U.S. DEPARTMENT OF ENERGY

Hydrogen and Fuel Cell Activities, Progress and Plans: September 2013 to August 2016

Fourth Report to Congress
December 2017

United States Department of Energy
Washington, DC 20585

Message from the Secretary

The enclosed report, *Hydrogen and Fuel Cell Activities, Progress and Plans*, is the fourth in a series.[1] 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 report covered September 2010 to August 2013. This report covers the period 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 Paul Ryan**
  Speaker of the House of Representatives

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

- **The Honorable Maria Cantwell**
  Ranking Member, Senate Committee on Energy and Natural Resources

- **The Honorable Greg Walden**
  Chairman, House Committee on Energy and Commerce

- **The Honorable Frank Pallone, Jr.**
  Ranking Member, House Committee on Energy and Commerce

- **The Honorable Lamar Smith**
  Chairman, House Committee on Science, Space, and Technology

- **The Honorable Eddie Bernice Johnson**
  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 Ms. Jennifer Loraine, Deputy Assistant Secretary for Senate Affairs or Mr. Marty Dannenfelser, Deputy Assistant Secretary for House Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Rick Perry

Executive Summary

This report documents the activities of the Department of Energy's (DOE's) 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 (FY 2013 to FY 2016) EERE led activities related to DOE's Hydrogen and Fuel Cells Program (the Program), which addressed the full range of barriers facing the development and deployment of hydrogen and fuel cell technologies. The Program integrates the activities of four DOE offices: Energy Efficiency and Renewable Energy (EERE), Nuclear Energy (NE), Fossil Energy (FE), and Science (SC) to meet each office's distinctive needs and goals[2]. This Program has been integral to the important progress in these technologies in recent years. The year 2015 was a landmark year for hydrogen and fuel cells. After decades of research and development and the demonstration of various generations of prototype fuel cell electric vehicles (FCEVs) by a number of global automakers, 2015 saw the first commercial FCEVs in history sold to regular consumers. Advances achieved through the Program's efforts can be seen in the marketplace today: commercial customers are choosing fuel cells for the benefits they offer, and growing sales and manufacturing volumes for applications, such as forklifts and backup power, are lowering costs, increasing consumer confidence, and growing the domestic supplier base.

EERE's efforts have led to more than 580 hydrogen and fuel cell related patents, more than 45 commercial technologies, and about 65 technologies projected to be commercialized within three-to-five years. In addition, EERE has successfully stimulated early markets for fuel cells through strategically targeted deployments that are cost-shared with industry partners: deployments of more than 1,600 fuel cells in key early markets have led to roughly 18,000 additional orders for fuel cells by industry, with no additional DOE funding.

Since the last report period, September 2010 through August 2013, Hyundai started leasing its Tucson FCEV and Toyota announced FCEVs for sale, right on track with DOE's original plans for research and development and resulting in commercial decisions being made in the 2015 timeframe. Several other companies also plan to release FCEVs very soon, including Honda, GM, Daimler, and BMW. To support the technical progress needed to enable widespread commercialization, from FY 2013 to FY 2016, DOE pursued a strong, strategically balanced portfolio of hydrogen and fuel cell activities. Approximately $478 million in budget authority as allocated by the Department was put toward these efforts in EERE and the Office of Science.

Over the period covered by this report, the Program continued to make progress toward the goals laid out in its developmental roadmap (the *Hydrogen and Fuel Cells Program Plan*), which is being updated with an expected release in calendar year 2018. The Program's accomplishments are thoroughly documented every year in its *Annual Progress Report;* a summary of major accomplishments (including citations) is provided in both this report and

[2] https://www.hydrogen.energy.gov/index.html

shown on the "Accomplishments and Progress" page of the Fuel Cell Technologies Office website (http://energy.gov/eere/fuelcells/fuel-cell-technologies-office-accomplishments-and-progress).

HYDROGEN AND FUEL CELL ACTIVITIES, PROGRESS AND PLANS: SEPTEMBER 2013 TO AUGUST 2016

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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 mission of the Department of Energy's (DOE's) Hydrogen and Fuel Cells Program (the Program) is to enable the widespread commercialization of a portfolio of hydrogen and fuel cell technologies across multiple sectors. To enable market success of these technologies, and achieve the associated benefits of their widespread use, over the period covered by this report the Program conducted basic and applied research, technology development and demonstration, and diverse efforts to overcome institutional and market challenges. The Program integrates the activities of four DOE offices: Energy Efficiency and Renewable Energy (EERE), Nuclear Energy (NE), Fossil Energy (FE), and Science (SC) to meet each office's distinctive needs and goals[3].

Success of this mission plays a substantial role in overcoming our Nation's key energy challenges, including significant reductions in greenhouse gas emissions and oil consumption as well as improvements in air quality. Fuel cells also enable more efficient use of energy while increasing the diversity of our energy sources. Fuel cells can provide power from diverse domestic fuels, including hydrogen, natural gas and renewable sources, such as bio-methanol or biogas; however, the focus of the Program is hydrogen-based fuel cells. Fuel cells offer numerous potential advantages that make them appealing for end users, including quiet operation, low maintenance needs, and high reliability.

The Program's activities are documented at a high level in the *Hydrogen and Fuel Cells Program Plan*, which is being updated and is expected to be released in calendar year 2018. Detailed discussions of barriers and the current and planned activities are found in the hydrogen and fuel cell plans of the individual DOE offices, as follows:

- Office of Energy Efficiency & Renewable Energy (EERE): *Fuel Cell Technologies Office's Multi-Year Research, Development, and Demonstration Plan (MYRD&D Plan)*[4]
- Office of Fossil Energy (FE): *Hydrogen from Coal RD&D Plan*[5]
- Office of Science (SC): *Basic Research Needs for the Hydrogen Economy*[6]

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[3] https://www.hydrogen.energy.gov/index.html

[4] *Fuel Cells Technologies Program Multi-Year RD&D Plan,* U.S. Department of Energy, 2012, http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22.

[5] *Hydrogen from Coal RD&D Plan,* U.S. Department of Energy, September 2010, http://www.netl.doe.gov/File%20Library/Research/Coal/ccbtl/20100908_Draft_H2fromCoal-RDD_final.pdf.

[6] *Basic Research Needs for the Hydrogen Economy,* U.S. Department of Energy, February 2004, http://science.energy.gov/~/media/bes/pdf/reports/files/Basic_Research_Needs_for_the_Hydrogen_Economy_rpt.pdf

In addition, the Program coordinates with Fossil Energy's solid oxide fuel cell program and the energy technologies supported by DOE's Advanced Research Projects Agency-Energy (ARPA-E) Office. ARPA-E works to advance high-potential, high-impact energy technologies that are too early for private-sector investment, but can be meaningfully advanced with a small investment over a defined period of time. ARPA-E empowers America's energy researchers with funding, technical assistance, and market readiness.[7] The most recent results of the Hydrogen and Fuel Cells Program — with information on individual projects — are found in the *DOE Hydrogen and Fuel Cells Program Annual Progress Report*,[8] which summarizes each year's hydrogen and fuel cell activities and accomplishments for projects funded by the Program.

As shown in figure 2.1, the Program conducted a wide range of activities between FY 2013 and FY 2016 to address technological and non-technological barriers to commercialization. R&D efforts pursued key technology advances, including reducing the cost and improving the durability and performance of fuel cells; reducing the cost of producing, delivering, and storing hydrogen; and improving the capacity of hydrogen storage systems. Real-world demonstrations were conducted to validate performance and provide feedback to R&D efforts.

The Program also aimed to act as a catalyst in the transition from R&D to early deployment. This was accomplished through a strategy integrating real-world demonstrations; public outreach and education; strategic deployments in key early markets; development and dissemination of critical safety information; and efforts to enable nationally and internationally harmonized codes and standards. These activities were integrated into a well-planned timeline to maximize their benefits and enable a broader transformation of the marketplace.

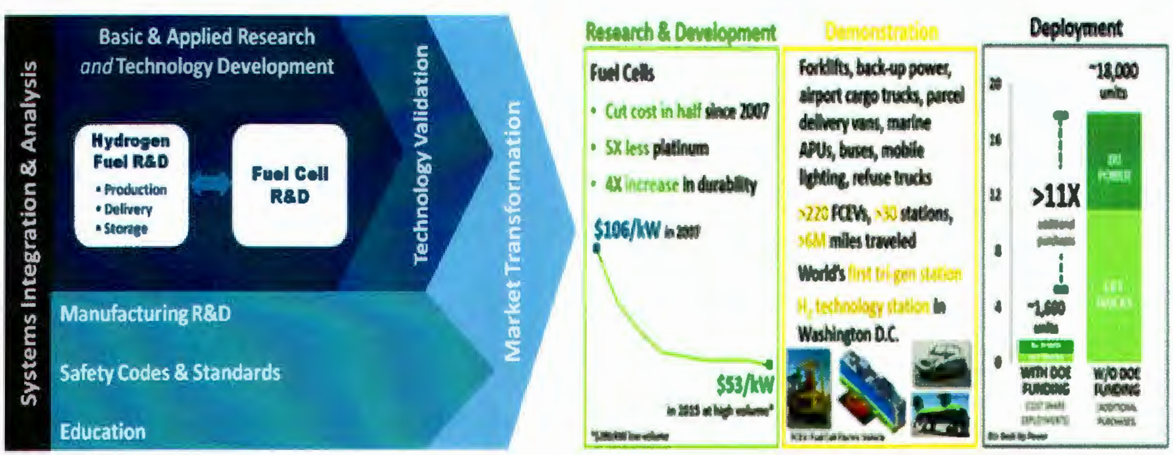

Figure 2.1. *The Program's activities are well integrated to enable the widespread commercialization of hydrogen and fuel cell technologies, which will reduce petroleum use, greenhouse gas emissions, and criteria air pollutants, and will contribute to a more diverse energy supply and more efficient use of energy.*

[7] The Advanced Research Projects Agency-Energy (ARPA-E) was established in 2009. http://arpa-e.energy.gov.

