U.S. DEPARTMENT OF ENERGY

Hydrogen and Fuel Cell Activities, Progress, and Plans: August 2007 to August 2010

Second Report to Congress
August 2013

United States Department of Energy
Washington, DC 20585

Message from the Assistant Secretary for Energy Efficiency and Renewable Energy

The enclosed report, *Hydrogen and Fuel Cell Activities, Progress and Plans,* is provided in response to section 811(a) of the Energy Policy Act of 2005 (EPACT), P.L. 109-58, enacted in August 2005. The Department submitted the first required report in January 2009; the enclosed report presents and overview of the Department's hydrogen and fuel cell–related activities from the time of that report through August 2010.

Pursuant to statutory requirements, this report is being provided to the following members of Congress:

The Honorable Joseph R. Biden, Jr.
President of the Senate

The Honorable John Boehner
Speaker of the House of Representatives

The Honorable Rodney P. Frelinghuysen
Chairman, House Subcommittee on Energy and Water Development

The Honorable Marcy Kaptur
Ranking Member, House Subcommittee on Energy and Water Development

The Honorable Dianne Feinstein
Chair, Senate Subcommittee on Energy and Water Development

The Honorable Lamar Alexander
Ranking Member, Senate Subcommittee on Energy and Water Development

The Honorable Ron Wyden
Chairman, Senate Committee on Energy and Natural Resources

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

The Honorable Fred Upton
Chairman, House Committee on Energy and Commerce

The Honorable Henry Waxman
Ranking Member, House Committee on Energy and Commerce

The Honorable Barbara Mikulski
Chairman, Senate Committee on Appropriations

The Honorable Richard Shelby
Ranking Member, Senate Committee on Appropriations

The Honorable Harold Rogers
Chairman, House Committee on Appropriations

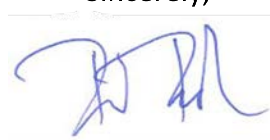
The Honorable Nita Lowey
Ranking Member, House Committee on Appropriations

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

The Honorable Eddie Bernice Johnson
Ranking Member, House Science, Space and Technology Committee

If you have any questions or need additional information, please contact me or Mr. Brad Crowell, Acting Assistant Secretary for Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,



Dr. David T. Danielson

Executive Summary

The Department of Energy (DOE) is conducting a comprehensive program that fulfills the provisions of Title VIII of the Energy Policy Act of 2005 (EPACT).[1] DOE is pursuing the development of hydrogen and fuel cell technologies as part of a diverse portfolio for reducing emissions and petroleum use. In addition to hydrogen and fuel cells, this portfolio includes batteries, next-generation biofuels, and advanced combustion technologies in the transportation sector, and wind, solar, geothermal, and water power technologies in the stationary power sector. DOE's Hydrogen Program (the Program)—together with other DOE activities—addresses the full range of barriers facing the development and deployment of hydrogen and fuel cell technologies.

Since the Department's last report to Congress on hydrogen and fuel cell activities,[2] the Program has continued to make substantial progress in all major areas, including:

- Reducing the projected cost of fuel cell systems for transportation applications from $73/kW in 2008 to $61/kW in 2009; preliminary studies estimated this cost to be $51/kW at the end of 2010 (cost projections assume high-volume manufacturing). These cost reductions reflect substantial progress toward the Program's 2015 target of $30/kW.
- Demonstrating improved fuel cell durability under real-world conditions, with some fuel cell vehicles in 2010 showing a durability of more than 2,500 hours of operation in real-world conditions (or approximately 75,000 miles of driving). The Program's target for durability is 5,000 hours (~150,000 miles) by 2015 in laboratory testing and 5,000 hours by 2017 in real-world demonstrations.
- Making significant advances in key components for fuel cells, including improved membrane electrode assemblies that have shown >7,000-hour durability in fuel cell stacks in the lab, under automotive cycling conditions.
- Reducing the cost of producing hydrogen from multiple renewable pathways, including reducing the projected cost of hydrogen produced from electrolysis at the refueling site to less than $5.70 per gallon gasoline equivalent (gge), dispensed and untaxed. This builds on the Program's earlier accomplishment of reducing the projected cost of hydrogen from distributed natural gas to $3/gge, which met the 2015 cost target (all of these cost projections assume high-volume production).
- Demonstrating a driving range of up to 254 miles for vehicles operating on the road, under real-world conditions, and verifying the potential for a 430-mile range in certain vehicle platforms.

[1] Public Law 109-58 (Aug. 8, 2005).
[2] *Hydrogen and Fuel Cell Activities, Progress, and Plans: Report to Congress,* January 2009, http://hydrogen.energy.gov/pdfs/epact_report_sec811.pdf.

These selected examples represent a steady rate of progress on many fronts, which has been enabled by the Program's diverse RD&D portfolio. This portfolio closely integrates efforts in basic science research, applied research and technology development, and demonstrations of systems under real-world conditions. In addition to these efforts, the Program is also fulfilling the sections of EPACT that call for action in addressing non-technological barriers to the commercialization of hydrogen and fuel cell technologies, including critical needs in the areas of safety, codes and standards, and education. All of the Program's activities—which include efforts in fuel cells; hydrogen production and delivery; hydrogen storage; basic science research; manufacturing R&D; technology validation; safety, codes & standards; education; systems analysis; and market transformation—"support the transition of primary industry to a fully commercialized hydrogen economy," as specified in section 811(a)(2) of EPACT.

During FY 2008 – FY 2010, the Department continued to fund a robust portfolio of activities, dedicating approximately $788 million to these efforts. The Department also launched the investment of $41.9 million in Recovery Act[3] funding to deploy fuel cells in early market applications. This funding complements the Program's expanded market transformation efforts aimed at stimulating early markets for hydrogen and fuel cell technologies. The Program has also maintained its high-level strategic approach, as documented in the last report to Congress, including: collaboration with major industry partners in the FreedomCAR and Fuel Partnership, work with the Hydrogen and Fuel Cells Technical Advisory Committee, strategic coordination with the Hydrogen and Fuel Cells Interagency Task Force and Interagency Working Group, and adherence to a regime of rigorous internal and external review, including annual merit reviews and reviews by the National Academies.

As discussed in the last report, substantial progress has been made and the Program is on track to meet its key targets for fuel cell vehicles; however, these targets and the planned developmental timeline for hydrogen and fuel cell technologies were not intended to meet the deployment goal specified in EPACT of 100,000 hydrogen-fueled vehicles by 2010. Instead, the DOE timeline was developed and has been refined to reflect a pace of progress that is considered technically feasible based on input from a wide range of stakeholders, including industry, academia, and national laboratory experts. While fuel cell and hydrogen technology development is currently on track to meet key 2015 technology-readiness targets—including reducing fuel cell cost to $30/kW, improving fuel cell durability to 5,000 hours, and reducing the cost of hydrogen to $2–3 per gallon gasoline equivalent—it is too early to determine whether the commercial sector will develop sufficiently to achieve EPACT's 2020 vehicle deployment goal of 2.5 million hydrogen-fueled vehicles, as identified in section 811(a)(4). However, analyses conducted by Oak Ridge National Laboratory[4] and the National Academies[5] indicate that deployment scenarios of similar scale are realistic within the next 10–15 years, given

[3] The "Recovery Act" refers to the American Recovery and Reinvestment Act of 2009, Public Law 111-5 (Feb. 17, 2009).

[4] D. Greene, et al., *Transition to Hydrogen Fuel Cell Vehicles & the Potential Hydrogen Energy Infrastructure Requirements,* Oak Ridge National Laboratory, March 2008, www-cta.cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2008_30.pdf.

[5] "Transitions to Alternative Transportation Technologies—A Focus on Hydrogen," National Academy of Sciences, 2008; the full report is available from: http://books.nap.edu/catalog.php?record_id=12826 .

sufficient supporting policies and incentives. The Program continues to work with key industry partners in a number of activities that will help industry determine when the technologies are ready for commercialization and deployment.

The Program will continue to pursue a broad portfolio of R&D and market transformation activities for fuel cell applications across multiple sectors, using a variety of technical approaches and diverse sources of fuel. These efforts will span the full spectrum of technology readiness: from early market applications that are already viable or are expected to become viable in the next few years, such as forklifts, backup power, and portable power applications; to mid-term markets that are expected to emerge in the 2012 – 2017 timeframe, such as residential combined-heat-and-power systems, auxiliary power units, fleet vehicles, and buses; and longer-term markets that are expected to emerge in the 2015 – 2020 timeframe, including light-duty passenger vehicles and other transportation applications.

The Program periodically updates its planning documents—including the *Hydrogen and Fuel Cells Program Plan* and the Office of Fuel Cell Technologies' *Multi-year Research, Development, and Demonstration Plan*—to reflect changes in the status of the technologies and in the evolving policy and market environment. Formal updates are usually issued every three-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.

HYDROGEN AND FUEL CELL ACTIVITIES, PROGRESS AND PLANS: SECOND REPORT TO CONGRESS

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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 Program — Activities under EPACT Title VIII

II.1 Introduction

The DOE's Hydrogen Program (the Program) is a comprehensive portfolio of activities that address a range of technological and non-technological barriers facing the development and deployment of hydrogen and fuel cell technologies. The ultimate goals of the Program are to reduce oil use and carbon emissions in the transportation sector and to enable clean, reliable energy for stationary and portable power generation. Activities conducted under the purview of the Program, along with other DOE hydrogen- and fuel cell-related activities, fulfill the provisions of EPACT and support what EPACT section 811(a) refers to as "the transition of primary industry (or a related industry) to a fully commercialized hydrogen economy." This report is the second in a series of recurring reports required by EPACT section 811(a). The first report, delivered in January 2009, covered the period from 2004 through 2008. The Program's activities from FY 2008 – FY 2010 are described below, in accordance with the language in EPACT Section 811(a) that requires the Department to prepare a report every three years after the initial report was due to Congress.

The Program integrates the RD&D activities of four DOE offices: Energy Efficiency and Renewable Energy (EERE), Nuclear Energy (NE), Fossil Energy (FE), and Science (SC). Figure II.1 provides an overview of the Program's organizational structure.

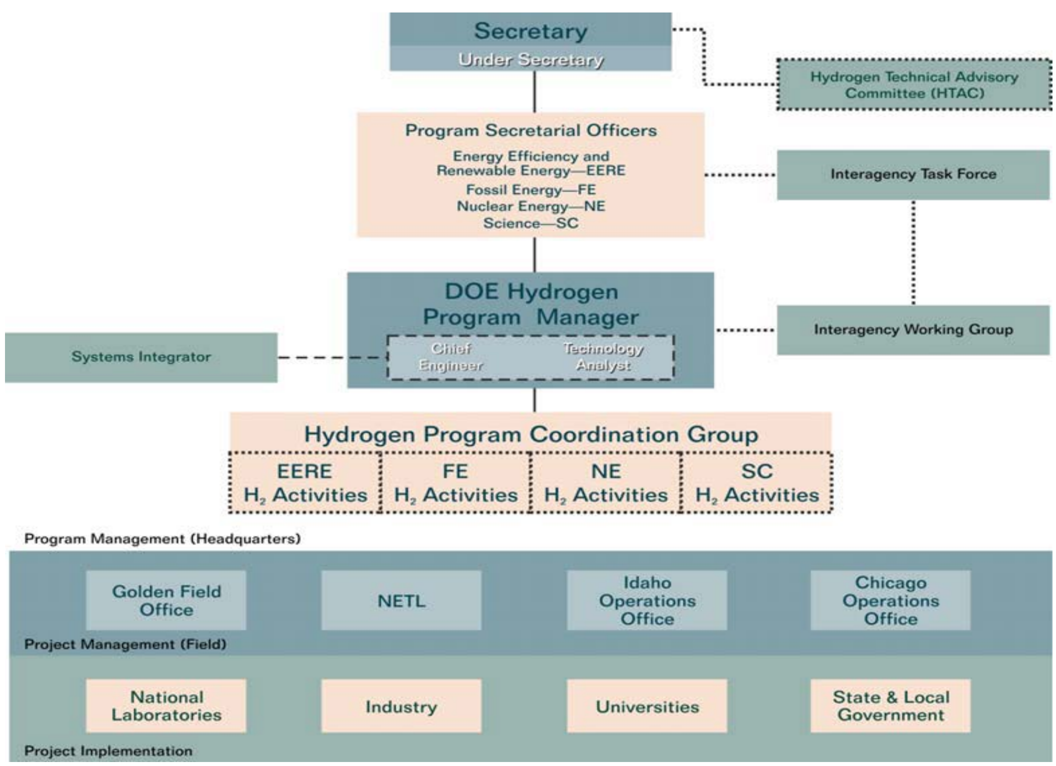

Figure II.1. *The Hydrogen Program's organizational structure.*

Hydrogen Program activities are documented at a high level in the *Hydrogen Posture Plan*[6] (an updated version, the *Hydrogen and Fuel Cells Program Plan*, will be released in 2010); detailed discussions of the barriers and the current and planned RD&D activities can be found in the hydrogen and fuel cell R&D plans of the individual DOE offices, as follows:

- Office of Energy Efficiency & Renewable Energy (EERE): *Fuel Cell Technologies Program Multi-Year RD&D Plan*[7]
- Office of Fossil Energy (FE): *Hydrogen from Coal RD&D Plan*[8]
- Office of Science (SC): *Basic Research Needs for the Hydrogen Economy*[9]

The most recent results—with information on individual projects—can be found in the following documents:

- The Hydrogen Program's *Annual Merit Review Proceedings*.[10] The Program's applied research and technology development projects are reviewed during an annual merit review and peer evaluation meeting. Presentations from these projects are made publicly available in the *Proceedings.*
- The Hydrogen Program's *Annual Progress Report*,[11] which summarizes the year's hydrogen and fuel cell activities and accomplishments for projects funded by the Program.

