, 2019. http://iphe.net/partners.