[8] *U.S. Department of Energy Hydrogen Program Annual Progress Report*, www.hydrogen.energy.gov/annual_progress.html.

The following sections provide a summary of DOE's activities from FY 2013 to FY2016 under Title VIII of EPACT (*Progress and accomplishments by these activities are discussed in section 7 of this report*):

SCIENCE - BASIC RESEARCH

Basic Science Research addressing critical challenges related to hydrogen storage, production, and fuel cells is supported by the Office of Basic Energy Sciences within the DOE Office of Science. This basic research complements the applied research and development projects 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.

Examples of basic research most relevant to the Program's activities are:

- *Hydrogen Storage:* nanostructured materials; theory, modeling, and simulation to predict behavior and design new materials; and novel analytical and characterization tools.
- *Fuel Cells:* nanostructured catalysts and materials; integrated nanoscale architectures; novel fuel cell membranes; innovative synthetic techniques; theory, modeling, and simulation of catalytic pathways, membranes, and fuel cells; and novel characterization techniques.
- *Hydrogen Production:* long term approaches such as photobiological and direct photochemical production of hydrogen; single atom catalysts for water-gas shift, hydrogen evolution, and fuel cells to minimize the dependence on precious metals.

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. This, in turn, will lead to improvements in the performance, cost, and reliability of fuel cell technologies and technologies for hydrogen production and storage.

EERE - APPLIED RESEARCH, DEVELOPMENT, AND DEMONSTRATION

Hydrogen Fuel R&D focused on materials and chemical research and technology development to enable the production of low-cost hydrogen fuel from diverse, low-carbon domestic pathways and to address key challenges to hydrogen delivery and storage.

The **hydrogen production** aspect of these efforts included R&D of technologies for:

- Small- to mid-scale hydrogen production technologies (e.g., electrolysis, reforming of renewable liquids) for distributed production at fueling sites, or at city-gate facilities and

- Large-scale centralized production technologies (e.g., biomass and coal gasification, wind and solar-powered electrolysis, solar-driven high-temperature thermochemical cycles, as well as direct solar conversion, including photobiological and photoelectrochemical pathways).

The Program's **hydrogen delivery** efforts sought to reduce the cost of technologies for transporting hydrogen from centralized production facilities, and reduce the cost of compressing, storing, and dispensing hydrogen at the fueling site. The key overarching goal for all production and delivery pathways was to reduce the cost of hydrogen to <$4.00/gallon gasoline equivalent[9] (gge), delivered and dispensed.[10,11] The **hydrogen storage** component of this sub-program focused on the R&D of low-pressure materials-based storage that will enable widespread commercialization of fuel cell systems for diverse applications.

The Program also conducted R&D to explore advanced conformable and low-cost high-pressure storage technologies. The primary goal of the program's hydrogen storage efforts were to enable a driving range of >300 miles across all vehicle platforms while meeting the packaging, cost, safety, and performance requirements of current and future vehicle markets.

Fuel Cell R&D pursued advances in fuel cell stack components, system balance of plant components, and subsystems to address the challenges of improving the durability, reducing the cost, and improving the performance (power, start-up time, transient response, etc.) of fuel cell systems for transportation, stationary, and early market applications. Key goals were to develop:

- A transportation fuel cell power with 65 percent peak efficiency that can achieve 5,000-hour durability (ultimate 8,000 hours) corresponding to 150,000 miles and be mass produced at a modeled cost of $40/kW by 2020 (ultimate $30/kW);

- Stationary fuel cell systems for distributed power generation for a cost of $1,000-$1,500/kW and a durability of 60,000–80,000 hours, depending on size and application.[12]

The Program also conducted R&D of fuel cells for early market applications including auxiliary power units and backup power systems.

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[9] The energy content of a gallon of gasoline and a kilogram of hydrogen are approximately equal on a lower heating value basis; a kilogram of hydrogen is approximately equal to a gallon of gasoline equivalent (gge) on an energy content basis.

[10] This cost range results in equivalent fuel cost per mile for a hydrogen fuel cell vehicle compared to gasoline hybrid vehicles in 2020. The full explanation and basis can be found in U.S. Department of Energy (DOE) Record 11007 (see www.hydrogen.energy.gov/program_records.html).

[11] All costs in this plan are in 2007 dollars to be consistent with EERE planning which uses the energy costs from the 2009 Annual Energy Outlook.

[12] $1,500/kW translates to a levelized cost of electricity of about $0.08/kWh using natural gas https://www.hydrogen.energy.gov/pdfs/11014_medium_scale_chp_target.pdf.

DOE's Office of Fossil Energy also conducted efforts in solid oxide fuel cells (SOFCs) from FY 2013 to FY 2016, which aimed to reduce the cost and improve the performance of SOFCs. These activities were focused primarily on fuel cells for megawatt-scale, near-zero-emissions stationary power. 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.

Manufacturing R&D developed processes and technologies to reduce the cost of manufacturing fuel cells and systems for the production, delivery, and storage of hydrogen, while maintaining quality and durability. Industry needs these low-cost, high-volume manufacturing processes to produce affordable hydrogen and fuel cell components and systems and to develop a competitive domestic supplier base.

Systems Analysis conducted extensive crosscutting analysis to enable a comprehensive understanding of the major issues involved in hydrogen and fuel cell systems. Examples include technology analysis for specific program elements, policy and infrastructure analysis, and high-level implementation and market analysis, such as:

- Conducting analysis of hydrogen production pathways;
- Evaluating impacts of technology advancements on fuel cell cost;
- Studying the feasibility of using fuel cells for combined heat, hydrogen, and power (tri-generation);
- Analyzing the impacts of hydrogen quality on fuel cell performance and infrastructure; and
- Determining the reductions in greenhouse gas (GHG) emissions and petroleum use from "well-to-wheels" or life cycle analyses.

Risk analyses determined the effects of certain variables on the probability of meeting the Program's targets and help identify risk mitigation strategies. Analysis of employment opportunities and needs, manufacturing capability and growth potential, and overall domestic competitiveness were also critical parts of the sub-program's activities.

These efforts provided tools to integrate Program activities and measure progress toward goals. Results were used in EERE's higher-level benefits assessments to estimate the potential effects of the Program's R&D efforts on energy security, the environment, and the economy.

Safety, Codes & Standards addressed critical needs regarding hydrogen safety and the development of codes and standards, which are essential for commercialization of hydrogen-based products and systems. To address the lack of safety data, inconsistent safety practices, and the general lack of knowledge regarding the safe use of hydrogen, this sub-program developed safety knowledge tools, including hydrogen best practices and lessons-learned, as well as educational resources (on-line and classroom) for first responders, researchers, and permitting officials. These efforts also involved establishing and ensuring safe practices within all Program activities.

To support the development and harmonization of national and international codes and standards, this sub-program conducted underlying R&D needed to ensure the technical soundness of codes and standards; improved access to standards and model codes; supported the harmonization of domestic standards; shared lessons-learned regarding siting and permitting; and played a leading role in international efforts to harmonize standards. The sub-program also conducted testing of low-cost, durable hydrogen sensor technologies that can be implemented in various hydrogen applications.

Technology Validation provided an essential function in the transition of hydrogen and fuel cell technologies from the lab to commercialization. Systems were validated in the field through exposure to real environmental conditions. The technology was in the customer's hands and was exposed to real-world operations and related maintenance situations. Performance of the technologies against various technical targets (such as durability, reliability, and availability) and cost targets were evaluated, while potential risks related to market development were mitigated. The Technology Validation Program met its objectives through extensive data collection and evaluation for a variety of hydrogen and fuel cell applications. Data were collected to determine whether performance and cost targets were met under realistic operating conditions, provide feedback on progress, and efficiently manage the research elements of the program while providing redirection as needed. Detailed evaluation results were catalogued by the National Renewable Energy Laboratory (NREL) in the form of composite data products (CDPs).[13]

Market Transformation identified strategic opportunities to grow early markets for hydrogen and fuel cells and directly assists in the deployment of commercial and near-commercial hydrogen and fuel cell systems. The primary goal of Market Transformation was to increase deployments in key early markets, where a modest amount of new orders can have a significant impact on public awareness and acceptance and reduce the total cost of ownership. Early market deployments can also stimulate further market activity by supporting the growth of domestic industry, overcoming some of the logistical and other non-technical challenges associated with adoption of these new technologies, and establishing key elements of the infrastructure essential for later market growth.

In addition to their direct impact on the market, deployments can provide data on real-world operation, lessons-learned from early adopters, and information that is used to validate the benefits of the technologies. These activities made up a key final phase in the

[13] National Renewable Energy Laboratory, Hydrogen and Fuel Cell Composite Data Products, available at: http://www.nrel.gov/hydrogen/cdp_topic.html

Program's comprehensive strategic timeline for moving technologies from the laboratory to self-sustaining commercialization, and they are closely coordinated and integrated with the Program's demonstration and education and outreach efforts.

Education and Outreach activities addressed the knowledge barriers that can impede the acceptance of hydrogen and fuel cell technologies. These efforts focused on developing resources and conducting outreach to increase the understanding of the benefits of the technologies and address safety, codes, and standards concerns. Particular attention was paid to key audiences, such as potential early market end-users, emergency responders, safety and code officials, state and local governments, and educators. These efforts also facilitated the expansion of hydrogen and fuel cell curricula at educational institutions.

FE AND NE - APPLIED RESEARCH DEVELOPMENT AND DEMONSTRATION

FE and NE had no funded activities during this reporting period.