There are also several other Department activities that are not included in the Hydrogen Program budget but significantly contribute to achieving the Program's goals. These include research and development efforts in technologies for: high-temperature stationary fuel cells; hybrid electric vehicles; carbon sequestration and carbon management; biomass and biorefinery systems; wind energy; solar energy; and geothermal energy. The Hydrogen Program collaborates and coordinates with all of these activities, as well as with hydrogen- and fuel cell-related efforts in other federal agencies, including the Department of Transportation (DOT), the Department of Defense (DOD), the National Science Foundation (NSF), and the National Institute of Standards and Technology (NIST). In particular, DOE collaborates extensively with DOT on its Fuel Cell Bus Program and its work addressing the safety, regulatory, and codes and standards issues specific to DOT's mission.

[6] *Hydrogen Posture Plan,* U.S. Department of Energy, December 2006, www.hydrogen.energy.gov/pdfs/hydrogen_posture_plan_dec06.pdf.

[7] *Fuel Cells Technologies Program Multi-Year RD&D Plan,* U.S. Department of Energy, April 2009, www.eere.energy.gov/hydrogenandfuelcells/mypp.

[8] *Hydrogen from Coal RD&D Plan,* U.S. Department of Energy, September 2009, www.fossil.energy.gov/programs/fuels/publications/programplans/2009_Draft_H2fromCoal_Sept30_web.pdf.

[9] *Basic Research Needs for the Hydrogen Economy,* U.S. Department of Energy, February 2004, www.sc.doe.gov/bes/hydrogen.pdf.

[10] *U.S. Department of Energy Hydrogen Program Annual Merit Review Proceedings*, www.hydrogen.energy.gov/annual_review.html.

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

II.2 Summary of Program Activities

As shown in figure II.2, the Program conducts a wide range of activities to address major technological and non-technological barriers to commercialization. These include R&D to address key technological barriers in the areas of fuel cell cost and durability, hydrogen cost, and hydrogen storage capacity, along with demonstration activities to validate technologies under real-world conditions. The Program's efforts to address non-technological barriers include: facilitating the development of safety practices and codes and standards; supporting development of a domestic manufacturing and supplier base; increasing public awareness and acceptance; and investigating options for the development of a hydrogen supply and delivery infrastructure.

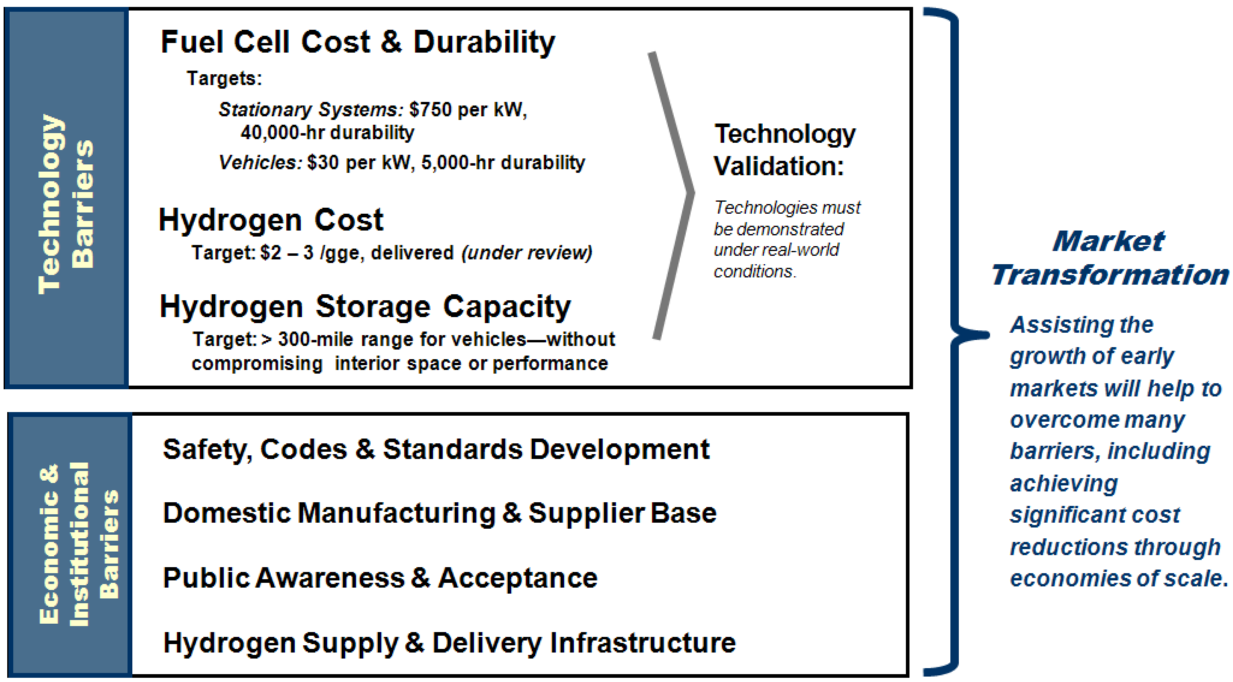

Figure II.2. *The Program's activities are well integrated and address both technological and non-technological barriers to commercialization.*

The following sections provide a summary of the Department's activities under Title VIII of EPACT:

a. Hydrogen Production & Delivery: The Program is focusing on materials research and technology to address key challenges to hydrogen production and delivery and to enable low cost, carbon-free hydrogen fuels from diverse pathways. The effort encompasses small-scale hydrogen production through renewable liquids reforming and electrolysis and large-scale centralized production through biomass and coal gasification, wind and solar-powered electrolysis, solar driven high temperature thermochemical cycles, as well as through biological and direct photoelectrochemical pathways. This subprogram also includes technologies for hydrogen transportation and distribution (e.g., pipelines, tube trailers, and liquefaction), as well as for compression, storage, and dispensing. The key objective for all production/delivery pathways is to reduce the cost of hydrogen to $2 to $3 per gallon gasoline equivalent (gge), delivered and untaxed—this target is currently under review.

From FY 2008 – FY 2010 the Program provided $160 million for hydrogen production and delivery R&D (which includes hydrogen production from renewable sources, hydrogen production from coal, nuclear-based hydrogen production, and hydrogen delivery), funding more than 115 projects. During this period, an additional $7.6 million was awarded for hydrogen production and delivery projects through the Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) Program.

Renewable hydrogen production R&D and hydrogen delivery R&D are planned for continuation, subject to appropriations, along with basic science research in areas relevant to hydrogen production. Development of nuclear-based high-temperature electrolysis technologies has been conducted as part of the Next Generation Nuclear Plant project.

b. Hydrogen Storage: The Program is developing hydrogen storage technologies through R&D on materials and approaches that enable widespread commercialization of fuel cell systems for diverse applications across the stationary power, portable power, and transportation sectors. The primary focus has been on high-capacity approaches for on-board vehicular hydrogen storage. R&D is being conducted on advanced materials for low-pressure storage, as well as on advanced conformable and low-cost tank technologies and storage systems. Key targets are system storage capacities of 5.5% hydrogen by weight and 45 grams per liter by 2015. The development of efficient, low-cost, high-capacity hydrogen storage systems will also be beneficial for the use of fuel cells in stationary applications, for hydrogen fueling stations, and for hydrogen and fuel cell systems for capturing and storing surplus energy from intermittent renewable power.

The Program's National Hydrogen Storage Project includes four centers of excellence and about 40 independent projects, and involves the participation of approximately 45 universities, 10 national labs, and 15 industry developers. From FY 2008 – FY 2010, the Program provided $132 million for hydrogen storage R&D, funding approximately 80 projects. During this period, an additional $100,000 was awarded for hydrogen storage projects through the SBIR/STTR Program.

c. Fuel Cells: The Program's fuel cell R&D efforts 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. These advances are necessary to enable fuel cells to expand into new markets and compete with other advanced technologies, and they will require improvements in fuel cell stack and balance of plant components. The key objectives are to develop a vehicular polymer electrolyte membrane (PEM) fuel cell power system with 60 percent peak efficiency and a 5000-hour lifespan (150,000 miles) at a cost of $30/kW (at large manufacturing volumes), and to develop a stationary PEM fuel cell system with 40 percent efficiency and a 40,000-hour lifespan at a cost of $750/kW. The Program is also conducting RD&D efforts on small solid-oxide fuel cell (SOFC) systems in the 1- to 10-kW range, with possible applications in the markets for auxiliary propulsion units (APUs) and critical power, remote power, and combined-heat-and-power systems.

Major research areas for both transportation and stationary applications are: membranes; catalysts and supports; water transport in the fuel cell stack; effects of impurities on fuel cell performance; and characterization and analysis. From FY 2008 – FY 2010, the Program provided $218 million for fuel cell R&D, funding more than 90 fuel cell projects. During this period, an additional $950,000 was awarded for fuel cell projects through the SBIR/STTR Program for Phase I and Phase II projects.

DOE's Office of Fossil Energy (FE) has also been conducting an effort in SOFCs, the Solid State Energy Conversion Alliance (SECA) Program, aimed at reducing the cost and improving the performance of SOFCs, primarily for use in larger, megawatt-scale, near-zero emissions stationary-power applications. The Hydrogen Program coordinates with SECA and keeps abreast of this Program's progress in SOFCs as it relates to distributed energy generation.

d. Basic Science Research: The Office of Basic Energy Sciences (BES) within the DOE Office of Science supports fundamental scientific research addressing critical challenges related to hydrogen storage, production, and fuel cells. 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. The subjects of basic research most relevant to the Program's critical path technologies 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.

By maintaining close coordination between basic science research and applied R&D, the Program is ensuring that discoveries and related conceptual breakthroughs achieved in basic research programs will provide a foundation for the innovative design of materials and processes that will lead to improvements in the performance, cost, and reliability of fuel cell technologies and technologies for hydrogen production and storage. This is accomplished in various ways—for example, through monthly coordination meetings between the participating offices within DOE, and at the researcher level by having joint meetings with participation from principal investigators who are funded by the participating offices.

From FY 2008 – FY 2010, the Program provided $113 million for basic science research, funding more than 120 projects.

e. Manufacturing R&D: This effort is aimed at developing and demonstrating processes and technologies that reduce the manufacturing cost of fuel cells and systems for the production, delivery, and storage of hydrogen—while ensuring quality and reliability. These low-cost, high-volume manufacturing processes are critical tools that industry needs to produce affordable hydrogen and fuel cell components and systems and to develop a robust and competitive domestic supplier base.

Activities are being conducted in coordination with the Department of Commerce and the White House Office of Science and Technology Policy's Interagency Working Group on Manufacturing R&D.[12] A research and development technology roadmap has been developed with industry, identifying critical technology development needs for high-volume manufacturing. Planned activities include: designing innovative and cost-effective manufacturing processes and technologies and supporting the technical, market, economic, and other analyses to address manufacturability and cost reduction.

From FY 2008 – FY 2010, the Program provided $14 million for manufacturing R&D, funding more than 10 projects. An additional $1 million was provided for manufacturing R&D projects through the SBIR/STTR Program.

f. Technology Validation: To fully assess and validate the results of the Program's R&D efforts, the Program is conducting technology validation activities. These activities include fuel cell vehicle and infrastructure demonstrations, stationary power demonstrations, and projects that integrate renewable power generation and hydrogen production. The Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project[13] (also known as the "National Hydrogen Learning Demonstration"), launched in April 2004, has brought together four teams of industry partners to operate fuel cell vehicles and all essential hydrogen infrastructure elements to evaluate progress and to identify challenges encountered when hydrogen and fuel cell technologies are operated in real-world environments. The teams are led by Chevron and Hyundai-Kia, Chrysler and BP, Ford and BP, and GM and Shell, with additional participation from hydrogen suppliers, fuel cell suppliers, utility or gas companies, fleet operators, system and component suppliers, small businesses, universities, and government entities.

[12] Interagency Working Group on Manufacturing R&D, www.manufacturing.gov/interagency/IWGRD_priortopics.asp?dName=IWGRD.

[13] For more information on the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, see: www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/fleet_demonstration.html.