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 2013 to FY 2016, DOE pursued a strategically balanced portfolio of hydrogen and fuel cell activities, as described in section 2 of this report.
    - During this period, approximately $478 million in budget authority as allocated by the Department, below the Congressional control level, was put toward the Program's efforts (see fig. 3.1).[14]

	FY 2013	FY 2014	FY 2015	FY 2016	TOTAL
Fuel Cell R&D	41,266	32,423	32,063	33,962	139,714
Hydrogen Fuel R&D	31,681	34,466	34,155	39,763	140,065
Manufacturing R&D	1,899	2,879	2,911	2,948	10,637
Systems Analysis	2,838	3,000	3,000	3,000	11,838
Technology Validation	8,514	6,000	11,000	7,000	32,514
Safety, Codes & Standards	6,808	6,909	6,901	6,906	27,524
Market Transformation	2,838	2,841	3,000	3,000	11,679
NREL Site-Wide Facility Support	0	1,000	1,800	1,900	4,700
SBIR/STTR	2,139	3,410	2,170	2,471	10,190
EERE Hydrogen & Fuel Cells Total	**97,983**	**92,928**	**97,000**	**100,950**	**388,861**
Fossil Energy	0	0	0	0	0
Nuclear Energy	0	0	0	0	0
Basic Energy Sciences	25,769	19,922	18,499	24,686[15]	88,876
DOE Hydrogen & Fuel Cells Total	**123,752**	**112,850**	**115,499**	**125,636**	**477,737**
Fossil Energy Solid Oxide Fuel Cell	23,800	25,000	30,000	30,000	108,800
ARPA – E	2,114	33,000	0	Footnote[16]	35,114
DOE Total	**149,666**	**170,850**	**145,499**	**155,636**	**621,651**

Figure 3.1. Enacted *Budget for DOE hydrogen and fuel cell activities.*

- A key element of DOE's 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,

[14] 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.
[15] BES final funding amounts are determined at the close of each fiscal year
[16] Solicitation underway – funding will be finalized in FY 2017 once awards are made

technology-neutral approach, pursuing advances for a wide range of applications, with varying time frames for commercial success (fig 2.2).

- The Fuel Cell Technologies Office launched three national lab-led consortia in 2016 as part of the DOE's Energy Materials Network, which was established in support of the President's 2011 Materials Genome Initiative and advanced manufacturing priorities. The goal of the Materials Genome Initiative is expediting the deployment of new materials to market by two-fold, and increasing new materials' likelihood of being commercialized by ensuring closer integration between researchers and industry throughout the development process.

  The Energy Materials Network was launched by DOE in February of 2016, and is currently composed of seven consortia. [17] Each consortium is focused on specific materials classes, and will follow four key defining principles: 1) identifying and assembling world-class capabilities that are unique to the National Laboratories, 2) assisting interested stakeholders in identifying capabilities that are relevant to their application, 3) launching user-friendly online portals of materials data, and 4) expediting access to the labs through short-form versions of contractual agreements.

  - ElectroCat: The Electrocatalysis Consortium (ElectroCat) is an initiative to accelerate the development of catalysts made without platinum group metals (PGM) for use in automotive fuel cell applications.
  - FC-PAD: The Fuel Cell Consortium for Performance and Durability (FC-PAD) aims to enhance the performance and durability of polymer electrolyte membrane fuel cells, while simultaneously reducing their cost.
  - HyMARC: The Hydrogen Materials—Advanced Research Consortium (HyMARC) aims to address unsolved scientific challenges in the development of viable solid-state materials for storage of hydrogen onboard vehicles. Better onboard hydrogen storage could lead to more reliable and economic hydrogen fuel cell vehicles.
  - HydroGEN: Consortium on Advanced Water Splitting Materials, is an initiative to accelerate the research and development of advanced water splitting technologies for large-scale renewable hydrogen production, with a specific emphasis on advanced electrolytic, solar photoelectrochemical, and solar thermochemical hydrogen production pathways.

[17] The initial consortia launched through the Energy Materials Network in 2016 include: LightMat (Vehiclea Technologies Office), ElectroCat (Fuel Cell Technologies Office), and CaloriCool (Building Technologies Office). More information about these three consortia and the network is available here: http://energy.gov/eere/energy-materials-network/energy-materials-network

H2USA

- In 2013, the Program and stakeholders developed a framework for H2USA, a public-private collaboration to help address hydrogen infrastructure challenges and enable the widespread commercial adoption of fuel cell electric vehicles (FCEVs).

  As of the end of FY 2016, H2USA consisted of 45 participants, including the state of California, developers, car companies, and hydrogen providers. The number of partners has increased more than fourfold since its launch. In direct support of H2USA, DOE launched the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project in 2014 to leverage capabilities at the National Laboratories to address the technology challenges related to hydrogen refueling stations.

  Jointly led by Sandia National Laboratories and that National Renewable Energy Laboratory, H2FIRST is a strong example of DOE's efforts to bring national lab capabilities and facilities together to address immediate and mid-term challenges faced by the industry.

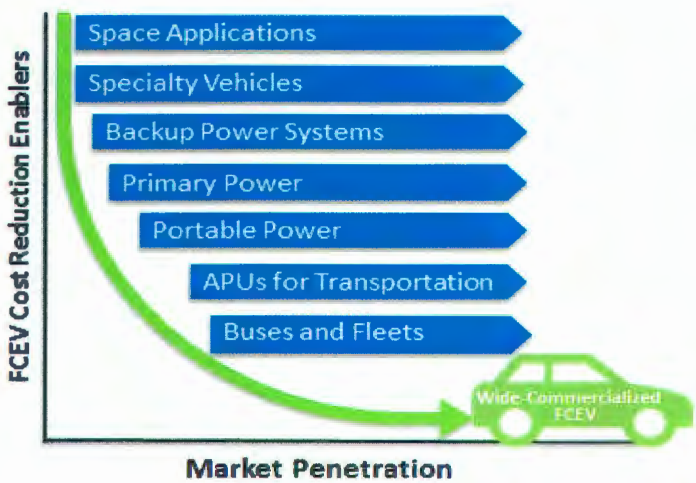
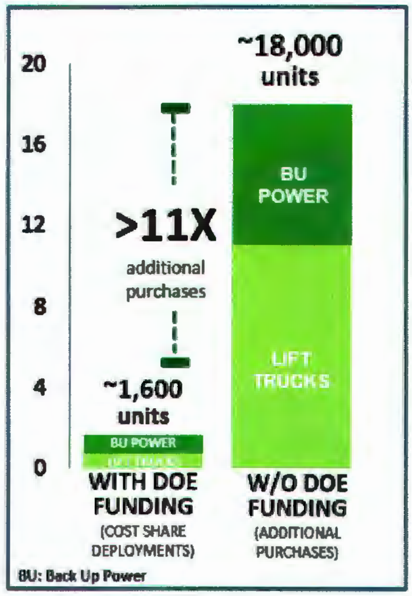


Figure 3.2. *A representation of how fuel cell markets can progress as costs come down. DOE is pursuing advances in hydrogen and fuel cell technologies for a variety of applications. Growth in early markets helps reduce costs industry-wide, strengthen consumer acceptance, expand the infrastructure, and overcome a variety of logistical challenges.*

Figure 3.3. *The Program has successfully catalyzed commercialization through targeted deployments of fuel cells in key early markets. Cost-shared deployments of approximately 1,600 fuel cells in material handling equipment and backup power installations have led to an estimated 9,000 additional orders by industry customers since 2013, with no additional DOE funding. These orders represent about half of the total orders since 2009.*



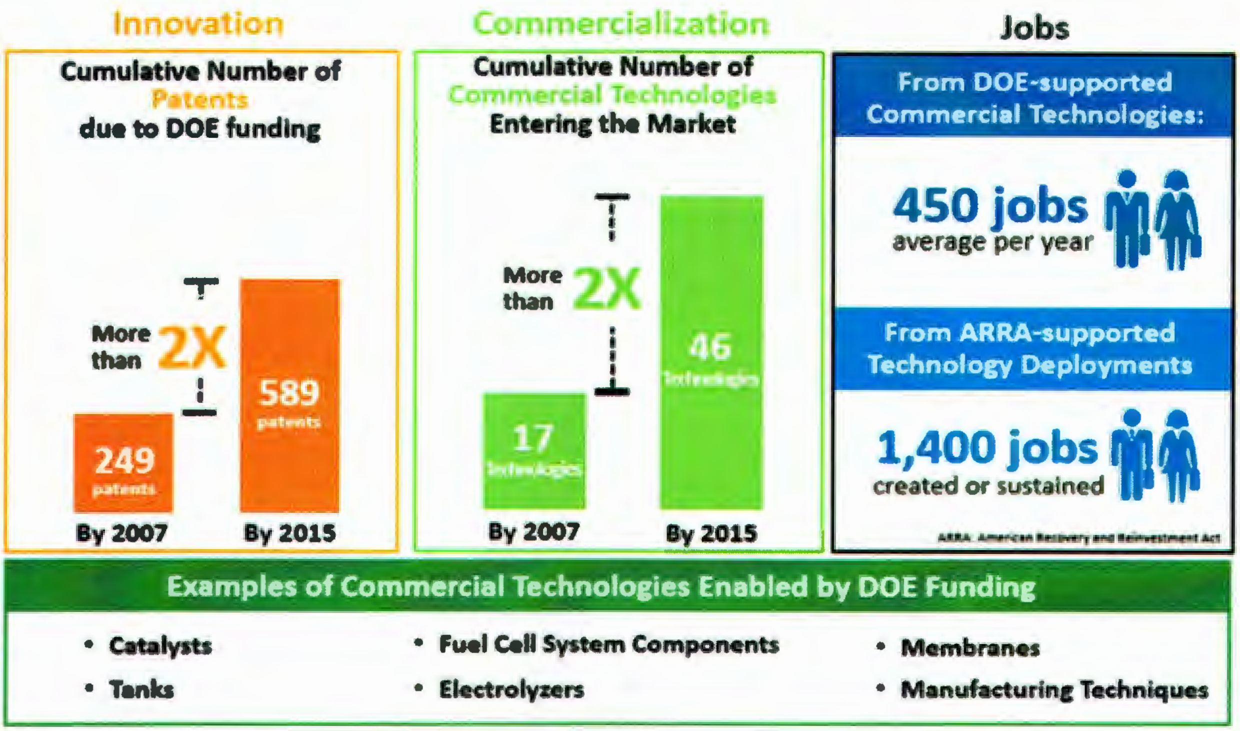
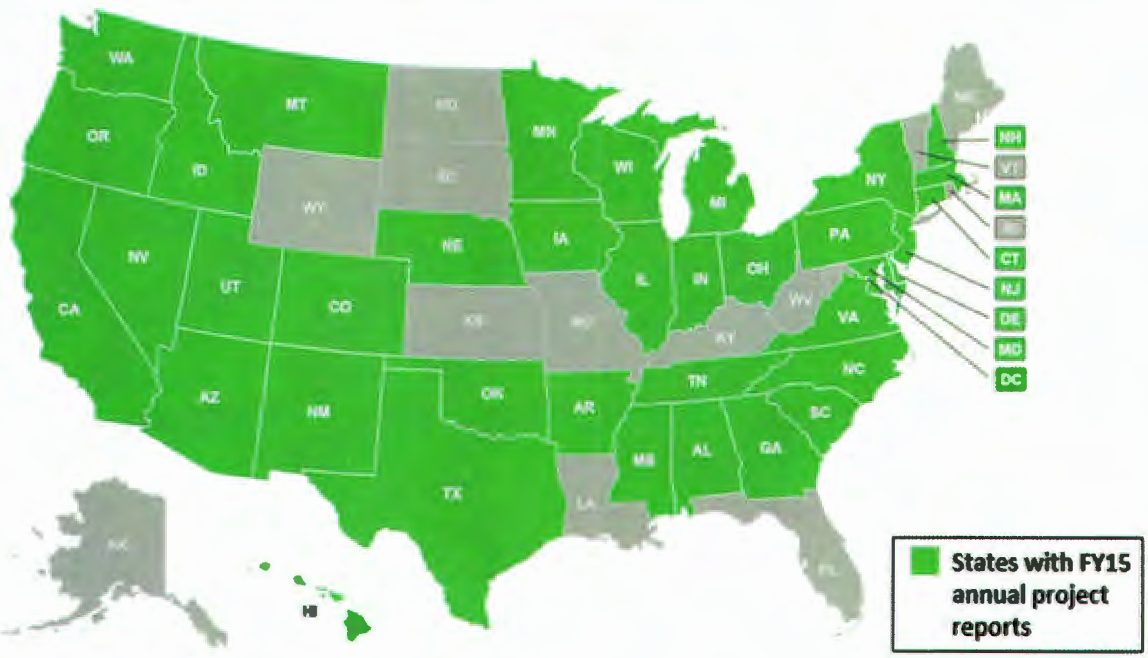


Figure 3.4. EERE *funding has led to a two fold increase in the number of patents since 2007 with approximately 190 new patents since 2013,*[18] *and twice the commercial products entering the market than in 2007. Major innovations include catalysts, membranes, and hydrogen storage technologies. In 2014, more than 450 jobs were created or retained from the commercialization of these products and over 1,400 jobs were created or sustained due to the Recovery Act. The data for 2016 will be finalized in fiscal year 2017.*

[18] https://www.hydrogen.energy.gov/pdfs/review13/03_satyapal_plenary_2013_amr.pdf

Fuel Cell Technologies Office Activities By State
Prime and Subcontract Recipients



Source: FY 2015 Annual Progress Report- Project Listings by State
(https://www.hydrogen.energy.gov/pdfs/progress15/xv_project_listing_by_state_2015.pdf)

Figure 3.5. *U.S. Map of Projects Funded*

- DOE leveraged other established strategic partnerships by:
  - Collaborating with members of the U.S. DRIVE Partnership[19] 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 cell technologies.

- DOE conducted three annual reviews of the Program (the 2014, 2015, and 2016 *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 and provide valuable feedback to principal investigators and DOE managers.[20] The most recent review, in June 2016, included nearly 120 projects, almost 370 reviewers, and more than 1800 attendees.

[19] Other members of the U.S. Drive partnership include automakers, energy companies, and electric utilities, http://energy.gov/eere/vehicles/vehicle-technologies-office-partnerships

[20] U.S. Department of Energy Hydrogen Program Annual Merit Reviews, www.hydrogen.energy.gov/annual_review.html.

- DOE collaborated with international partners, representing several leading economies, through the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE).[21] IPHE includes members from 18 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;
  - Advance policy and regulatory actions to support widespread deployment;
  - Raise the profile of these technologies with policy-makers and the public; and
  - Monitor technology developments in hydrogen, fuel cells, and complementary technologies.

[21] International Partnership for Hydrogen and Fuel Cells in the Economy, www.iphe.net.

IV. Changes Made to the Strategy Reflecting Results of Learning Demonstrations[22]

Response to EPACT section 811(a)(3)

As described in Section 2 of this report, the Program's demonstration efforts were conducted by the Technology Validation sub-program. They played an essential role between FY 2013 and FY 2016 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. As of the end of FY2016, these efforts developed and released to the public more than 400 "composite data products" (or CDPs).[23]

The results from these demonstration efforts largely confirmed DOE's strategies for hydrogen and fuel cells. However, based upon the reliability data from these demonstrations, the Program placed a greater emphasis on improved and novel hydrogen fueling infrastructure component development and demonstration, such as the H2FIRST project.

The Program's demonstration projects were a steady and invaluable source of data for the Program and for external stakeholders. While the Program has demonstrated more than 220 FCEVs and dispensed more than 1.3 million kilograms of hydrogen since 2006, a summary of key examples for 2013 to 2016 is provided below.

- Since 2013, the Program has collected and evaluated data on 55 FCEVs traveling a total of 1.4 million miles.[24] The results show continued improvements in durability and fuel economy including a greater than 50 percent increase in durability since 2009 from 2,500 hours to 3,900 hours.[25] The results also showed significant improvements in on road vehicle driving range, achieving up to 300 miles per fill and a fueling time of less than four minutes.[26] As a result of these data and automaker feedback, the Program has increased their fuel cell stack durability target from 5,000 hours in 2020 to an ultimate target of 8,000 hours and augmented its efforts on composite storage through three additional projects since 2013 to lower the cost of carbon fiber composites for 700 bar onboard storage.

- An additional 63,000 kilograms of hydrogen have been dispensed at hydrogen stations since 2013.[27] The data from the learning demonstrations show that reliability of stations and their components continues to be an area of concern as there are only a few stations (around 20 in California as of August 2016) to support the rollout of FCEVs

[22] Learning demonstrations is a term specifically used in EPACT subsection 811(a)(3)
[23] "Fuel Cell and Hydrogen Technology Validation" web page, NREL, http://www.nrel.gov/hydrogen/cdp_topic.html.
[24] http://www.nrel.gov/hydrogen/images/cdp_fcev_53.jpg.
[25] Hydrogen and Fuel Cells Program Record 15014: https://www.hydrogen.energy.gov/pdfs/15014_fuel_cell_stack_durability.pdf
[26] http://www.nrel.gov/hydrogen/docs/cdp/cdp_2.jpg
[27] "Fuel Cell and Hydrogen Technology Validation" web page, NREL, http://www.nrel.gov/hydrogen/cdp_topic.html

to consumers and their availability to drivers is a priority. Compressors and dispensers are the top two components that require unscheduled maintenance at the stations, and are followed closely by the stations safety systems.[28] To address these issues, the Program initiated the H2FIRST project in 2014. This project address the technology challenges related to hydrogen refueling stations. The Program also issued a funding opportunity announcement in FY 2016 and selected three projects on innovative compressor designs. Also, in the FY 2017 Congressional Budget Request, the Program requested a $3 million increase in the Safety, Codes and Standards Subprogram budget ($10 million total) to provide a scientific basis for the promulgation of essential codes and standards and to accelerate infrastructure acceptance.

- The Program also confirmed the success of the fuel cell-powered material handling equipment and backup power applications. As a result, the Program discontinued funding for both of these applications which are now beginning to be competitive and focused instead on other early markets. The Program is now funding new demonstration projects in fuel cell range extenders for battery-powered parcel delivery vans, airport ground support equipment, and marine applications.

[28] http://www.nrel.gov/hydrogen/images/cdp_infr_21.jpg.

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 significant progress that DOE made toward its technology development goals between FY 2013 and FY 2016. This progress has gone a long way toward enabling widespread 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 increasing emphasis on 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. The year 2015 was a landmark year for hydrogen and fuel cells. After decades of research and development (R&D) and the demonstration of various generations of prototype fuel cell electric vehicles (FCEVs) by a number of global automakers, this year saw the first commercial FCEVs in history, being sold to regular consumers. In November 2014, Hyundai started leasing its Tucson FCEV, and in October 2015, Toyota announced FCEVs for sale, right on track with DOE's original plans for R&D resulting in commercial decisions being made in the 2015 timeframe. Several other companies — including Honda, GM, Daimler, and BMW — plan to soon release FCEVs.[29]

In addition to the H2USA partnership announced in the United States, major government-industry partnerships have been established in Germany, Japan, the United Kingdom, France, and Scandinavia to enable the rollout of FCEVs and address related hydrogen infrastructure challenges.

While progress was substantial and DOE's efforts over the period covered by this report were on track to meet key technology-readiness targets, DOE's developmental timeline for hydrogen and fuel cell technologies was not intended to meet the deployment goal specified in EPACT Section 811(a)(4)(A) of 100,000 hydrogen-fueled vehicles by 2010. While DOE has already achieved cost reductions enabling the production of hydrogen from natural gas on a cost-competitive basis and is on track to enable widespread availability of hydrogen from renewable resources, the ultimate decision rests with industry whether to deploy these technologies and produce sufficient hydrogen for the commercial rollout of FCEVs.

[29] http://energy.gov/eere/articles/first-commercially-available-fuel-cell-electric-vehicles-hit-street

Over 50 stations are expected to be operational in California in 2016. In general, hydrogen may be delivered to stations from a central production facility in either gaseous or liquid form or it may be produced on-site from methods like steam methane reformation, electrolysis (electrically-driven separation of water into hydrogen and oxygen), or tri-generation. Tri-generation uses a stationary fuel cell and an opportunity fuel like a wastewater treatment facility's digester gas to generate electricity, heat, and hydrogen for vehicle fueling. In some instances hydrogen may be delivered via a direct pipeline link from a major production facility. For example, at the Torrance California station, an existing supply line between a hydrogen production facility and an oil refinery was accessed to divert a stream of hydrogen to the vehicle fueling station.