Additional technology validation projects are demonstrating fuel cells in distributed energy applications and examining the operation of integrated renewable-based power generation and hydrogen production technologies. Current and planned projects involve hydrogen generation from solar, wind, and geothermal energy. These include techno-economic analysis of hydrogen as an energy storage medium for intermittent renewables and "peak-shaving."

From FY 2008 – FY 2010, the Program provided $57 million for technology validation, funding the National Hydrogen Learning Demonstration and five independent projects.

g. Safety, Codes & Standards: DOE is addressing critical needs regarding hydrogen safety concerns and the development of codes and standards, which are essential for establishing a receptive market environment for hydrogen-based products and systems. This activity is working to resolve the lack of safety data, the variation in safety practices, and the general lack of knowledge and training regarding the safe use of hydrogen. The Program is establishing and ensuring safe practices for all its activities; these practices and lessons-learned are being used to promote the safe use of hydrogen throughout the industry. This work includes the development of sensor technologies and the creation of comprehensive information resources, such as a best-practices handbook.

To facilitate commercialization of hydrogen and fuel cell technologies, the Program is conducting the underlying R&D needed for the development of technically sound codes and standards. The Program is also improving access to standards and model codes, supporting the harmonization of domestic standards, sharing lessons-learned regarding siting and permitting, and helping to coordinate the harmonization of international standards. These efforts involve extensive collaboration with the DOT, other governments, and established national and international code development and standards development organizations.

From FY 2008 – FY 2010, the Program provided $37 million for efforts in safety, codes and standards, funding more than 20 projects.

h. Education: The Program is addressing the knowledge barriers that may impede the acceptance of fuel cell and hydrogen technologies. Overcoming these barriers is important to enabling the successful implementation of early-market fuel cell and hydrogen applications, as well as the longer-term market adoption and acceptance that are required to realize the full benefits of hydrogen and fuel cell technologies across multiple sectors of the economy.

These efforts focus on developing resources and outreach to increase the understanding of the benefits of relevant technologies and to address safety, codes, and standards concerns. Particular attention is paid to key audiences, such as potential early market end-users, state and local governments and their stakeholders, local communities, and educators. Activities include developing materials for the various key audiences and training modules for safety and code officials and emergency responders. The Program also facilitates the expansion of hydrogen and fuel cell curriculum at educational institutions.

From FY 2008 – FY 2010, the Program provided $10 million for its education efforts, funding more than 20 projects.

i. Systems Analysis and Systems Integration: The Program is conducting systems analysis and systems integration activities to ensure that the Program is well-integrated and its efforts are directed in the most effective way. Systems Analysis conducts extensive cross-cutting lifecycle analysis, emissions analysis, and environmental analysis to enable a comprehensive understanding of the major issues involved in potential hydrogen and fuel cell systems. Some specific issues include: the impacts of various technology pathways (well-to-wheels energy and environmental issues), resource needs and impacts, cost elements and drivers, key cost and technological gaps, alternative means for meeting Program goals, progress toward Program targets, and energy-related economic benefits.

Systems Integration provides tools to integrate all Program activities and to measure progress toward goals. By providing a structured approach to the research, design, development, and validation of complex systems, Systems Integration ensures that system-level targets are identified, verified, and met. This also helps to minimize the delays and unforeseen costs that inevitably arise in the process of developing complex systems. Both of these activities play important roles in Program decision-making, planning, and budgeting.

From FY 2008 – FY 2010, the Program provided $24 million for systems analysis, funding more than 20 projects.

j. Market Transformation: To ensure that the benefits of its efforts are realized, the Program has initiated activities to facilitate the growth of early markets for portable, stationary, and specialty-vehicle fuel cells. The growth of these early markets will help reduce costs by enabling economies of scale, which will result in increased market opportunities for fuel cells. In addition, the success of these early markets will help overcome a number of barriers that will also face the broader vehicular marketplace, including the lack of reliability data in the field, the need for applicable codes and standards, the lack of user confidence, and the inherent resistance to new technologies.

The development of niche-market applications for hydrogen fuel cells has been identified as the quickest way to achieve early market penetration. A study conducted for the Program by the Battelle Memorial Institute, *Identification and Characterization of Near-Term Direct Hydrogen PEM Fuel Cell Markets,*[14] identifies fuel cells to power forklifts and to provide backup power for telecommunications and emergency response as promising near-term opportunities.

Another aspect of the Market Transformation subprogram, which is consistent with EPACT section 783, "Federal Procurement of Stationary, Portable, and Micro Fuel Cells," is to facilitate hydrogen and fuel cell technology use by federal "early adopters." These projects provide valuable data on the status of the technologies in real-world operation and information that will be used to validate the benefits of the technologies and potential needs for further R&D. Between FY 2008 and FY 2010, the Program partnered with other federal agencies to provide technical guidance and assistance with the following activities:

- The Defense Logistics Agency's effort to place more than 120 units of fuel-cell powered material-handling equipment (e.g., forklifts) into service at its distribution centers across the country
- The Department of Defense's installation of 14 fuel cell systems (over 500 kW) that provide backup power to military installations across the country
- The U.S. Postal Service's operation of two fuel cell vehicles in regular mail delivery service
- The Federal Aviation Administration's installation of 25 fuel cell back-up power systems at remote telecommunication towers
- The Department of Defense's planned deployment of seven hydrogen buses at military installations across the country
- The Department of Defense's planned installation of a renewable-energy-to-hydrogen production facility in Hawaii to provide hydrogen for two buses

From FY 2008 – FY 2010, the Program provided $20 million for market transformation activities, to accelerate the deployment of fuel cells in early market applications.

II.2.1 American Recovery and Reinvestment Act

A critical part of the Program since FY 2009 has been the American Recovery and Reinvestment Act (Recovery Act or ARRA), which provided DOE with $41.9 million to accelerate the commercialization and deployment of fuel cells in the market. With approximately $54 million in cost-share funding from industry participants—for a total of nearly $96 million—the funding is supporting the deployment of nearly 1,000 fuel cell

[14] For a brief summary of early market opportunities for PEM fuel cells, see the Program's fact sheets on forklifts and backup power, at: www1.eere.energy.gov/hydrogenandfuelcells/education/pdfs/early_markets_forklifts.pdf and www1.eere.energy.gov/hydrogenandfuelcells/education/pdfs/early_markets_backup_power.pdf. For the full report by the Battelle Memorial Institute, see: www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pemfc_econ_2006_report_final_0407.pdf.

systems in emergency backup power, material handling, and combined heat and power applications.[15] The major accomplishment resulting from these investments is the development of a competitive domestic supply base for components and fuel cell systems, decreased costs of fuel cells in the market place and demonstration of economic and performance benefits of fuel cells. Through these cost savings, and the practical experience gained during the projects, we expect to see increasing potential for fuel cells to provide competitive power options for stationary, portable, and specialty vehicle applications. This will in turn lead to reductions in carbon emissions, the creation of jobs, and a broadening of our nation's clean energy technology portfolio.

[15] Fuel Cell Market Transformation Recovery Act Projects, http://www1.eere.energy.gov/hydrogenandfuelcells/awards.html.

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

During FY 2008 – 2010, DOE:

- Dedicated approximately $756 million[16] to support the RD&D of hydrogen and fuel cell technologies (quantitative results are summarized in Chapter IV).
- Launched the investment of $41.9 million in Recovery Act funding in April 2009 for fuel cell technology to accelerate the commercialization and early market deployment of fuel cells; and to build a robust fuel cell manufacturing industry in the United States with accompanying jobs in fuel cell manufacturing, installation, maintenance, and support services.
  - Twelve projects were competitively selected to develop and deploy a variety of fuel cell technologies including polymer electrolyte, solid oxide, and direct-methanol fuel cells in stationary, portable, and specialty vehicle applications.
  - Nearly 1,000 fuel cell systems are planned. As of the end of July 2010, 205 fuel cell lift trucks and eight fuel cell back-up power systems for cellular communications towers have been deployed. To date, a total of at least 36 jobs have been created or retained as a result of these projects.

Figure III.1. *Illustrates locations throughout the country with fuel cell deployments resulting from the Program's efforts, directly supporting the requirements of EPACT.*

[16] See figures V.1 and V.2

- Expanded the Fuel Cell Technologies Program to include technical and financial support for key strategic deployments of fuel cells in early markets, which will help industry to achieve the economies of scale needed for significant cost reductions. Progress made in this activity will assist in the growth of a domestic supplier base. Due to the Program's efforts, major companies such as Spirit, AT&T, and Pacific Gas and Electric (PG&E) are installing fuel cells for emergency and backup power needs.

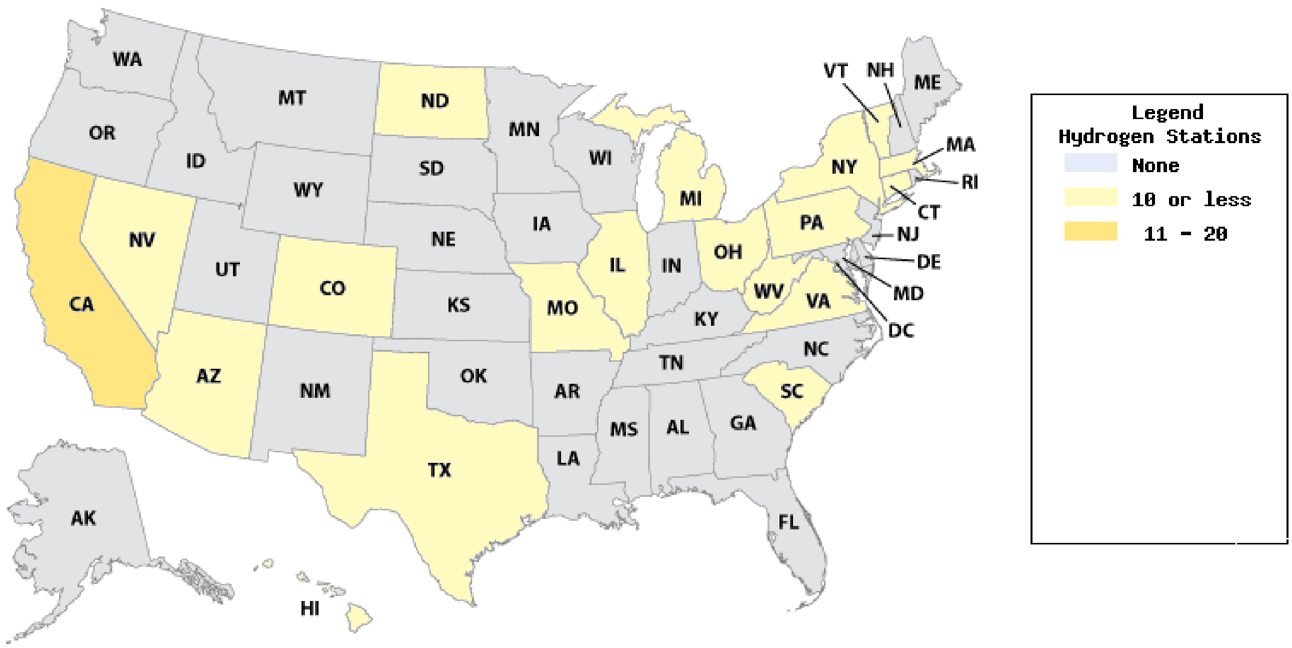

Figure III.2. *Hydrogen fueling stations are located throughout the country, and over 100,000 fuel cell vehicle refuelings have been completed. Many are available to the public, while some are located on sites of major companies like Sprint, AT&T, and PG&E.*
(Source: NREL, www.afdc.energy.gov/afdc/fuels/hydrogen_locations.html.)

- Continued collaboration with Chrysler, Ford, General Motors, major energy companies (ExxonMobil, ConocoPhillips, Chevron, BP, and Shell), and two electric utilities (Southern California Edison and DTE Energy), known as the FreedomCAR and Fuel Partnership,[17] to help the Program evaluate research results and establish the technical requirements for hydrogen and fuel cell technology development.

- Continued work with the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC),[18] which advises the Secretary of Energy on the programs and activities conducted under Title

[17] For more information on the Partnership, see: www1.eere.energy.gov/vehiclesandfuels/about/partnerships/freedomcar/index.html, and *The FreedomCAR and Fuel Partnership Plan*, www1.eere.energy.gov/vehiclesandfuels/about/partnerships/freedomcar/index.html.

[18] For more information on the Hydrogen and Fuel Cell Technical Advisory Committee, see: www.hydrogen.energy.gov/advisory_htac.html.

VIII of EPACT of 2005. During the period of FY 2008-2010, HTAC held nine meetings and delivered two annual reports to DOE.