The source of hydrogen provided via pipelines could continue to serve a variety of end uses, but it is also likely that some of the source hydrogen will be produced at central facilities specifically with the intent of fueling FCEVs.[30] Although DOE is not funding public stations, the Program is collaborating with California's state agencies to collect and analyze data from their station deployment effort. See Figure 5.1 below.

Figure 5.1. California Energy Commission's 2015 Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP) Hydrogen Station Funding Awards

CEC 2015 ARFVTP Hydrogen Station Funding Awards		
June 2015 –$2.7 million		
Supplier	**Total Award**	**Station Location**
Air Products & Chemicals, Inc.	$1.5 million	Woodland Hills, Santa Monica, Los Angeles (2), Irvine
Air Liquide Industrial US LP	$300,000	Anaheim
H2 Frontier, Inc.	$300,000	Chino
Linde LLC	$300,000	San Juan Capistrano
First Element Fuel Inc.	$300,000	San Francisco
August 2015 - $3.9 million		
HTEC Hydrogen Technology & Energy Corporation	$300,000	Woodside
ITM Power Inc.	$300,000	Riverside
Ontario CNG Station Inc.	$300,000	Ontario
HyGen Industries, LLC	$600,000	Rohnert Park, Orange
First Element Fuel Inc.	$2.4 million	San Jose, Hayward, Los Angeles (2), Long Beach, Coalinga, Truckee, Santa Barbara
September 2015 - $1.5 million		
First Element Fuel Inc.	$900,000	Costa Mesa, Saratoga, La Canada-Flintridge
Air Products & Chemicals, Inc.	$300,000	Irvine
H2 Frontier, Inc.	$300,000	Gardena
December 2015 - $2.64 million		
Air Products & Chemicals, Inc.	$480,000	Lawndale, Redondo Beach
Air Liquide International US LP	$240,000	Palo Alto
HyGen Industries, LLC	$240,000	Pacific Palisades
Linde LLC	$480,000	Foster City, Mountain View
First Element Fuel Inc.	$1.2 million	Campbell, Mill Valley, South Pasadena, San Diego, Lake Forest

[30] McKinney, Jim, et al. 2015. Joint Agency Staff Report on Assembly Bill 8: Assessment of Time and Cost Needed to Attain 100 Hydrogen Fueling Stations in California. California Energy Commission. Publication Number: CEC-600-2015-016

Outside of California, future expansion is anticipated in other early market areas of the Nation. The northeast states currently have multiple efforts underway including a grant program in Connecticut, development of a multi-state regional plan, and anticipated station development through private partnerships (e.g., Toyota-Air Liquide).[31]

While FCEV and station costs are still high, the aggressive deployment plans of California, Japan, and Western Europe would result in significant cost reduction associated with higher production and more robust supply chains, e.g., up to 50 percent reduction for stations.[32]

In its approach to supporting the development of hydrogen infrastructure, rather than directly funding demonstrations of stations and vehicles, the Program conducted a rigorous assessment of the challenges and needs involved in developing a hydrogen infrastructure — both from an R&D and business-case perspective. This included resources such as H2FAST, a financial analysis tool that can model individual hydrogen stations or groups of up to 10 stations. H2FAST is one of many tools the Program used to enable infrastructure buildout. The Program also closely coordinated with H2USA members. As described in Section 3 of this report, the H2USA collaboration brought together automakers, government agencies, gas suppliers, and the hydrogen and fuel cell industries to coordinate research and identify cost-effective solutions to deploy hydrogen infrastructure. The collaboration's initial proposed activities were primarily focused on the underlying analysis needed to form a coherent strategy for a coordinated rollout of FCEVs and hydrogen infrastructure.

Efforts by this new collaboration will build on past work by DOE and industry, including extensive analysis of the costs and tradeoffs of different options for hydrogen production, delivery, and utilization, as well as analysis of policies for sustaining the early years of hydrogen and fuel cell technology deployment. These analyses have included the development of models to better understand the combined effects of different vehicle market penetration rates, geographic and spatial layouts of fueling stations, hydrogen production and delivery options, and policies and incentives.

[31] https://www.airliquide.com/united-states-america/air-liquide-announces-locations-several-hydrogen-fueling-stations-northeast.

[32] McKinney, Jim, et al. 2015. Joint Agency Staff Report on Assembly Bill 8: Assessment of Time and Cost Needed to Attain 100 Hydrogen Fueling Stations in California. California Energy Commission. Publication Number: CEC-600-2015-016)

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 2013 to July 2016. 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.

In addition to their recommendations, the National Academies also recognized the importance of "continued research attention and government funding" for hydrogen and fuel cells.[33] However, the Hydrogen and Fuel Cell Technical Advisory Committee has expressed concern that DOE's efforts in hydrogen and fuel cells are not currently funded at a sufficient level.[34]

From FY 2013 to FY 2016, DOE pursued a strategically balanced portfolio of hydrogen and fuel cell activities, as described in section 2 of this report. The progress that is outlined in Section 7 has been achieved through relatively stable funding over the same time period.

One issue that may impact the commercialization of fuel cell vehicles is the expiration of the tax credit for fuel cell electric vehicles and the investment tax credit for hydrogen fueling infrastructure. Both of these tax credits expired at the end of December 2016.

[33] The full report is available from: http://www.nap.edu/catalog.php?record_id=18262.
[34] Letter from John Hofmeister, HTAC Chair, to Secretary of Energy Ernest Moniz, July 15, 2013 (will be posted online at http://hydrogen.energy.gov/advisory_htac.html)

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.

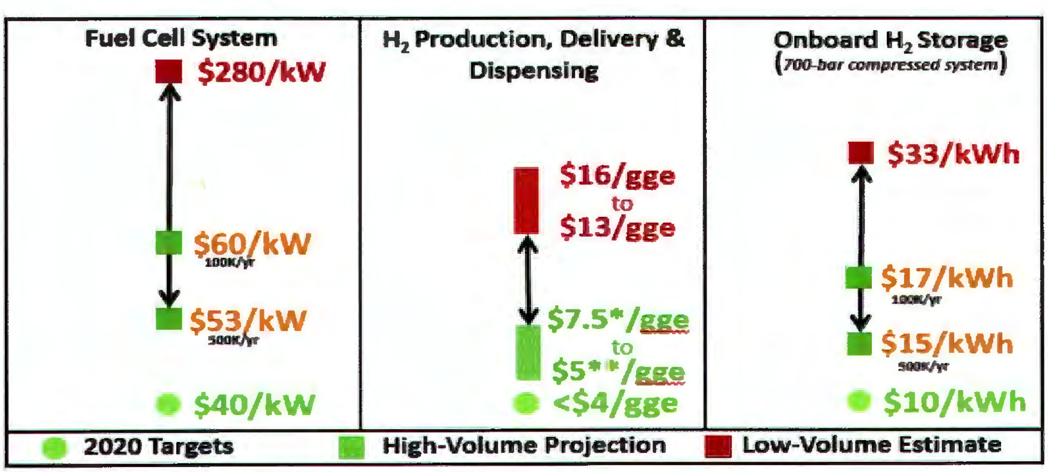
Efforts funded by the Fuel Cell Technologies Office between FY2013 and FY2016 led to more than 580 patents, more than 45 commercial technologies, and about 65 technologies that are projected to be commercialized within three-to-five years. The innovation enabled by the Program has translated into commercial 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.

In addition, DOE has successfully stimulated early markets for fuel cells through strategically targeted deployments, cost-shared with industry partners. Deployments of more than 1,600 fuel cells in key early markets have led to roughly 18,000 additional orders for fuel cells by industry, *with no additional DOE funding.*[35]

The Program's accomplishments are thoroughly documented every year in the *Annual Progress Report*. From September 2013 to August 2016, the Program published three *Annual Progress Reports*, which included more than 300 detailed reports from individual projects, spanning nearly 1,000 pages. 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). A few examples of progress are shown in figure 7.2.

The remainder of the response to section 811(a)(7) of EPACT ("updates to the developmental roadmap...") is covered in section 8 of this report. Furthermore, this section of the report (section 7) covers progress toward vehicle deployment and infrastructure goals, as it reports general progress and accomplishments by the Program.

Figure 7.1. ***Cost Targets and Status***



[35] DOE Hydrogen and Fuel Cells Program Records #12013 and #11017, http://hydrogen.energy.gov/program_records.html.

Figure 7.2. Progress and Accomplishments - Key Examples

Fuel Cell R&D

- ✓ Increased fuel cell durability from 2,500 hours in 2013 to more than 3,900 hours in 2016 (a 56% increase).
- ✓ The catalyst specific power of fuel cells increased from 6 kW/g of platinum group metal (PGM) in 2013 to 6.8 kW/g PGM in 2016 (a 13% increase).
- ✓ Reduced automotive cost from $55/kW in 2013 to $53/kW in 2016 based on projections to high-volume manufacturing, while also improving the catalyst activity and limiting the amount of heat produced by the fuel cell vehicle system.

Hydrogen Fuel R&D

Hydrogen Production and Delivery

- ✓ Reduced the cost of producing hydrogen from natural gas to a point that is cost-competitive with gasoline. Modeled costs of hydrogen (assuming high-volume production and widespread deployment) have been projected at approximately $2.00 per gallon of gasoline equivalent (gge) produced (less than $4.50/gge produced, delivered, and dispensed for 700 bar fueling)
- ✓ Reduced the projected high-volume cost of producing hydrogen from renewables through several pathways, including distributed polymer electrolyte membrane electrolysis ($3.40-$6.60/gge), distributed reforming of bio-derived liquids ($3.20-$7.90/gge), and central biomass gasification ($2.10-$4.20/gge);
- ✓ Demonstrated the viability of directly integrating advanced electrochemical water-splitting technologies with renewable wind and solar power sources, leveraging process intensification to simplify power-conditioning and other balance of system requirements to reduce costs;
- ✓ Developed operational strategy to reduce capital cost of gaseous hydrogen refueling stations by ~40% compared to conventional approaches in 2013, and licensed to industry
- ✓ Initiated the HydroGEN Energy Materials Network to accelerate the discovery and development of innovative materials systems for enabling advanced water splitting technologies for cost-effective, large-scale renewable hydrogen production
- ✓ Developed and demonstrated the Hydrogen Station Equipment Performance (HyStEP) mobile testing device for enabling rapid hydrogen station commissioning by collecting the data needed to validate station fueling protocols; and deployed at multiple California stations since 2015.
- ✓ Set a world record in magnetocaloric materials demonstrating a 100°K temperature span that successfully liquefied gas from room temperature; providing validation of a new magnetocaloric technologies with the potential to dramatically improve efficiency of hydrogen liquefaction

Hydrogen Storage

- ✓ Developed technologies that reduce the projected high-manufactured volume cost of 700 bar, Type IV, compressed hydrogen storage systems for FCEVs from $17/kWh (2013 baseline) to $15/kWh (2015 projections)
- ✓ Demonstrated a potential 18% cost reduction for high-strength carbon fiber, compared to the baseline (Toray T-700S), through development of an alternative low-cost precursor
- ✓ Developed, validated, and made publically available computational models for complete materials-based storage systems for use by researchers and system developers
- ✓ Developed advanced materials-based hydrogen storage technologies and reduced cost of advanced compressed hydrogen storage systems; the three Hydrogen Storage Materials Centers of Excellence and independent projects prepared and characterized hundreds of novel hydrogen storage materials and developed an online database with more than 3,000 unique entries including key material properties

Manufacturing R&D

- ✓ Developed a new process to manufacture a 3-layer MEA that will reduce the projected high-volume cost by more than 25%
- ✓ Developed in situ defect detection technologies and demonstrated quality control techniques for fuel cell components at more than 30 ft/min
- ✓ Established regional efforts to strengthen domestic supply chain

Figure 7.2. Progress and Accomplishments (continued)

Systems Analysis

- ✓ Developed a comprehensive, world-class suite of models and tools (e.g., Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation [GREET]; the Hydrogen Analysis Production Model (H2A); HDSAM; MSM; JOBS; H2FAST), that serve as a toolbox covering well-to-wheels petroleum, emissions, and water consumption analyses; hydrogen production and delivery cost evaluations; jobs growth analyses; and market penetration/infrastructure payback assessments
- ✓ Developed and implemented rigorous, market-driven methodologies to determine metrics (e.g., near- and long-term hydrogen cost targets), sensitivity analyses, and assessments of value propositions; and determined the impact of DOE funding in terms of patents, commercial technologies, return on investment, and jobs

Safety, Codes & Standards

- ✓ Conducted materials compatibility, risk assessment, and hydrogen behavior R&D to provide a sound technical basis for development of critical codes and standards (e.g., NFPA 2 and the Global Technical Regulations); this R&D contributed to a reduction in required separation distances by as much as 50% for gaseous hydrogen storage in the 2016 edition of NFPA 2 compared with the previous code requirements which were based on NFPA 55
- ✓ Developed valuable resources to improve hydrogen safety, including the National Hydrogen and Fuel Cell Emergency Response Training Resource and H2Tools.org, a centralized online location designed to disseminate hydrogen safety resources such as best practices and lessons learned, as well as user-specific safety information to facilitate and streamline the permitting process for hydrogen installations

Technology Validation

- ✓ The demonstration evaluated 55 FCEVs traveling more than 1.4 million miles since 2013. These vehicles have shown continued improvement in durability and have demonstrating an on road stack durability of 3,900 hours with the longest running stack achieving 5,600 hours. Additionally data collected on 46 tonnes of hydrogen dispensed since 2013, increasing the total to 92 tonnes dispensed, has validated an average fill time of 3.7 minutes for SAE J2601 H70-T40 fills
- ✓ Collected and analyzed data from fuel cell buses, demonstrating fuel economies 1.6-1.7 times greater than diesel ICE buses and 1.95 times higher than natural gas ICE buses; documented a single fuel cell power plant that had reached 20,000 hours, exceeding the 2016 target
- ✓ Demonstrated that the mean electrical efficiency of stationary fuel cells (>100 kW) exceeded the 2015 DOE target of 43% (on a lower heating value basis)

Market Transformation

- ✓ Provided technical assistance, project development, and data collection support to several federal agencies, including assistance with early adoption demonstrations by the U.S. Department of Defense (DOD), the Federal Aviation Administration (FAA)
- ✓ Doubled the number of fuel cell lift truck and backup power deployments by industry since 2013 to more than 18,000 with no additional DOE funding
- ✓ Published nearly 400 success stories through news articles, blogs, press releases, and media announcements; conducted 70 webinars, reaching about 6,000 attendees; reach more than 13,000 subscribers through our monthly newsletter
- ✓ Engaged more than 3,000 people at key conferences and meetings

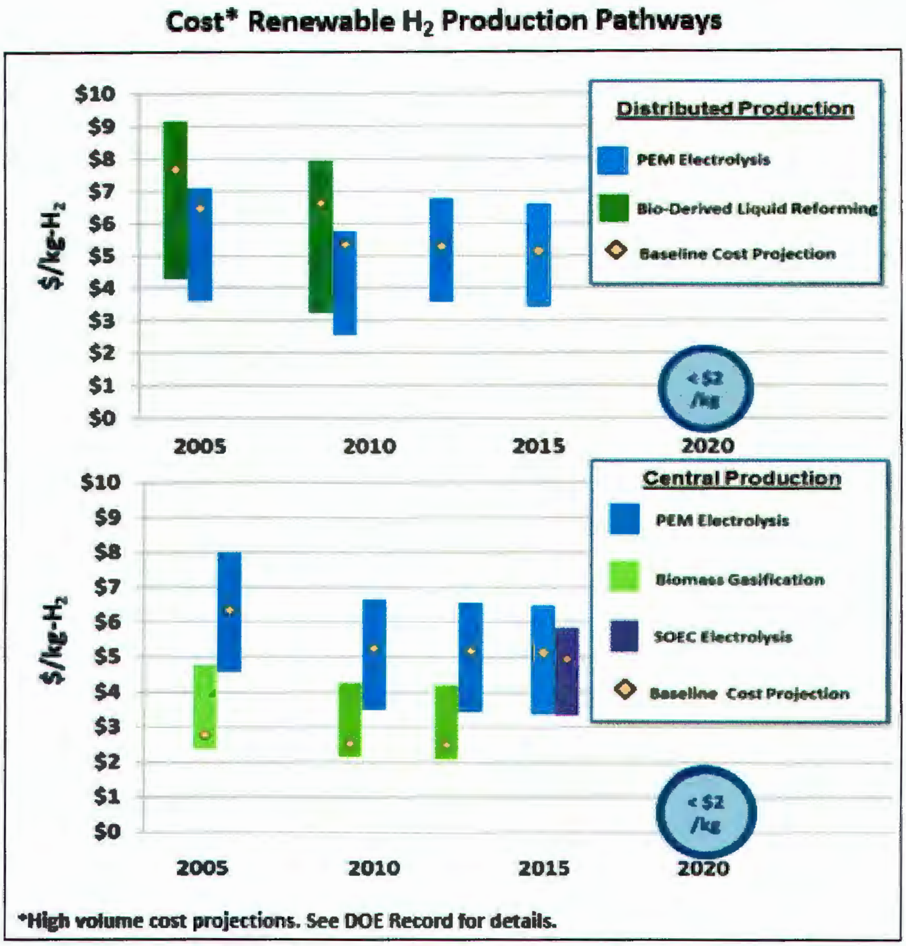


Figure 7.3
Reductions in hydrogen production cost
Status of hydrogen cost (un-dispensed and un-taxed) is shown for distributed and central pathways in vertical bars, reflecting values based on a range of assumptions including feedstock and capital cost variability. Bars for different years in each pathway reflect documented technology improvements for the pathway in the corresponding time period. Baseline costs are shown in diamonds. The 2020 target is from the 2015 FCTO Multi-Year RD&D Plan.[33]

[36] The status of the projected H_2 production costs (shown as vertical bars to reflect sensitivities to major feedstocks and capital costs) up to 2013 has been documented in the Program record #14005: https://www.hydrogen.energy.gov/pdfs/14005_hydrogen_production_status_2006-2013.pdf; 2015 values use the same analysis and are based on published H2A cases found at https://www.hydrogen.energy.gov/h2a_prod_studies.html. Techno-economic assumptions are consistent with the updated models used in the 2015 MYRD&D Plan.