- Continued interaction with the Hydrogen and Fuel Cell Interagency Task Force (ITF) and Interagency Working Group (IWG), which focus their efforts on federal leadership of early technology adoption and opportunities for interagency partnerships to demonstrate and deploy hydrogen fuel cell technologies in early market applications.
  - Activities involved collaboration with DOD, a member of the ITF, on efforts to install fuel cells for emergency backup power at DOD sites in conjunction with DOD's Construction Engineering and Research Laboratory (CERL) and on the deployment of fuel-cell powered material handling equipment through DOD's Defense Logistics Agency (DLA).
- Conducted three annual reviews of the Program (Annual Hydrogen Program Merit Review and Peer Evaluation).[19] The last review in the period covered by this report, in June 2010, included nearly 300 projects, almost 200 reviewers, and more than 1,800 registered attendees.
- Initiated investigations of new approaches to overcoming the challenge of developing a hydrogen delivery infrastructure in the absence of sufficient vehicles and demand (the "chicken-and-egg" dilemma). These efforts include the development and demonstration of an innovative concept of producing hydrogen from stationary fuel cells generating heat and power (the "combined-heat-hydrogen-and-power," or CHHP, approach), which would enable hydrogen to be produced for fuel cell vehicles with minimal stranded capital in the initial stages of market introduction.
- Engaged the domestic and international codes and standards development organizations to establish critical requirements for the development of hydrogen and fuel cell codes and standards needed for the commercialization of these technologies.
- Continued collaboration through the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE),[20] with members from 16 nations and the European Commission to organize and implement effective, efficient, and focused international research, development, demonstration, and commercial utilization activities, and to provide a forum for advancing policies and common codes and standards.

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

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

IV. Progress toward Goals

As described in chapter III of this report, the Program is conducting activities to address a range of barriers facing the development and commercialization of hydrogen and fuel cell technologies. This chapter discusses the Program's progress toward the goals laid out in its developmental roadmap (the *Hydrogen Posture Plan*) and progress made toward EPACT's deployment goals. In the course of this discussion, the current state of technology demonstration and the role of the Program in achieving deployment goals are addressed.

IV.1 Progress toward Program Goals

Since 2008, the Program's efforts have advanced hydrogen and fuel cell technologies and achieved several significant accomplishments. DOE-supported activities have:

Hydrogen Production and Delivery

- Reduced the cost of producing hydrogen[21] using renewable resources through several production pathways, including distributed electrolysis ($4.90 – $5.70/gge), centralized electrolysis from wind ($2.70 – $3.50/gge),[22] photoelectrochemical direct water splitting ($4 – $10/gge),[23] and biological ($3 – $12/gge).[24]
- Demonstrated a system that directly integrates wind power, solar power, and water electrolysis, reducing and simplifying power conditioning between the renewable energy source and the electrolyzer, and resulting in a reduced hydrogen production cost.[25]
- Improved hydrogen-from-coal technologies: hydrogen flux rates greater than 400 scfh/ft^2 have been observed for best alloy membranes. Baseline alloy membranes show stable performance for 200 scfh/ft^2 during lifetime reactor testing, meeting the Program's 2010 targets for flux.
- Operated integrated laboratory-scale, hydrogen from nuclear power, high-temperature electrolysis unit for 45 days achieving 5,650 liters per hour peak output at 12 kWe input. [26]
- Reduced the cost of hydrogen delivery by achieving a 30% reduction in tube trailer costs, 20% reduction in pipeline costs, and a 15% reduction in liquid hydrogen costs (see figure IV.1).[27]
- Developed fiber-reinforced polymer (FRP) pipes that can be used for delivery of

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[21] Production costs are based on projections to high-volume production; centralized production costs do not include delivery and station costs.

[22] *Current (2009) State -of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis*, NREL, September 2009, http://hydrogen.energy.gov/pdfs/46676.pdf.

[23] *Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production*, Directed Technologies Inc., December 2009, www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pec_technoeconomic_analysis.pdf

[24] *Technoeconomic Boundary Analysis of Biological Pathways to Hydrogen Production*, Directed Technologies Inc., September 2009, www1.eere.energy.gov/hydrogenandfuelcells/pdfs/46674.pdf.

[25] K. Harrison, et al., *Characterizing Electrolyzer Performance for Use in Wind Energy Applications*, presented at the American Wind Energy Association's WINDPOWER Annual Conference, June 2006, www.nrel.gov/hydrogen/pdfs/40100.pdf

[26] S. Herring, "FY 2009 Laboratory-Scale High Temperature Electrolysis System," 2009 Annual Progress Report, http://hydrogen.energy.gov/pdfs/review09/pd_14_herring.pdf.

[27] R. Farmer, "Fuel Cell Technologies Program Overview," *2010 Annual Merit Review Proceedings*, 2010, www.hydrogen.energy.gov/pdfs/review10/pln005_farmer_2010_o_web.pdf.

gaseous hydrogen and show no long-term aging effects to date from high-pressure hydrogen. A new polymer has also been identified, with reduced hydrogen permeation rates (significantly less than 0.1 percent per day) that are equivalent to natural gas permeation rates in today's polymer transmission lines.[28]

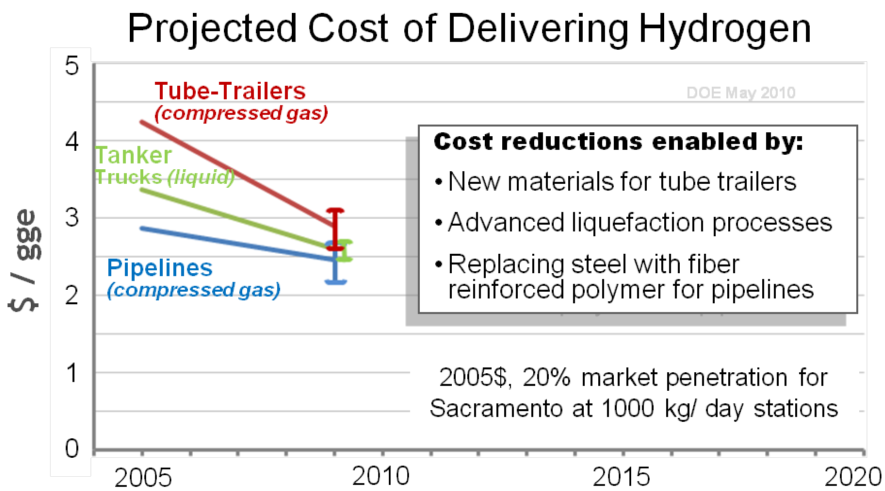

Figure IV.1. *Projected cost of delivering hydrogen.*

Hydrogen Storage

- Identified several promising new materials for high-capacity, low-pressure, on-board hydrogen storage systems. New materials have provided more than 50 percent improvement in storage capacity since 2004, with some materials achieving nearly 10 percent material-based capacity by weight. R&D conducted to modify the performance characteristics of these materials has demonstrated potential for room temperature storage in sorbent materials (which would normally require cryogenic temperatures) and has increased the rates at which hydrogen is released from materials (including increasing the release rate from one material by a factor of 60).[29]
- Developed and demonstrated a novel "cryo-compressed" tank concept. This tank achieved a system gravimetric capacity of 5.4 percent by weight (wt %), which exceeds the Program's 2010 system target of 4.5 wt %, and has a volumetric system capacity of approximately 31 g/L.[30] Other remaining challenges, including cost, are being addressed by the program—for example, the Program's efforts in developing low-cost precursors for carbon fiber will help reduce system cost.

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[28] T. Adams, "FY 2009 SRNL Hydrogen Delivery Project—Hydrogen Permeability and Pipeline Integrity/Fiber Reinforced Composite Pipeline," 2009 Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress09/iii_17_adams.pdf.

[29] L. Simpson, "Overview of the DOE Hydrogen Sorption Center of Excellence" *2010 Annual Merit Review Proceedings, 2010,* www.hydrogen.energy.gov/pdfs/review10/st014_simpson_2010_o_web.pdf.

[30] "Hydrogen Storage Sub-Program Overview," *2007 Annual Progress Report*, DOE Hydrogen Program, 2007, p. 337, www.hydrogen.energy.gov/pdfs/progress07/iv_0_introduction.pdf.

- Developed and evaluated more than 400 material approaches experimentally and millions computationally.

Fuel Cell Systems R&D

- Reduced the projected high-volume cost of automotive fuel cells to $61/kW in 2009, more than a 75% reduction in cost since 2002 (see figure IV.2).[31,32] Preliminary studies estimated this cost to be $51/kW at the end of 2010.
- Demonstrated improved durability of fuel cell systems in vehicles operating under real-world conditions from, 950 hours in 2006 to 2,500 hours (or approximately 75,000 miles) today (see figure IV.3).[33]
- Demonstrated durable membrane electrode assembly with low platinum group metal (PGM) content—simultaneously meeting DOE's 2010 durability and PGM content targets[34]
  - Demonstrated membrane durability of more than 5,000 hours, with load cycling in single cell testing (>7,300-hour durability has been demonstrated in MEAs with higher PGM content)
  - Demonstrated operation with PGM total content of <0.2 g_{PGM}/kW, in both single cell and stack testing

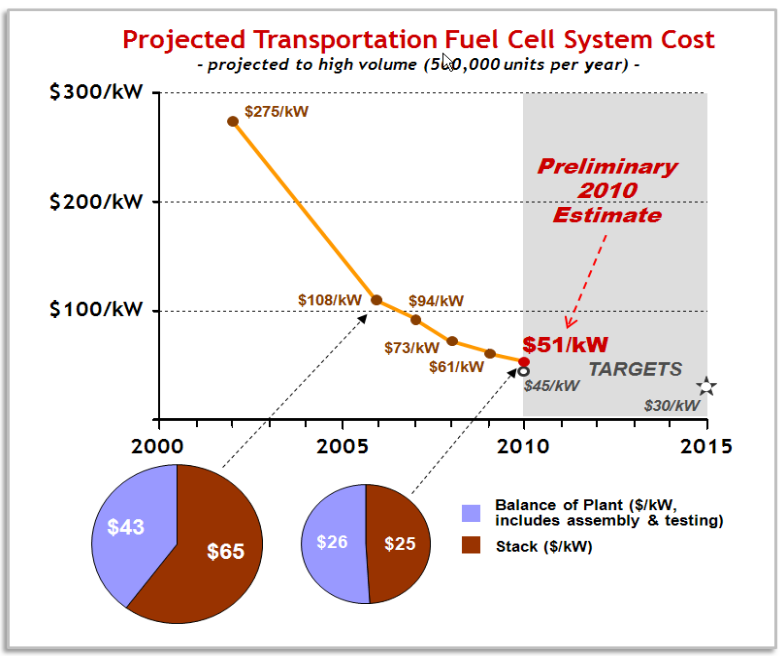

Figure IV.2. *Projected transportation fuel cell system cost.*

[31] Based on projection to high-volume manufacturing (500,000 units/ year).

[32] U.S. Department of Energy Hydrogen Program Records #5005 and #9012, www.hydrogen.energy.gov/program_records.html. The projected costs of $275/kW and $61/kW are based on 2002 and 2009 dollars, respectively.

[33] K. Wipke, et al., "Controlled Hydrogen Fleet and Infrastructure Analysis," 2010 Annual Merit Review Proceedings, 2010, www.hydrogen.energy.gov/pdfs/review10/tv001_wipke_2010_o_web.pdf.

[34] Mark K. Debe, "Advanced Cathode Catalysts and Supports for PEM Fuel Cells," 2010 Annual Merit Review Proceedings, 2010, http://www.hydrogen.energy.gov/pdfs/review10/fc001_debe_2010_o_web.pdf.

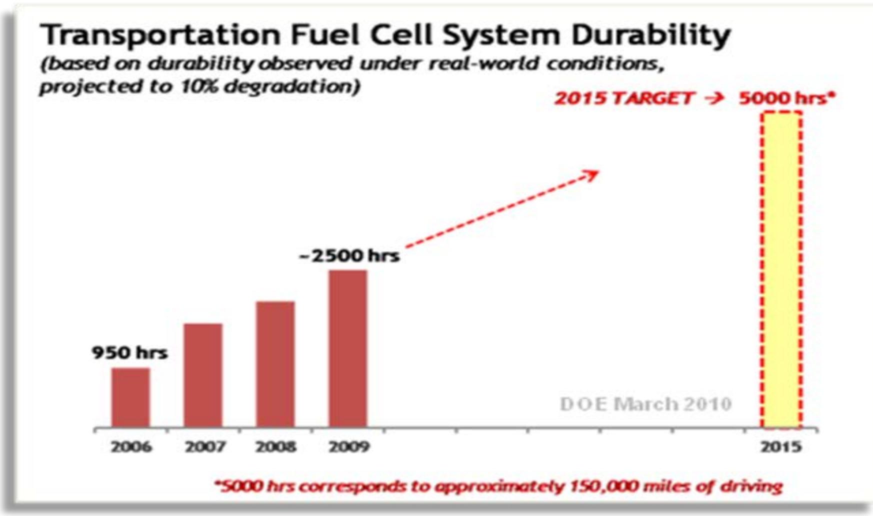

Figure IV.3. *Transportation fuel cell system durability.*

- Developed a non-PGM catalyst with mass-transport corrected activity exceeding the DOE 2010 target of 130 A/cm^3 at 0.8 V.[35]

Manufacturing R&D

- Reduced the cost of gas diffusion layers by 53% through manufacturing R&D.[36]
- Demonstrated 25% fuel cell cost reduction from novel 3-layer MEA manufacturing process.[37]

Technology Validation

- Deployed 144 fuel cell vehicles and 23 hydrogen fueling stations in learning demonstrations. These vehicles have traveled over 2.5 million miles and the fueling stations have produced or dispensed over 150,000 kg of hydrogen. Vehicles and infrastructure in these demonstrations have validated the status of several critical path technologies in integrated systems under real-world operating conditions, including:
    - Vehicular fuel cell efficiency of 53 to 59 percent
    - Vehicular fuel cell system projected durability of 2,500 hours (nearly 75,000 miles)
    - Vehicle range of more than 250 miles[38]

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[35] P. Zelenay, “Advanced Cathode Catalysts,” 2010 Annual Merit Review Proceedings, 2010, http://www.hydrogen.energy.gov/pdfs/review10/fc005_zelenay_2010_o_web.pdf.
[36] J. Morgan, “Reduction in Fabrication Costs of Gas Diffusion Layers,” 2010 Annual Merit Review Proceedings, 2010, www.hydrogen.energy.gov/pdfs/review10/mn002_morgan_2010_o_web.pdf.
[37] C. Busby, “Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies Engineered for Rapid Conditioning,” 2010 Annual Merit Review Proceedings, 2010, www.hydrogen.energy.gov/pdfs/review10/mn004_busby_2010_o_web.pdf.
[38] K. Wipke, et al., “Controlled Hydrogen Fleet and Infrastructure Analysis,” 2010 Annual Merit Review Proceedings, 2010, www.hydrogen.energy.gov/pdfs/review10/tv001_wipke_2010_o_web.pdf.

- Collected and analyzed data from a total of nine fuel cell buses operated in revenue transit service in the United States. These buses have shown fuel economy improvements of 48 to 123 percent over conventional diesel buses and compressed natural gas baseline buses, with ranges of approximately 300 miles. Upcoming projects will add data from as many as 22 new or improved-design fuel cell buses.[39]

Safety, Codes & Standards

- Conducted safety R&D to provide a sound technical basis for the development of critical codes and standards for hydrogen and fuel cell technologies. A key outcome is the development of a comprehensive hydrogen code -NFPA 2: Hydrogen Code Document.
- Developed and launched online resources to disseminate hydrogen safety information and facilitate the process of permitting hydrogen installations, including: The Hydrogen Safety Best Practices Manual, the Technical Reference on Hydrogen Compatibility of Materials Manual, the Regulators' Guide to Permitting Hydrogen Technologies, the Hydrogen Safety Bibliographic Database, the Hydrogen Incidents and Lessons Learned Database, and the Permitting Hydrogen Facilities Compendium.
- Deployed two web-based introductory courses for first responders[40] and code officials[41] and an advanced-level, hands-on first responder training.

Education

- Launched the "Increase Your H2IQ Public Information Program"[42] which includes radio spots, podcasts, and print materials.
- Disseminated hydrogen and fuel cell course materials to over 8,000 middle school and high school teachers. Developed 25 university courses and curriculum modules at 5 universities for general science and engineering programs and specialized hydrogen and fuel cell concentrations.
- Conducted more than 40 workshops, seminars, and briefings across the country to help state and local decision-makers understand, identify, and assess opportunities for fuel cell deployment.

Systems Analysis

- Developed the Macro-System Model, a tool that integrates several analytical models into a single interface. This provides the capability to estimate the economics, primary energy source requirements, and emissions of full production and delivery pathways consistently and holistically.

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[39] L. Eudy, "Technology Validation: Fuel Cell Bus Evaluations," 2010 Annual Merit Review Proceedings, 2010, www.hydrogen.energy.gov/pdfs/review10/tv008_eudy_2010_p_web.pdf.

[40] "Introduction to Hydrogen Safety for First Responders," http://hydrogen.pnl.gov/FirstResponders/.

[41] "Introduction to Hydrogen Safety for Code Officials," www.hydrogen.energy.gov/training/code_official_training.

[42] "Increase Your H2IQ," www1.eere.energy.gov/hydrogenandfuelcells/education/h2iq.html.

- Developed the Fuel Cell Power (FCPower) Model, a financial tool for analyzing high-temperature, fuel cell-based tri-generation systems. The model, which quantifies energy inputs/outputs and greenhouse gas emissions, is used by the Program to determine the cost of delivered energy in tri-generation systems that provide onsite-generated hydrogen and electricity.
- Completed a number of important analyses, including: well-to-wheels analysis that shows the potential for significant reductions in emissions and petroleum use from many hydrogen fuel cell vehicle pathways (see figure IV.4);[43] energy storage analysis, which shows that hydrogen-based energy storage for electric utilities could provide a cost-competitive alternative to peak power shortly after 2012; and analyses of

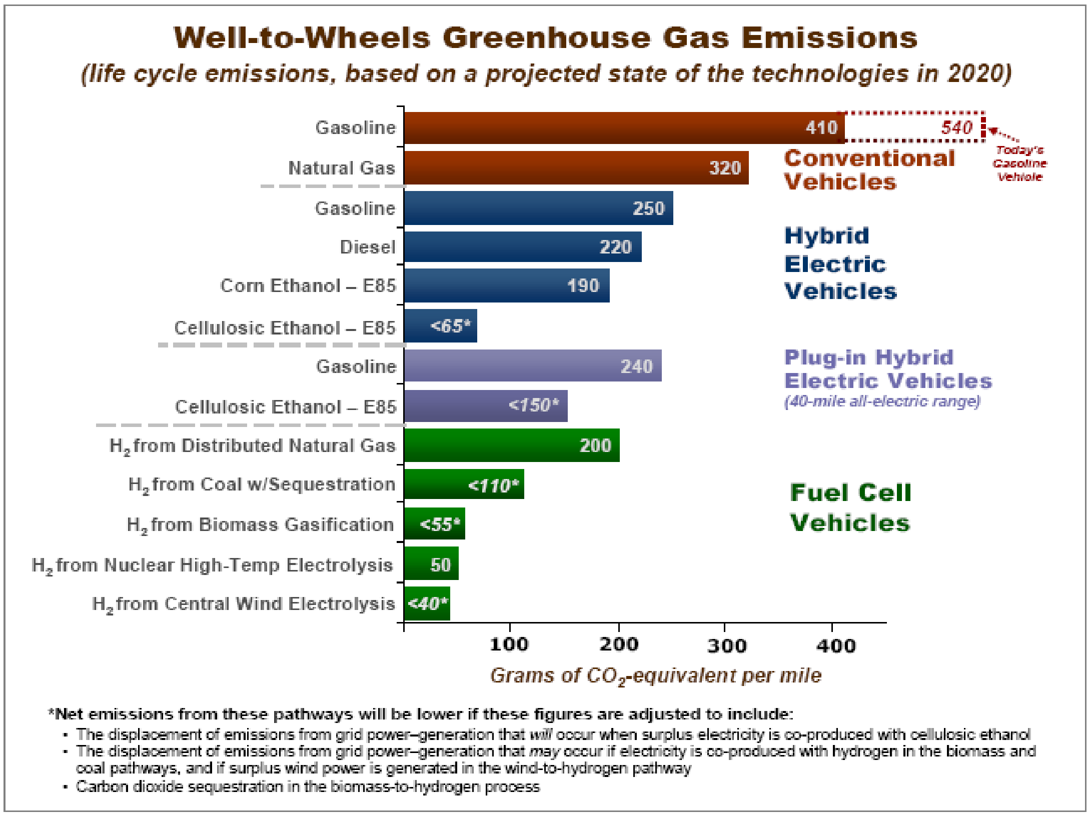

Figure IV.4. *Well-to-wheels analysis[44] shows substantial potential reductions in greenhouse gas emissions through the use of a variety of advanced transportation technologies, including fuel cell vehicles using hydrogen from a variety of sources.*

[43] U.S. Department of Energy Hydrogen Program Record #9002, www.hydrogen.energy.gov/program_records.html.
[44] Ibid.

early market applications for fuel cells, which show potential greenhouse gas emissions reductions from fuel cells in early market applications[45] and predicts that a modest program of government purchases could reduce the cost of fuel cells enough to enable certain fuel cell applications to become self-sustaining in the marketplace.[46]

Market Transformation

- Documented 143 patents and nearly 30 commercial technologies resulting from EERE-funded R&D.[47]
- In partnership with key public and private stakeholders, conducted a 31-stop cross-country "Hydrogen Road Tour" in August 2008 to showcase hydrogen transit buses and hydrogen passenger vehicles from nine automakers.
- Provided technical assistance, project development, and data collection support to several federal early adoption demonstrations including:
    - The Department of Defense:
        - Defense Logistics Agency's effort to place over 120 forklifts at its distribution centers across the country
        - installation of 14 fuel cell systems (>500kW) that provide backup power to military installations across the country
        - planned installation of a renewable energy to hydrogen production facility in Hawaii to provide hydrogen for 2 hydrogen ICE buses
        - planned installation of 7 hydrogen ICE buses at military installations across the country
    - The Federal Aviation Administration installation of 25 fuel cell back-up power systems at remote telecommunication towers
    - The U.S. Postal Service's operation of 2 fuel cell vehicles in regular mail delivery service

Recovery Act

- Awarded $41.9 million in Recovery Act funding to accelerate the commercialization and deployment of fuel cells. With approximately $54 million in cost-share funding from industry participants—for a total of nearly $96 million—the new funding will support immediate deployment of nearly 1,000 fuel cell systems in emergency backup power, material handling, and combined heat and power applications.
- As of July 2010:
    - 206 fuel cell powered lift trucks have been deployed;

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[45] *Full Fuel-Cycle Comparison of Forklift Propulsion Systems* (PDF 2 MB), Argonne National Laboratory, October 2008, www1.eere.energy.gov/hydrogenandfuelcells/pdfs/forklift_anl_esd.pdf.; and *Fuel Cycle Comparison for Distributed Power Technologies*, Argonne National Laboratory, November 2008, www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fuel_cycle_comparison_report.pdf.

[46] D. Greene, *Bootstrapping a Sustainable North American Proton Exchange Membrane Fuel Cell Industry: Could a Federal Acquisition Program Make a Difference?*, 2008, http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2008_183.pdf.

[47] *Pathways to Commercial Success: Technologies and Products Supported by the Hydrogen, Fuel Cells and Infrastructure Technologies Program*, 2009, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pathways_success_hfcit.pdf.

- Fuel cells have already been installed as backup power at 8 cell tower sites, with an additional 8 sites pending construction; and
- 75 portable fuel cells as handheld power generators for small consumer electronics are being sent to users as test units.

IV.2 Progress toward Deployment Goals in EPACT Title VIII

The Program is making significant progress toward the technology development goals it has set to enable industry to commercialize fuel cell vehicles and hydrogen infrastructure.

However, the planned 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, and the cost of fuel cells is still too high and their durability too low to enable industry to meet this goal. While fuel cell and hydrogen technology development is currently on track to meet key 2015 technology-readiness targets—including reducing fuel cell cost to $30/kW, improving fuel cell durability to 5,000 hours, and reducing the cost of hydrogen to $2–3 per gallon gasoline equivalent—it is too early to determine whether industry can achieve EPACT's 2020 vehicle deployment goal of 2.5 million hydrogen-fueled vehicles. However, analyses conducted by Oak Ridge National Laboratory[48] and the National Academies[49] indicate that deployment scenarios of similar scale are realistic within the next 10–15 years, given sufficient supporting policies and incentives. In partnership with the automobile and energy industries, the Program continues to play a key role in validating the technologies, determining their readiness for commercialization, and analyzing the infrastructure and policies required for a variety of market penetration scenarios.

Since 2003, there have been more than 300 hydrogen-powered vehicles[50] demonstrated on the road and more than 60 hydrogen stations[51] installed in the U.S.; these efforts represent the first stage in laying the groundwork for widespread FCV commercialization. In September 2009 a number of auto manufacturers from around the world signed a letter of understanding supporting fuel cell vehicles in anticipation of widespread commercialization,[52] beginning in 2015. In addition, General Motors and Honda have begun to deploy vehicles in limited consumer test markets.

Program research and development seeks to achieve performance and cost targets that enable transportation technology readiness in the 2015 timeframe. Ultimately, however, it

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[48] D. Greene, et al., *Transition to Hydrogen Fuel Cell Vehicles & the Potential Hydrogen Energy Infrastructure Requirements,* Oak Ridge National Laboratory, March 2008, www-cta.cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2008_30.pdf.

[49] "Transitions to Alternative Transportation Technologies—A Focus on Hydrogen," National Academy of Sciences, 2008; the full report is available from: http://books.nap.edu/catalog.php?record_id=12826

[50] "Inventory of Current Fuel Cell and Other Hydrogen-Power Vehicles," Hydrogen Analysis Resource Center, U.S. Department of Energy, http://hydrogen.pnl.gov/filedownloads/hydrogen/datasheets/U.S.%20Hydrogen-Fueled%20Vehicle%20Database%20September%202009.xls, (accessed August 6, 2010).