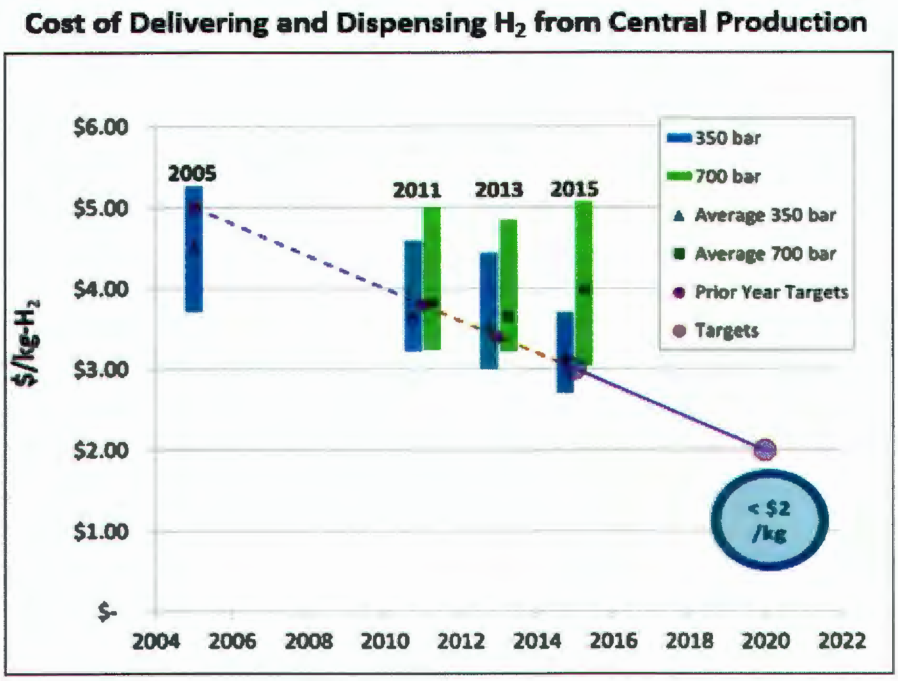


Figure 7.4
Reductions in Cost of Hydrogen Delivery
Projections of hydrogen delivery and dispensing costs from centralized production. Cost projections in any given year have been derived using the Hydrogen Delivery Scenario Analysis Model versions 2.2, 2.3, and 3.0.[34]

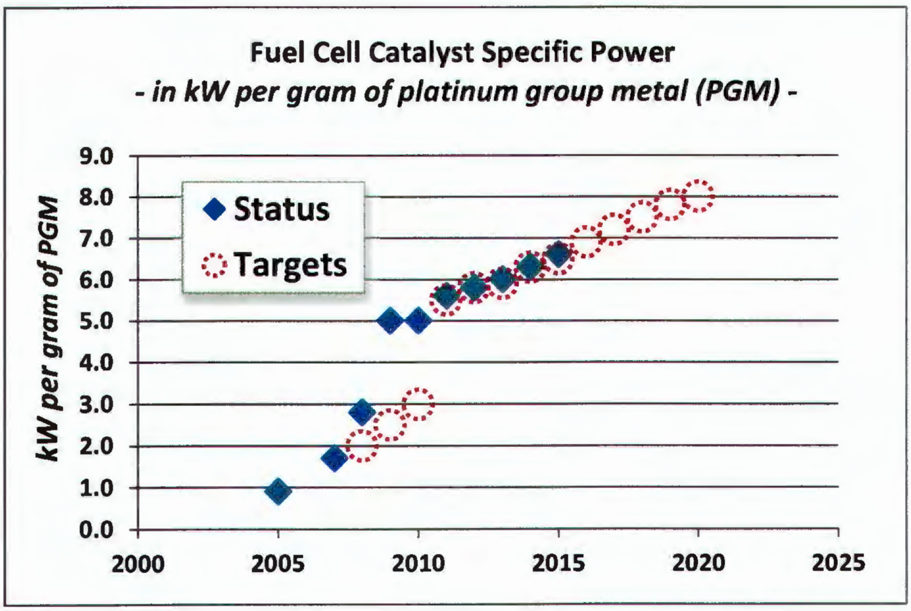


Figure 7.5.
Reducing Platinum Content of Fuel Cells. *The catalyst specific power of fuel cells has improved by about 500% since 2005, resulting in a five-fold reduction in platinum content.*[35]

[37] The range of projections is due to the variety of gaseous and liquid delivery pathways considered. All projections were based on the following common assumptions: 1) refueling stations are deployed in an average-sized U.S. city, represented by Indianapolis, 2) mature penetration of fuel cell electric vehicles (10-15%), 3) 2007 year dollars, 4) refueling station capacity of 750-1000 kg/day at 100% utilization, 5) centralized production facility is located 100 km (62 miles) from city, 6) all components are manufactured at economies of scale.

[38] "Platinum Group Metal Loading," DOE Hydrogen & Fuel Cells Program Record #9018, http://hydrogen.energy.gov/pdfs/9018_platinum_group.pdf

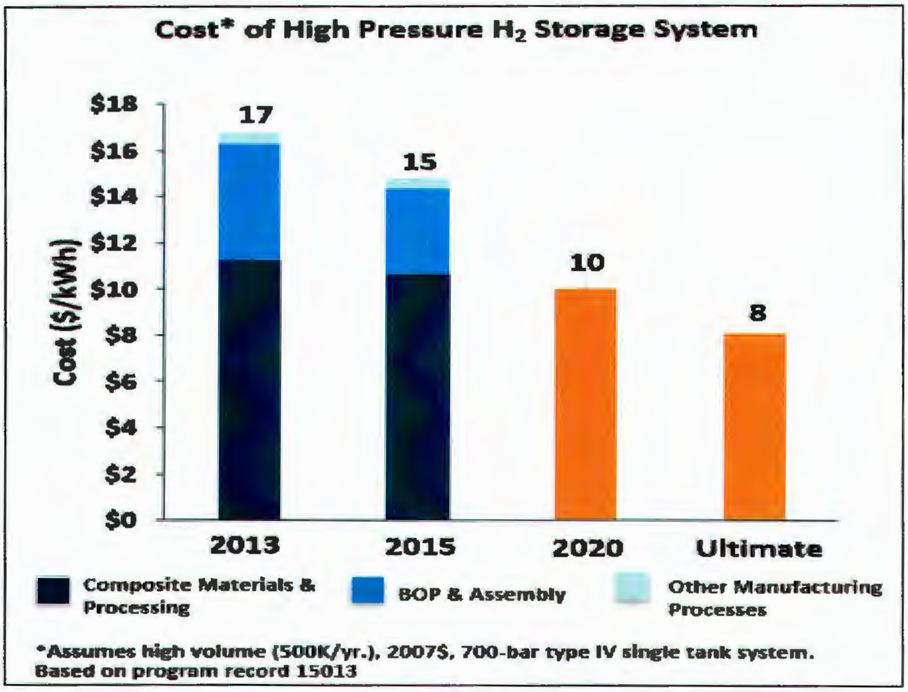


Figure 7.6. ***Cost of High Pressure Hydrogen Storage System.*** *The cost of high pressure hydrogen storage systems has decreased by 12% since 2013.*

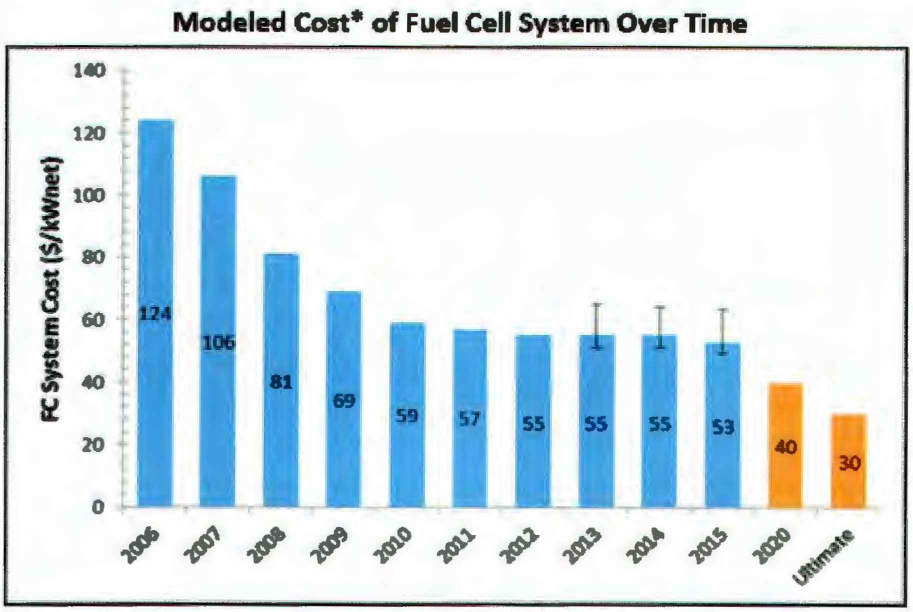


Figure 7.7. ***Cost of Fuel Cell System over Time.***

*** 80-kW_{net} PEM fuel cell system projected to high-volume* manufacturing**

NOTE: The 2016 final fuel cell system cost will be available in FY 2017.