[51] "Operational Hydrogen Fueling Stations in the United States," Hydrogen Analysis Resource Center, U.S. Department of Energy, http://hydrogen.pnl.gov/filedownloads/hydrogen/datasheets/Operational_Hydrogen_Fueling_Stations.xls (accessed August 6, 2010).

[52] Fuel Cell Works, "Major car manufacturers sign Letter of Understanding on fuel cell electric vehicles", September 2009. http://fuelcellsworks.com/news/2009/09/09/major-car-manufacturers-sign-letter-of-understanding-on-fuel-cell-electric-vehicles

is the decision of industry whether to proceed with commercialization and when to do so. The most recent estimate of numbers of FCVs on the road in the 2012 to 2018 timeframe is based on automaker feedback to the California Fuel Cell Partnership.[53]

Fuel Cell Vehicles		
Phase I	Phase II	Phase III
Through 2012	2013-2015	2016-2018
450	4,200	54,300

Fuel Cell Buses		
Field Testing	Full-scale Demo	Commercialization
2009-2011	2012-2014	2015-2017
15-17	20-60	60-150

Figure IV.5. *California Fuel Cell Partnership.*

The Program is also placing greater emphasis on activities that can stimulate early markets for stationary and portable fuel cell applications. Early markets such as fuel cells for stationary power, auxiliary power, and specialty vehicles continue to grow. In 2009, over 24,000 fuel cells were shipped, a 40 percent increase over 2008.[54] The adoption of fuel cell technologies in early market applications supports commercialization, helps build a domestic manufacturing and supplier base expands the growth of the green job market, and helps overcome non-technical challenges to the expansion of hydrogen and fuel cell technologies into the broader vehicular marketplace.

In 2010, the Program's key goals were to develop hydrogen and fuel cell technologies for:

1) Early markets such as stationary power (prime and back up), lift trucks, and portable power in the 2010 – 2012 timeframe,
2) Mid-term markets such as residential combined-heat-and-power systems, auxiliary power units, fleets and buses, in the 2012 to 2015 timeframe, and
3) Long-term markets including mainstream transportation applications with a focus on light duty vehicles, in the 2015 to 2020 timeframe.

IV.2.1 Technology Validation Progress: Vehicle and Infrastructure Demonstrations

The Program's Learning Demonstration provides the opportunity to test, demonstrate, and validate components and complete systems in real-world environments. To date, this project has demonstrated 144 fuel cell vehicles and 23 hydrogen fueling stations,[55]

[53] *Hydrogen Fuel Cell Vehicle and Station Deployment Plan: A Strategy for Meeting the Challenge Ahead, Progress and Next Steps*, California Fuel Cell Partnership (CaFCP), April 2010, www.cafcp.org/sites/files/FINALProgressReport.pdf.

[54] *2009 Fuel Cell Today Industry Review*, Fuel Cell Today, 2009.

[55] K. Wipke, et al., "Controlled Hydrogen Fleet and Infrastructure Analysis," 2010 Annual Merit Review Proceedings, 2010, www.hydrogen.energy.gov/pdfs/review10/tv001_wipke_2010_o_web.pdf.

gathering data on many aspects of the performance of vehicles and fueling installations, including fuel cell efficiency, fuel economy, driving range, fuel cell durability, vehicle safety, hydrogen quality, refueling rates, infrastructure safety, as well as many other metrics. A few key metrics are shown in table IV.1.

	Current Status *(based on learning demo)*	**Program Targets: Phase 1 – In Progress**	**Program Targets: Phase 2 –Planned**
System Efficiency	53–59%	**2009 Target:** 60%	**2015 Target:** 60%
Fuel Cell System Durability	2,500 hours *(~ 75,000 miles)*	**2009 Target:** 2,000 hours *(~ 60,000 miles)*	**2015 Target:** 5,000 hours *(~150,000 miles)*
Vehicle Range	up to 254 miles	**2009 Target:** 250 miles	**2015 Target:** 300 miles
Fuel Cost	\$7.70 - \$10.30 *(projected, from distributed natural gas)* \$10.00 - \$12.90 *(on-site electrolysis)*[56]	**2009 Target:** \$3/gge	**2015 Target:** \$2–3/gge
Average Refueling Rate	0.77 kg/min	**2007 Target:** 1.0 kg/min	**2012 Target:** 1.67 kg/min

Table IV.1. *Status and targets for the National Hydrogen Learning Demonstration.*[57]

Additional examples of demonstration activities in the United States include the following:

- In July 2008, Honda began leasing fuel cell vehicles to a limited number of retail consumers in Southern California and Japan. The combined sales plan for Japan and U.S. calls for about 200 units within three years.[58]
- Several fuel cell bus programs exist in the United States. Currently, 14 hydrogen fuel cell buses are operating in seven states, and an additional 22 buses are planned in eight states.[59]
- General Motors deployed over 100 fuel cell vehicles for a consumer test market between 2008 and 2010, and have begun to update these vehicles for the next

[56] Outside of this project, DOE independent panels estimated the cost of producing hydrogen to be: \$2.75-\$3.50/kg using distributed natural gas reforming (2006) and \$4.90-\$5.70 using distributed electrolysis (2009); projections assume stations produce 1500 kg/day and are built at rate of 500/year.

[57] K. Wipke, et al., "Controlled Hydrogen Fleet and Infrastructure Analysis," 2010 Annual Merit Review Proceedings, 2010, www.hydrogen.energy.gov/pdfs/review10/tv001_wipke_2010_o_web.pdf.

[58] "Honda Begins Leasing FCX Clarity Fuel Cell Vehicle in Japan," Honda Press Release, November, 2008, http://world.honda.com/news/2008/4081125FCX-Clarity/.

[59] Summary Table of U.S. Fuel Cell Bus Demonstrations, National Renewable Energy Laboratory, www.nrel.gov/hydrogen/docs/us_fcb_projects.xls (accessed July 28, 2010).

demonstration phase.[60] Thirty-two of these vehicles are part of the Program's learning demonstration fleet.

IV.2.2 Infrastructure Analysis

Introducing hydrogen as an energy carrier will involve major changes in the country's view of energy storage and vehicle and fueling infrastructure. The majority of the associated technical challenges, costs, and risks will manifest in the near-term, when markets are very small and the infrastructure is immature. Therefore, it is critical to conduct sound analysis to support the decision-making process and inform the policy-making arms of the government as well as other key decision-makers.

To explore the requirements and impacts of potential market-penetration scenarios, the Program, in partnership with industry, is analyzing the costs and tradeoffs of different options for hydrogen production, delivery, and utilization, as well as examining which policies might be most effective in sustaining the early years of hydrogen and fuel cell technology deployment. These analyses include 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.

Scenario Analysis

Through workshops with industry, academia, and national laboratories,[61] a set of hydrogen penetration scenarios and transition models were identified and developed in the Oak Ridge National Laboratory (ORNL) study, *Transition to Hydrogen Fuel Cell Vehicles & the Potential Hydrogen Energy Infrastructure Requirements*. These models and scenarios were used to develop a plausible set of pathways—including policy actions—that could provide decision-makers with well-informed options. This activity was also undertaken to address the recommendation by the National Academies that "DOE should map out and evaluate a transition plan consistent with developing the infrastructure and hydrogen resources necessary to support the committee's [*NAS's Committee on Alternatives and Strategies for Future Hydrogen Production and Use*] hydrogen vehicle penetration scenario or another similar demand scenario."[62]

The analysis examined three vehicle market penetration scenarios identified by industry.[63] These scenarios do not represent a proposed strategy or plan on the part of DOE or

[60] "GM Continues Project Driveway Fuel-Cell Development Program, Phases in Second-Gen Technology," *Car and Driver*, March 23, 2010, http://blog.caranddriver.com/gm-continues-project-driveway-fuel-cell-development-program-phases-in-second-gen-technology/.

[61] Attendees included automobile and energy company representatives, industrial gas company representatives, analysts, national laboratories, and DOE program managers.

[62] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs,* Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, p. 118. The full report is available from: www.nap.edu/catalog/10922.html.

[63] D. Greene, et al., *Transition to Hydrogen Fuel Cell Vehicles & the Potential Hydrogen Energy Infrastructure Requirements,* Oak Ridge National Laboratory, March 2008, www-cta.cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2008_30.pdf.

industry, nor do they represent a prediction or an indication of what is possible. The market penetration rates used were developed to facilitate analysis of the infrastructure and policy needs that may arise under a variety of scenarios.

A key conclusion of the scenario analysis was that networks of fueling stations should be established in a limited number of urban centers—i.e., hydrogen clusters, not highways—during the market introduction period. Also called a "lighthouse" scenario, this approach could maximize coverage and be a cost-effective way to provide the early infrastructure.

The analysis also considered policies that could be used to help share the costs of bringing FCVs to market and to address two key economic barriers: (1) the lack of an existing fueling infrastructure and (2) the high cost of FCVs at low production volumes. The costs of each of the policy cases considered were calculated for the three vehicle market penetration scenarios. Key findings of the policy analysis are:

- Transition policies appear to be essential to overcome the initial economic barriers to hydrogen-powered transportation. This seems to be true even if the technologies in FCVs deliver superior performance and fuel economy than those in advanced hybrid internal combustion vehicles.
- The highest total annual government expenditure under the policy cases examined was about $6 billion[64]— the same magnitude of spending expected to be provided by the ethanol tax credit in 2012 (which is the year when FCVs enter the commercial market in the scenarios examined).
- Directed policies of cost-sharing and tax credits over a decade could enable the industry to bring competitive automotive and infrastructure products to the marketplace by 2025 if performance and cost targets for fuel cells and hydrogen storage are met.

In 2008, the National Research Council (NRC) Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies released the report, *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*, which was required by EPACT section 1825. This independent analysis by the National Academies shows a positive outlook for fuel cell technologies, and its key findings on vehicle market penetration rates and estimated government cost to support a transition to fuel cell vehicles agree with the results of the ORNL study.

IPHE Infrastructure Workshop

Assuring adequate fueling infrastructure for customers is one of the biggest barriers to hydrogen fuel cell vehicle commercialization. Fuel retailers lack the financial incentive to build new hydrogen stations, because demand is likely to remain too low in the near-term to achieve an adequate return on investment. Consumers, however, need reassurance that

[64] In 2004 dollars.

convenient fueling infrastructure will be available, or they will not purchase fuel cell vehicles. To be successful, the commercial launch of fuel cell vehicles must be synchronized with the availability of enough retail-ready hydrogen fueling stations to satisfy customer needs in these areas.

The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) has recognized the importance of this challenge and has taken on "accelerating the market penetration and early adoption of hydrogen and fuel cell technologies and their supporting infrastructure" as a strategic priority. The February 25 – 26, 2010, IPHE Infrastructure Workshop explored the market implementation needs for hydrogen fueling station development and examined international plans, activities and strategies for hydrogen vehicles and infrastructure.[65] This interactive workshop was coordinated by IPHE, DOE, and the California Fuel Cell Partnership (CaFCP), to engage more than 80 professionals representing a wide variety of stakeholders and expertise in, developing creative and practical solutions for establishing hydrogen infrastructure in the near-term. Responding to the strategic issues and information gaps discussed during the workshop, the Program plans to conduct a rigorous assessment of challenges and needs—both from an R&D and business case perspective—to develop the appropriate strategy for vehicle and infrastructure rollout.

[65]IPHE Infrastructure Workshop, February 25 – 26, 2010, Sacramento, CA. (Workshop proceedings are available at www.iphe.net/docs/Events/iphe_infrastructure_workshop_feb2010.pdf; additional documents from the workshop can be found at www.iphe.net/workshops.html.)

V. Program Funding

The following figures show FY 2008 – FY 2010 appropriations for DOE fuel cell and hydrogen activities. Figure V.2 shows EERE funding for hydrogen and fuel cells broken out into key activities.

	FY 2008 Approp.	FY 2009 Approp.	FY 2010 Approp.
EERE Fuel Cell Technologies	206,241	195,865	170,297
Fossil Energy	14,891	20,151	13,970
Nuclear Energy	9,668	7,340	5,000
Basic Science	36,483	38,284	38,053
DOE Hydrogen & Fuel Cells Total	**267,283**	**261,640**	**227,320**

Figure V.1. *DOE appropriations for hydrogen and fuel cell activities (excludes funding for megawatt-scale, non-hydrogen solid-oxide fuel cells that are currently funded under the Solid State Energy Conversion Alliance).*

	FY 2008 Approp.	FY 2009 Approp.	FY 2010 Approp.
Fuel Cell Stack Component R&D	42,344	61,133	61,170
Transportation Fuel Cell Systems	7,718	6,435	3,116
Dist. Energy Fuel Cell Systems	7,461	9,750	11,155
Fuel Processor R&D	2,896	2,750	168
Hydrogen Production and Delivery R&D	38,607	10,000	14,601
Hydrogen Storage R&D	42,371	57,823	31,149
Market Transformation	-	4,747	15,005
Safety, Codes & Standards	15,442	12,238*	8,653
Education	3,865	4,200*	2,000
Systems Analysis	11,099	7,520	5,408
Technology Validation	29,612	14,789*	13,005
Manufacturing R&D	4,826	4,480	4,867
EERE Hydrogen & Fuel Cells Total	**206,241**	**195,865**	**170,297**

Figure V.2. *EERE hydrogen and fuel cells appropriations. All activities shown are funded through the Fuel Cell Technologies Program unless otherwise noted. (*Funded through the Vehicle Technologies Program in FY 2009.)*

VI. External Input, Review, and Evaluation

The Program uses a number of mechanisms for obtaining external input, review, and evaluation. The National Academy of Sciences (NAS) conducts biannual reviews of DOE's R&D progress under the FreedomCAR and Fuel Partnership. The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) provides technical and programmatic advice to the Secretary of Energy on hydrogen and fuel cell research, development, and demonstration efforts. The Government Accountability Office (GAO) has also reviewed the Program and released its report in February 2008. In addition to these reviews, the Program receives feedback through its Annual Merit Review and Peer Evaluation Meeting,[66] which involves almost 200 technical experts reviewing individual RD&D projects and includes more than 1,000 participants every year.

The Program periodically revises its planning documents, including the *Hydrogen and Fuel Cells Program Plan* (formerly the *Hydrogen Posture Plan)* and the *Multi-Year Research, Development, and Demonstration Plan* to incorporate the recommendations of these reviews, as well as updates based on technological progress, programmatic changes, and policy decisions. Updates for these plans were initiated in 2010. Updates to the *Multi-Year Research, Development, and Demonstration Plan* take into account the most recent progress compared to targets and a reassessment of the targets themselves, based on requirements to be competitive with both incumbent and advanced technologies.

VI.1 Reviews and Reports by the National Academies

The National Academies' National Research Council (NRC) has provided valuable input to the Program. The NRC reviews and reports have acknowledged the progress of the Program and the FreedomCAR and Fuel Partnership and have affirmed the validity of their overall direction and strategy.

VI.1.1 Reviews of the FreedomCAR and Fuel Partnership

Reviews by the NRC assess progress in each of the research and program management areas as well as the responses of program management to recommendations made in prior reports.

In 2008, the NRC completed its Phase II Review of the Partnership. Key comments in the resulting report[67] included:

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

[67] The full report is available from: www.nap.edu/catalog.php?record_id=12113.

- "The FreedomCAR and Fuel Partnership is well planned, organized, and managed. It is an excellent example of an effective industry/government cooperative effort."
- "There has been significant progress in most areas since the Phase I report, and the committee commends management on its thorough and generally receptive responses to the recommendations in that report."
- "... [W]ith increased national interest in reducing greenhouse gas emissions, the research efforts of the Partnership are more needed than ever before."
- "DOE should accelerate the development and validation of tools that can be used to model propulsion system and vehicle technologies and fuels and determine their potential impact on the overall Partnership goals of reducing petroleum use and air pollutant and greenhouse gas emissions."
- "DOE and the Partnership should develop a long-range plan for technology validation that continues to at least 2015 ... DOE management should maintain adequate support for technical validation as it is essential to the overall Partnership. This support should be balanced and cover both the vehicles themselves and the fuel infrastructure needed."

In 2010, the NRC completed its Phase III review of the Partnership. Key outcomes of the review are documented in the report,[68] in which the committee:

- Expressed an overall opinion that the Partnership "is effective in progressing toward its goals," and that "there is evidence of solid progress in essentially all areas, even though substantial barriers remain."
- Recognized "three primary alternative pathways" for reducing petroleum consumption and greenhouse gas emissions in the transportation sector: (1) improved internal combustion engine vehicles coupled with greater use of biofuels, (2) expanded use of PHEVs and BEVs, and (3) hydrogen fuel cell vehicles.
- Expressed concern over the "major swings in funding" for hydrogen and fuel cell activities, and "strongly urges the DOE to maintain hydrogen-related funding at no less than the current level" to maintain a balance between near-term and long-term technologies.
- Identified cost, performance, and production, and infrastructure barriers and recognized the need for government involvement in precompetitive R&D of near- and long-term technologies.
- Suggested that the Partnership would be more effective with a more engaged Executive Steering Group (ESG), noting that the ESG has not met in two years.

[68] The full report is available from: http://www.nas.edu/morenews/20100630.html .

- Commended DOE for "substantial progress on the development and application of systems analysis tools" and recommends an increased focus on cradle to cradle (lifecycle) analyses.
- Stated that, "Onboard hydrogen storage is a key enabler for fuel cell vehicles and is one of the most critical parts of the program … The physical storage of hydrogen on vehicles as compressed gas (and to a lesser extent liquid hydrogen) has emerged as the technology path for the early introduction of fuel cell vehicles"—and recommended that DOE "consider management of a long-term/short-term joint portfolio."
- Highlighted safety as an important cross-cutting issue, noting that "addressing safety is an essential federal role. Most of the safety program would not happen without government funding and all of the work is appropriate."

VI.1.2 Specific Recommendations from the NRC Reviews and DOE Actions

Some specific recommendations from the Phase II and III reviews of the FreedomCAR and Fuel Partnership and actions taken by the Program include the following:[69]

- *"The Partnership should conduct sensitivity analyses on key fuel cell targets to determine the trade-offs and tolerances in engineering specifications allowable while still meeting fuel cell vehicle engineering requirements."* Sensitivity and risk analyses have already been employed by the Program through its Systems Analysis and Systems Integration activities. Although the Program aims to meet all key targets, its overarching goal is to advance the technology to allow developers to bring competitive products to market. Therefore, failure to meet a particular target does not necessarily mean that commercialization goals cannot be attained; design innovations, cost reductions, and/or operational accommodations can offset a shortfall in a particular area. As long as the right mix of targets has been adequately addressed, it will be up to the efforts of private industry, addressing market forces, to determine which adjustments and accommodations to make in order to enable commercialization.
- *"DOE should continue its studies of the transition to hydrogen, extending them to 2030-2035, a period during which the number of hydrogen vehicles in use could increase rapidly, and use the results of these studies as a basis for evaluating the potential roles of different transitional supplies of hydrogen …"* A key focus area for the Program's

[69] Full documentation of DOE actions and responses to NAS recommendations in the review of the Program's RD&D plan and the FreedomCAR and Fuel Partnership can be found in the following reports:

- *Actions and Evidence Supporting Implementation in Response to: Recommendations by the National Research Council and the National Academy of Engineering in its Report: "Review of the Research Program of the FreedomCAR and Fuel Partnership"*
- *Actions and Evidence Supporting Implementation in Response to: Recommendations by the National Research Council and the National Academy of Engineering in its Report: "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs"*

These are internal reports. CD copies, with supporting documents, are available upon request.

Systems Analysis efforts is analysis of options for hydrogen infrastructure development. DOE commissioned a study by the NAS that addresses transition needs from 2020 to 2050, which estimated the maximum practicable number of FCVs that could be deployed in U.S. by 2020 and beyond, together with the investments and government actions needed (see Section VI.1.3 for more information on this report). Additionally, the Program has funded a study on hydrogen infrastructure options for FCVs in the 2020 timeframe and beyond.

- *"DOE should establish a program to address all end-to-end safety aspects as well as codes and standards. Such a program could be viewed as an extension of the current quantitative risk analysis activity, which is focused on filling stations. This task should be adequately funded and expanded. The priority for expansion should go to (1) the vehicle and (2) the fuel distribution system."* With its energy partners, the Program is expanding quantitative risk analysis efforts to include on-site production, delivery infrastructure such as pipelines, liquid hydrogen storage, as well as distribution systems and home refueling. Regarding vehicles, original equipment manufacturers (OEMs) and final stage integrators/manufacturers are required to certify that all production vehicles are in compliance with federal safety requirements. The Department of Transportation has regulatory authority over vehicle safety under the Federal Motor Vehicle Safety Standards (FMVSS). DOT requirements have embedded risk assessment methodologies with which vehicle manufacturers must comply.
- *"DOE should continue to disseminate the results of the technical validation activity to supporting organizations outside the Partnership in order to promote widespread innovation and competition."* Over the last three years, DOE has reported the results of the Technology Validation activity at public forums such as the Fuel Cell Seminar, the National Hydrogen Association's annual conferences, the Fuel Cell Durability & Performance Conference, the Fuel Cell Expo and JHCF Conference (in Japan), the 23rd International Electric Vehicle symposium (EVS-23), etc. and plans to continue to do so. Various papers have also been published, such as progress reports published by NREL. Additionally, every year during the Hydrogen Program's Annual Merit Review, each of the learning demonstration projects presented to stakeholders.
- *"The DOE, with input from the fuel cell technical team, should evaluate, and in selected cases accelerate, the timing of the "go/no-go" decisions when it is evident that significant technological progress has been made and adopted by the OEMs."* DOE will review and evaluate the milestones in its *Multi-Year Research, Development and Demonstration Plan* (MYRDDP) and, with input from the fuel cell technical team, accelerate timing of go/no-go decisions in cases where significant technological progress has led to OEM adoption.

- *"The hydrogen storage program … should continue to be funded, especially the systems-level work in the Hydrogen Storage Engineering Center of Excellence. Efforts should also be directed to compressed gas-storage to help achieve weight and cost reductions while maintaining safety."* DOE plans to continue funding of the Engineering Center of Excellence through the end of the planned activities. In addition, projects will continue in the onboard hydrogen storage materials area, particularly in coordination with DOE's Office of Science, and an increased emphasis on compressed gas storage has begun.
- *"… [T]he current materials [for hydrogen storage]are not close to the long-range goals of the Partnership. Onboard hydrogen storage R&D risks losing out to near-term applications for future emphasis and funding. The management of a long-term/short-term joint portfolio should be given consideration."* DOE balances the project portfolio as needed. For example, re-balancing of the portfolio could occur in response to technical progress that is made or due to input from stakeholders that request that DOE emphasize areas of more immediate needs, such as materials for compressed gas storage. The review of the project portfolio is an ongoing activity within DOE.
- *"The Partnership should consider conducting a workshop to ensure that all potentially attractive high-temperature thermochemical cycles [for hydrogen production] have been identified, and it should carry out a systems analysis of candidate systems to identify the most promising approaches …"* DOE conducts regular meetings of the thermochemical hydrogen production working group to review progress and to recommend future directions. From these meetings and reviews, over 350 unique cycles have been analyzed, with three cycles identified as the most promising—the copper-chloride cycle, the ferrite cycle, and the sulfur-ammonia cycle. Additional workshops will be considered as necessary.
- *"The hydrogen compatibility (including embrittlement) program should be continued. The Partnership should have experts in hydrogen embrittlement review the operating conditions and materials in the high-pressure delivery and refueling stations…*The DOE Safety, Codes and Standards and Hydrogen Delivery subprograms include efforts in materials compatibility to develop efficient and reliable test methods using experts from U.S. industry, national laboratories, and universities, along with international experts. In addition, the Program participates in the Hydrogen Pipeline Working Group, which also addresses this recommendation.

VI.1.3 NAS Reports: "Transitions to Alternative Transportation Technologies—A Focus on Hydrogen" and "Transitions to Alternative Transportation Technologies—Plug-In Hybrid Electric Vehicles"

In 2008, the NRC's Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies released the report, "Transitions to Alternative Transportation Technologies—A Focus on Hydrogen," which was required by EPACT section 1825. Its key findings include:

- Concentrated efforts by private companies, together with the U.S. FreedomCAR Fuel & Partnership and other government-supported programs around the world, have resulted in significant progress toward a commercially viable hydrogen fuel cell vehicle since the publication in 2004 of the NRC report *The Hydrogen Economy*.
- By 2050, a portfolio of technologies, including FCVs, hybrids, advanced vehicle technologies, and biofuels, have the potential to eliminate the domestic use of petroleum in the light-duty vehicle sector and to reduce greenhouse gas emissions from light-duty vehicles to 20 percent of current levels.
- By 2020, the committee estimates the maximum practicable number of hydrogen fuel cell vehicles on the road to be around two million. This number could grow rapidly to about 60 million by 2035 and 200 million by 2050.
- To accelerate the penetration of FCVs, strong government policies will be required, and the government cost to support a transition to FCVs for the period from 2008 to 2023 is estimated to be $55 billion (this amounts to slightly more than $3.5 billion/year—the committee compared this value to ethanol subsidies, which were $2.6 billion in 2006 and are expected to grow to $15 billion/year by 2015).
- RD&D spending by the government from 2008 to 2023 is estimated to be $5 billion, which is about 30 percent of a total estimated spending of $16 billion.
- Synergies exist between the transportation sector and the electric power sector that could accelerate the potential oil and CO_2 reduction benefits from the use of hydrogen in both sectors.