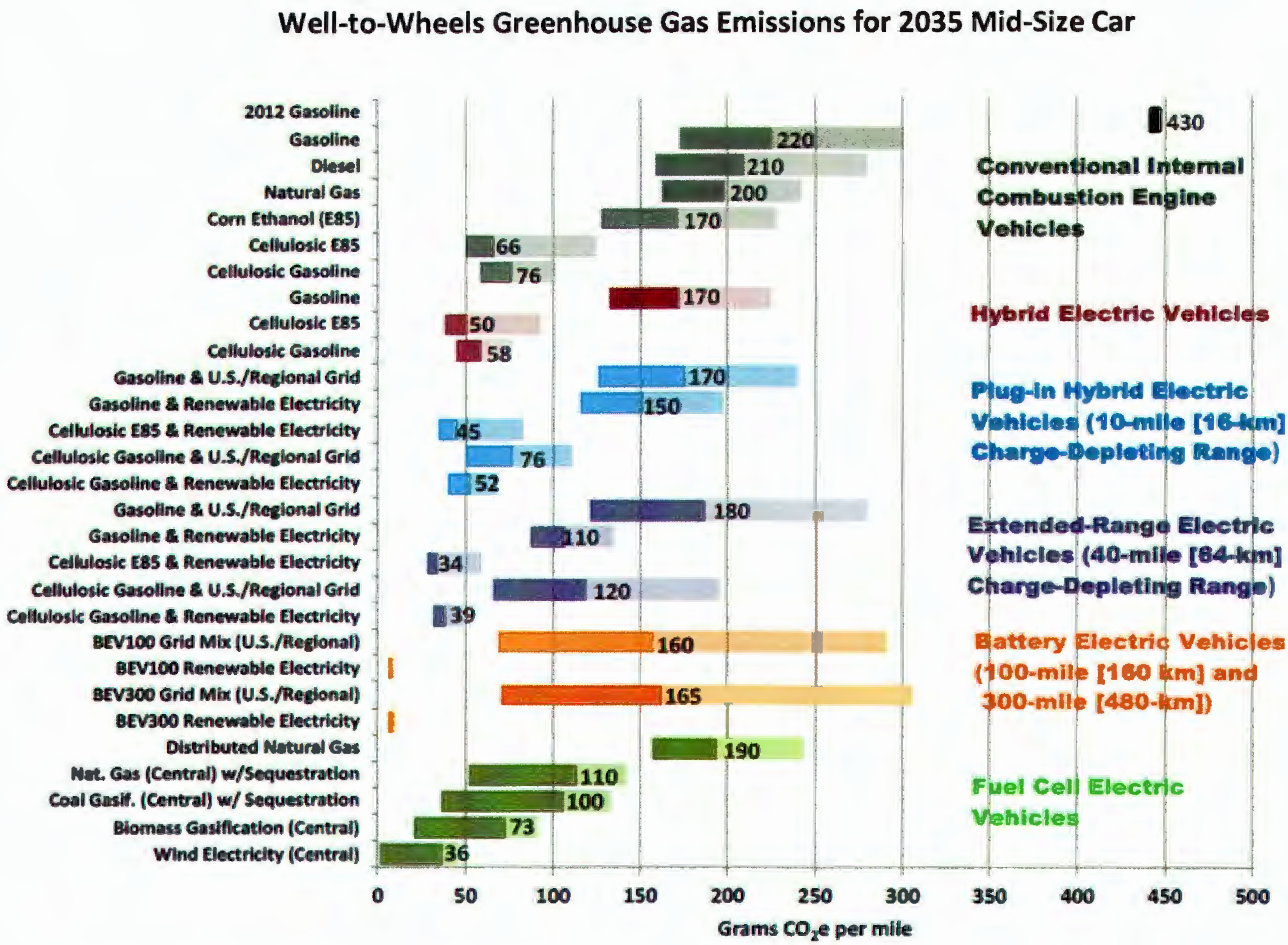


Figure 7.8. *Well-to-wheels analysis*[39] *shows substantial potential reductions in greenhouse gas emissions for several advanced transportation technologies, including fuel cell vehicles using hydrogen from a variety of sources. Ranges shown by the light portions of the bars reflect sensitivity to uncertainties associated with projected fuel economy of vehicles and selected attributes of fuels pathways, e.g., electricity credit for biofuels, electric generation mix, etc.*

[39] "Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles," DOE Hydrogen & Fuel Cells Program Record #13005, http://hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf.

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 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. EERE, FE, NE, and SC activities are reviewed by these panels, as applicable. In addition, the Program received feedback through its Annual Merit Reviews and Peer Evaluation Meetings,[40] which involve almost 370 technical experts reviewing over 120 RD&D projects and includes more than 1,800 participants every year.

The Program periodically revised 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 2018. The *MYRD&D Plan* was updated during 2012 and 2013. The next complete update of the *MYRD&D Plan* will occur in 2018. However, individual sections have been updated since 2013 to account for the most recent progress toward meeting targets, and it includes a reassessment of the targets themselves, based on requirements to be competitive with both incumbent and advanced technologies.

8.1 National Academies' Review of the U.S. DRIVE Partnership[41]

Reviews by the NRC assess progress in each of the partnership's research and program management areas as well as the responses of DOE program management to recommendations made in prior reports. In the most recent NRC review in 2013, key comments in the resulting report[42] included:

- ". . . the committee believes that the Partnership is effective in progressing toward its goals. There is evidence of solid progress in essentially all areas, even though substantial barriers remain."

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

[41] 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.

[42] The full report is available from: http://www.nap.edu/catalog.php?record_id=18262.

- "The fuel cell/hydrogen R&D is viewed by the committee as long-term, high-risk, high-payoff R&D that the committee considers not only to be appropriate, but also to be of the type that much of it probably would not get done without government support."

- "[Fuel cells] . . . along with the hydrogen fuel that they would consume, offer the promise of zero emissions (produced directly by the vehicle), high efficiency, and the smooth, quiet operation that goes with an electric propulsion system. With this focus, progress has been significant, with continuing increases in performance and decreases in projected costs essentially every year."

- ". . . the committee's assessment is that the fuel cell technical team is well coordinated and is aligned with respect to the achievement of the goals and the longer-term, high-risk technology challenges, especially as the automotive OEMs are now road testing prototype fuel cell vehicles."

- "Research aimed at significantly higher hydrogen storage capability needs to be maintained as a primary research focus. Materials-based storage at the level required to meet all program targets is considered theoretically achievable, yet no single material has been identified that simultaneously meets all of the targets (weight, volume, efficiency, cost, packaging, safety, refueling ability, etc.). The discovery and development of materials for effective onboard hydrogen storage is high-technical-risk R&D not likely to be accomplished without continued research attention and government funding."

- "The DOE continues to make important progress toward understanding and preparing for the transition to hydrogen fuel. In the continuing source-to-wheels analyses, seven pathways, including both distributed and centralized hydrogen production, have been assessed, and the key drivers for pathway costs, energy use, and emissions have been identified."

- "Progress has been made in all [hydrogen delivery and production] areas of the program. Delivery models have been developed that predict delivery and dispensing costs for different methods as a function of market penetration."

Specific recommendations from the latest NRC report included:

- "The DOE should establish backup technology paths, in particular for stack operation modes and stack components, with the fuel cell technical team to address the case of current technology selections determined not likely to meet the targets. The DOE should assess which critical technology development efforts are not yielding sufficient progress and ensure that adequate levels of support for alternative pathways are in place."

- "The hydrogen storage program is one of the most critical parts of the hydrogen/fuel cell vehicle part of the . . . Partnership—both for physical (compressed gas) and for materials storage. It should continue to be funded, especially the systems-level work in the Hydrogen Storage Engineering Center of Excellence."

- "The EERE should continue to work closely with the Office of Fossil Energy to vigorously pursue advanced chemical and biological concepts for carbon disposal as a hedge against the inability of geological storage to deliver a publicly acceptable and cost-effective solution in a timely manner."

- "Hydrogen delivery, storage, and dispensing should be based on the program needed to achieve the cost goal for 2017. If it is not feasible to achieve that cost goal, emphasis should be placed on those areas that would most directly impact the 2015 decision regarding commercialization. In the view of the committee, pipeline, liquefaction, and compression programs are likely to have the greatest impact in the 2015 time frame. The cost target should be revised to be consistent with the program that is carried out."

8.2 Review by the Hydrogen and Fuel Cell Technical Advisory Committee

EPACT section 807 requires 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*).

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."

Key comments from the HTAC 2015 annual report to DOE:[1]

Overall hydrogen and fuel cell industries continued to progress at a steady rate, with growing installations and R&D progress around the world. The year 2015 was marked by the achievement of key market development milestones in transportation, stationary, backup, and materials handling sectors.

However, 2015 is also a year that is called out in the U.S. Energy Policy Act of 2005 (EPACT) Title VIII as a milestone where the goals are:

1) *"To enable a commitment by automakers no later than year 2015 to offer safe, affordable, and technically viable hydrogen fuel cell vehicles in the mass consumer market and to enable production, delivery, and acceptance by consumers of model year 2020 hydrogen fuel cell and other hydrogen-powered vehicles that will have, when compared to light duty vehicles in model year 2005: 1) fuel economy that is substantially higher; 2) substantially lower emissions of air pollutants; and 3) equivalent or improved vehicle fuel system crash integrity and occupant protection;" and*

2) *"To enable a commitment not later than 2015 that will lead to infrastructure by 2020 that will provide: 1) safe and convenient refueling; 2) improved overall efficiency; 3) widespread availability of hydrogen from domestic energy sources; and 4) hydrogen for fuel cells, internal combustion engines, and other energy conversion devices for portable, stationary, micro, critical needs facilities, and transportation applications."*

Considerable progress has been made toward these goals since 2005, and the 2015 commitments have been partially met. Efforts such as H2USA have brought industry and government together in important ways toward achieving these goals. FCEVs by two manufacturers have now been fully safety certified and commercialized, with a third expected in 2016 and more in the 2018-2020 timeframe. However, this progress has been mostly driven by state-level zero-emission vehicle (ZEV) programs. Federal level support does not appear to be adequate to spur the developments that are necessary for the 2020 goals of EPACT 2005.

... key challenges for the hydrogen and fuel cell industry remain. Individual sectors have their specific challenges, including:

- *Evidence suggests that the U.S. is not clearly on track to meet the 2020 goals for hydrogen FCEVs and refueling infrastructure in the U.S. Energy Policy Act of 2005 (EPACT) Title VIII.*
- *Developing a sufficient and robust hydrogen refueling structure for FCEVs is an ongoing challenge, with only about 20 operational hydrogen stations in each of the U.S. (mostly California), Germany, and Japan and a handful in other countries, given unfavorable economics until the vehicle market further develops;*
- *Stationary fuel cell costs remain somewhat high compared to other forms of distributed power generation, at about $4,000-7,000 per kW but with higher operational efficiency and lower onsite emissions than combustion-based generators;*
- *Improved membrane electrode assembly integration is needed for hydrogen crossover reduction/mitigation along with a combination of membrane/catalysis advances for electrolyzers; and*

Overall, 2015 was an important and encouraging year for hydrogen and fuel cell system developments. Much progress is being made, but greater momentum is needed for these technologies to provide the larger benefits that they are capable of in the 2020 and beyond timeframe.

The Department has submitted four biennial reports outlining the recommendations by the committee and the Department's responses. The most recent report covers recommendations made during fiscal years 2014 and 2015, and it was submitted to Congress in July 2016.

8.3 Updates to Strategic Plans

The Program periodically updated 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. Formal updates are usually issued every three-to-five years, or as required. These updates include changes to plans for fuel cell research, development, and demonstration activities, and they address recommendations from external reviews and audits.

As described in Section 5 of this report, the Program coordinated closely with industry and other partners to understand the needs and develop strategies for the commercial rollout of FCEVs and hydrogen infrastructure. The Program also stayed closely attuned to international activities and strategies for FCEVs and hydrogen. In particular, the Program initiated information-sharing and analysis activities with Germany and Japan, which have substantial plans for developing hydrogen infrastructure.[43] The Program closely monitored similar hydrogen infrastructure initiatives recently launched in the United Kingdom, France, and Scandinavia. Any changes in strategy emerging from these collaborations will also be reflected in updates to future plans.

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