Following its 2008 report on hydrogen, in 2010 the same NRC committee released the report, "Transitions to Alternative Transportation Technologies—Plug-In Hybrid Electric Vehicles."[70] This report was required by EPACT section 1825 to compare hydrogen fuel cell vehicles to alternate advanced vehicle technologies. A key conclusion of the report is that a diverse approach to RD&D and market transformation—comprising a portfolio that includes efforts in hydrogen, batteries, and biofuels—will "enable the greatest reduction in oil use."

[70] The full report is available from: http://books.nap.edu/catalog.php?record_id=12826.

VI.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, formerly known as the *Hydrogen Posture Plan* (the newest edition will be called the *Hydrogen and Fuel Cells Program 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. The report shall be transmitted along with the President's budget proposal." The Department submitted the 2009 biennial report, covering the period from August 8, 2007 to August 7, 2009, outlining the recommendations by the committee and the Department's responses.

Since the writing of the 2009 biennial report, HTAC has offered several additional recommendations to the Secretary. The Department has implemented some of these recent recommendations and is initiating program activities that address others. The following are examples of recent HTAC recommendations, including DOE responses, where appropriate:

- *"Seek increased communication and regular exchange among programs within the office of Energy Efficiency and Renewable Energy, and with other DOE offices that have parallel or compatible research efforts. In smart grid, renewable generation, large-scale energy storage, carbon sequestration, or low carbon fuels, hydrogen and fuel cells have an important role to play. Frequent communication will lead to better planning and better use of resources … Seek increased collaboration with the Department of Defense, which has a strong interest in fuel cells for the capability they bring to the battlefield and the economy and the flexibility they bring to the domestic base structure."* The Fuel Cell Technologies Program leads robust communication and coordination efforts with other federal hydrogen and fuel cell activities, both intra-agency and inter-agency. These efforts involve coordination and collaboration with more than 10 federal agencies, including the Department of Defense (DoD), NASA, the Department of the Interior, the U.S. Postal Service, and the Department of Commerce. Particular emphasis has been placed on activities with the DoD, due to its high level of activity and funding for hydrogen and fuel cells. The Interagency Working Group on Hydrogen and Fuel Cells meets monthly.

- *"Conduct an evaluation of U.S. fuel cell manufacturing capability. Rumored bottlenecks in U.S. production would retard commercialization and also increase the risk that new plants and equipment will be built outside the U.S."* The Department is implementing a series of analysis activities to gather information and develop tools needed by the industry to grow their manufacturing processes in step with increasing market demand.
- *"Consider large, high-visibility demonstrations along the lines of Japan's Hydrogen Town in developing your FY 2012 budget. Activities in the States, such as California's vehicle deployment program, provide partnership opportunities that would leverage federal dollars."* The Department agrees with HTAC that highly visible demonstration projects provide significant benefits not only to help accelerate the development of technologies but also to serve as educational and training opportunities for the public and government officials. The Program currently is demonstrating key technologies to validate performance in integrated systems under real-world conditions with the Learning Demonstration Project. The Learning Demonstration is one of the largest demonstrations in the world, with more than 140 fuel cell vehicles and 23 fueling stations demonstrated. The Program is also implementing Recovery Act projects to enable deployment of up to 1,000 fuel cells for early applications, which further addresses this recommendation. The Program continues to work with international and domestic partners to strategically plan for hydrogen infrastructure development projects and demonstrations. These types of market transformation activities are essential for preparing markets for larger-scale implementation of hydrogen and fuel cell technologies.
- *Consider a large scale project to demonstrate the production and use of hydrogen in support of solar or wind power. A 2009 National Renewable Energy Laboratory study suggests hydrogen can be a significant energy storage option as the electric power grid accommodates an increasing amount of intermittent generation."* The Department is applying some of the lessons-learned from the 2003 – 2010 NREL wind-to-hydrogen project for a new project planned in partnership with the Office of Naval Research and the Hawaii Electric Light Company to implement a large-scale renewable energy demonstration on the Big Island of Hawaii. The project will utilize excess energy from geothermal and wind resources to produce hydrogen for grid power, emergency backup power, and fuel for transit buses. Multiple by-products such as fertilizer and oxygen will be evaluated to improve the overall value proposition. The project is expected to be operational within one year. A privately funded large-scale project has recently been initiated and DOE will evaluate the results before determining whether a large-scale DOE project is of value.

VI.3 Review by the Government Accountability Office

At the request of the House Committee on Science and Technology, the Government Accountability Office (GAO) conducted a review of DOE's hydrogen and fuel cell activities. Specifically, GAO assessed the extent to which DOE has: (1) made progress in meeting R&D targets; (2) worked with industry to set and meet R&D targets; and (3) worked with other federal agencies to develop and demonstrate hydrogen technologies.

To obtain a thorough understanding of DOE's activities, the GAO reviewed documents and interviewed DOE program managers, national laboratory scientists, company and industry association executives, independent experts, and state government officials. The GAO report, "*Hydrogen Fuel Initiative: DOE Has Made Important Progress and Involved Stakeholders but Needs to Update What It Expects to Achieve by Its 2015 Target (GAO-08-305),"*[71] was released on February 11, 2008.

The GAO report commended DOE for making important R&D progress, for effectively aligning its R&D priorities with industry, and for working with other agencies in coordinating activities and facilitating scientific exchanges. The report stated that DOE and industry officials attribute this progress to DOE's (1) planning process that involved industry and university experts from the earliest stages; (2) use of annual merit reviews, technical teams, centers of excellence, and other coordination mechanisms to continually involve industry and university experts to review the progress and direction of the program; (3) emphasis on both fundamental and applied science, as recommended by independent experts; and (4) continued focus on such high priority areas as hydrogen storage and fuel cell cost and durability. The GAO recognized DOE's increased efforts in stationary and portable fuel cell technologies—and the role that these technologies may play in paving the way for the commercialization of fuel cell vehicles. The GAO also acknowledged the creation of the Hydrogen and Fuel Cell Interagency Task Force to coordinate efforts at the policy level.

The GAO report stated that difficult technical challenges lie ahead, particularly in hydrogen storage and delivery, fuel cell cost and durability, and hydrogen infrastructure deployment. The GAO recommended that the *Hydrogen Posture Plan* be updated to provide an overall assessment of what DOE reasonably expects to achieve by its technology readiness date. GAO also recommended that the report include a discussion of how these expectations may differ from previous program plans and a projection of anticipated R&D funding needs.

The Program has either already implemented or is in the process of implementing the GAO's recommendations. The Program is updating its planning documents to reflect the progress made in all areas of the Program and any changes to the activities, milestones, deliverables, and timeline.

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[71] *Hydrogen Fuel Initiative: DOE Has Made Important Progress and Involved Stakeholders but Needs to Update What It Expects to Achieve by Its 2015 Target (GAO-08-305),* Government Accountability Office, February 2008, www.gao.gov/new.items/d08305.pdf.

VII. Future Activities and Updates to Strategic Plans

The Program periodically updates its planning documents—including the *Hydrogen and Fuel Cells Program Plan* and the Office of Fuel Cell Technologies' *Multi-year Research, Development, and Demonstration Plan*—to reflect changes in the status of the technologies and in the evolving 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.

In its approach to demonstration and deployment activities for FCVs and hydrogen infrastructure, the Program intends to conduct a rigorous assessment of the challenges and needs involved in developing a hydrogen infrastructure and enabling early vehicle markets—both from an R&D and business-case perspective—rather than directly funding increased demonstrations of stations and vehicles. Ongoing assessments of international plans, activities and strategies for hydrogen vehicles and infrastructure will play a fundamental role in the Program's activities in this area. In particular, the Program has initiated information-sharing and analysis activities with Germany and Japan since those countries' announcements of substantial plans for developing hydrogen infrastructure. All of this work will continue to build on the results of an international workshop[72] held in 2010 to determine optimum strategies for developing a hydrogen infrastructure.

The Program will continue to pursue a broad portfolio of R&D and market transformation activities for fuel cell applications across multiple sectors, using a variety of technical approaches and diverse sources of fuel. These efforts will span the full spectrum of technology readiness: from early market applications that are already viable or are becoming viable, such as forklifts, backup power, and portable power applications; to mid-term markets that are expected to emerge in the next few years, such as residential combined-heat-and-power systems, auxiliary power units, fleet vehicles, and buses; and markets that are expected to emerge in the 2015 – 2020 timeframe, including light-duty passenger vehicles and other transportation applications.

With this approach, the Program will continue to pursue activities to stimulate the markets for fuel cells as they achieve technology readiness, supporting more markets—and larger markets—as more technologies become viable. Supporting these markets will not only help

[72] IPHE Infrastructure Workshop, February 25 – 26, 2010, Sacramento, CA. (Workshop proceedings are available at www.iphe.net/docs/Events/iphe_infrastructure_workshop_feb2010.pdf; additional documents from the workshop can be found at www.iphe.net/workshops.html.)

achieve the economic, environmental, and energy security benefits that fuel cells provide in those specific applications, but it will complement the Program's longer-term R&D efforts by helping to increase current sales and manufacturing volumes, providing essential cost reductions—through economies of scale—for many of the same technologies that will be used in longer-term applications. Supporting earlier markets can also reduce many non-technological barriers to the deployment of hydrogen and fuel cell technologies and lay the groundwork for the larger infrastructure and supply base that will be needed for fuel cell vehicles.

The milestones and timetable for the Program's activities are shown in figure VII.1.

Figure VII.1 — Future Plans: Examples of Key Milestones

Fuel Cell Systems

1. **2013:** Develop a fuel cell system for portable power applications consumer electronics (<250 W) with an energy density of 1,000 Wh/L
2. **2015 :** Develop a 60% peak-efficient, direct hydrogen fuel cell power system for transportation applications, with 5,000-hour durability, that can be manufactured for $30/kW (at high volumes)
3. **2015:** Develop a fuel cell system for APUs with specific power of 40W/kg and power density of 35 W/L

Hydrogen Production[73]

Renewable Resources

1. **2015:** Develop technology to produce hydrogen through distributed reforming of renewable liquid fuels at refueling stations for a cost of <$3.80/gge at the pump
2. **2015:** Develop technology for producing hydrogen at centralized facilities integrating wind power and electrolysis, for a cost of <$3.10/gge at the plant gate
3. **2015:** Develop technology for distributed hydrogen production from electrolysis at a cost of <$3.70/gge at the pump
4. **2015:** Develop technology for hydrogen production from biomass gasification at centralized facilities, for a cost of <$1.60/gge at the plant gate
5. **2015:** Demonstrate plant-scale-compatible solar-driven high-temperature thermochemical hydrogen production for a cost of $6.00/gge at the plant gate
6. **2020:** Demonstrate plant-scale compatible photobiological water splitting systems to produce hydrogen at an energy efficiency of 5% (solar-to-hydrogen)
7. **2020:** Demonstrate plant-scale compatible photoelectrochemical water splitting systems to produce H_2 at an energy efficiency of 10% (solar-to-hydrogen)

[73] All production targets are based on modeled projections that assume high-volume production and widespread deployment of the technologies. "At the pump" cost targets include delivery, on-site storage, compression, and dispensing, but do not include taxes; "at the plant gate" cost targets do not include delivery, on-site storage, compression, dispensing, or taxes.

Hydrogen Delivery

1. **2015:** Reduce the cost of compression, storage, and dispensing at refueling sites to less <$0.80/gge.
2. **2015:** Verify targeted cost and performance for compression technologies
3. **2017:** Reduce the cost of transporting hydrogen from central production facilities to refueling sites to <$0.90/gge
4. **2020:** Reduce the overall cost of delivering hydrogen from centralized production facilities (at the plant gate) to the point of use (including transportation, on-site storage, on-site compression, and dispensing) to <$1/gge

Hydrogen Storage

1. **2015:** Develop and verify on-board storage systems achieving capacity of 5.5% by weight and an energy density of 1300 Watt-hours/liter

Manufacturing R&D

1. **2013:** Reduce the manufacturing cost of membrane electrode assemblies for PEM fuel cells by 25%, relative to 2008 baseline
2. **2015:** Reduce the cost of PEM fuel cell stack assembly and testing by 50%, relative to 2008 baseline

Technology Validation

1. **2014:** Validate stationary fuel cell system that co-produces hydrogen and electricity at 40% efficiency, with 40,000-hour durability
2. **2015:** Validate fuel cell vehicles achieving 5,000-hour durability (service life of vehicle) and a 300-mile driving range between fueling

Education, Safety, Codes, and Standards

1. **2015:** Conduct a quantitative risk assessment study to address and incorporate indoor refueling requirements to be adopted by code development organizations (National Fire Protection Association and International Code Council)

Systems Analysis

1. **2015:** Provide analysis of Program milestones and technology readiness goals—including risk analysis, independent reviews, financial evaluations, and environmental analysis—to identify technology gaps and risk mitigation strategies