January 2009

Hydrogen and Fuel Cell Activities, Progress, and Plans

Report to Congress

Preface

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

> **"(a) … 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;
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> (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;
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> (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
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> (8) any updates to strategic plans that are necessary to meet the goals described in paragraph (4).

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Executive Summary

The Department of Energy (DOE or "the Department") is conducting a comprehensive and focused program that fulfills the provisions of Title VIII of the Energy Policy Act of 2005 (EPACT). The Department'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.

The Program was accelerated in fiscal year (FY) 2004, when a number of activities in hydrogen and fuel cell research and development (R&D) within DOE were expanded and integrated into a coordinated effort, to implement the President's Hydrogen Fuel Initiative (HFI). Since that time, the Department has dedicated $1.2 billion (FY 2004 – FY 2008), fulfilling the President's five-year funding commitment to the initiative, including the competitive selection of nearly $830 million[1] (subject to appropriations) in research, development, and demonstration (RD&D) projects (nearly $1.2 billion with private sector cost-sharing), and has made significant progress in:

- Critical path technologies —
  - Reducing the projected cost of hydrogen production from distributed natural gas (assuming widespread deployment) from $5 to $3 per gallon gasoline equivalent (gge) (work is complete; achieved upper range of the Program's 2015 hydrogen production cost target: $2 – $3/gge);[2]
  - Reducing the projected, high-volume manufacturing cost of automotive fuel cell systems from $275/kW in 2002 to $73/kW in 2008[3] and improving the projected durability of fuel cell systems in vehicles from 950 hours in 2006 to 1900 hours in 2008.[4] The Program's 2015 targets are $30/kW and 5000-hour durability (approximately 150,000 miles of driving), which will enable fuel cells to be competitive with current gasoline internal combustion engine systems.
  - Identifying new materials that have the potential to increase hydrogen storage capacity by more than 50 percent,[5] and developing and demonstrating a novel "cryo-compressed" tank concept;
- Reducing the projected cost of hydrogen production using renewable-based technologies—e.g., electrolysis and distributed reforming of bio-derived liquids (ethanol, sugars)—from $5.90 to $4.80 per gge (assuming widespread deployment);[6]

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[1] U.S. Department of Energy Hydrogen Program Record #8001, www.hydrogen.energy.gov/program_records.html. The $830 million figure does not include funding that the Program contributed to competitively selected projects through the Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) Program.

[2] *Distributed Hydrogen Production From Natural Gas: Independent Review,* National Renewable Energy Laboratory, October 2006, www.hydrogen.energy.gov/pdfs/40382.pdf. All figures for production cost status and targets are in 2005 dollars.

[3] U.S. Department of Energy Hydrogen Program Records #5005 and #8019, www.hydrogen.energy.gov/program_records.html. The costs of $275/kW and $73/kW are in 2002 and 2008 dollars, respectively. The 2015 target of $30/kW is based on 2002 dollars.

[4] K. Wipke, "Completed Learning Demonstration Composite Data Products as of December 1, 2006," National Renewable Energy Laboratory, December 2006, slide 5, www.nrel.gov/hydrogen/docs/cdp/41090.ppt; and K. Wipke, et al., "Fall 2008 Composite Data Products," National Renewable Energy Laboratory, September 2008, slide 4, www.nrel.gov/hydrogen/docs/cdp/cdps_fall_2008.ppt.

[5] U.S. Department of Energy Hydrogen Program Record #5037, www.hydrogen.energy.gov/program_records.html.

[6] U.S. Department of Energy Hydrogen Program Record #5040, www.hydrogen.energy.gov/program_records.html; and "Low-Cost, High-Pressure Hydrogen Generator," *2007 Annual Progress Report,* DOE Hydrogen Program, 2007, www.hydrogen.energy.gov/annual_progress.html.

- Developing technologies for the production of hydrogen from coal that will enable increased efficiency, reduced cost, and improvements in hydrogen purity;
- Improving the efficiency and durability of fuel cells for distributed energy generation;
- Validating the status of the technology by demonstrating 122 fuel cell vehicles and 16 refueling stations.[7]

This progress has kept the Program on track to meet critical path technology goals by 2015 and will enable industry to make decisions regarding commercialization of hydrogen fuel cell vehicles and fueling infrastructure in the 2020 timeframe. However, some targets and milestones relating to non-critical path technologies—e.g., centralized hydrogen production and delivery systems—have slipped.

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. Substantial progress has been made in these areas, including:

- Characterizing the behavior of hydrogen and its compatibility with materials to provide valuable information to stakeholders regarding the safe use of hydrogen;
- Conducting R&D needed to facilitate the development of technically sound codes and standards;
- Supporting the development and harmonization of domestic codes and standards, and coordinating the harmonization of international codes and standards;
- Providing up-to-date educational resources, including a hydrogen education tool for first responders.

The Department has also addressed the sections of EPACT that deal with program planning and external coordination. Actions taken include:

- Issuing the *Hydrogen Posture Plan*,[8] a coordinated plan for the Department's Hydrogen Program that fulfills section 804 of EPACT;
- Establishing and convening the Hydrogen and Fuel Cell Technical Advisory Committee, which fulfills section 807 of EPACT;
- Establishing and convening the Hydrogen and Fuel Cell Interagency Task Force, which fulfills section 806 of EPACT.

All of the activities described above "support the transition of primary industry to a fully commercialized hydrogen economy," as specified in section 811(a)(2) of EPACT. In addition, in order to achieve critical reductions in cost, the Program has initiated new activities in market transformation and manufacturing R&D. The Program's market transformation efforts aim to grow the early markets for hydrogen and fuel cell technologies, which will enable industry to achieve the economies of scale that are needed for significant cost reductions. A key element of this effort involves encouraging and facilitating early adoption by federal agencies. The Program's Manufacturing R&D activity aims to reduce costs through

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[7] K. Wipke, et al., "Controlled Hydrogen Fleet and Infrastructure Demonstration Project, Fall 2008 Composite Data Products," National Renewable Energy Laboratory, September 2008, www.nrel.gov/hydrogen/docs/cdp/cdps_fall_2008.ppt.

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

improvements in manufacturing technologies and processes. Progress made in both the market transformation and manufacturing R&D efforts will also assist in the growth of a domestic supplier base.

In DOE's assessment, although significant progress has been made, fuel cell cost is still too high and durability still too low to enable industry to meet the deployment goal of 100,000 hydrogen-fueled vehicles by 2010, as specified in EPACT section 811(a)(4). Designs for vehicles manufactured in 2010 would need to be locked-in now, but automakers cannot provide vehicles based on current technology at an affordable cost or with a reasonable warranty. For example, a 2008 independent study estimated that the high-volume manufacturing cost of automotive fuel cell systems (using current technology and assuming 500,000 units per year) would be $73/kW, which equates to almost $6000 for an 80-kW system. This current technology would be more than twice as expensive as internal combustion engine systems. And, based on the highest demonstrated durability to date, fuel cell systems would have a lifespan of approximately 1900 hours, which equates to about 57,000 miles and is still substantially lower than today's estimated vehicular lifespan of 150,000 miles. Furthermore, while fuel cell technology development is currently on track to meet the Program's 2015 technology-readiness targets, it is too early to determine whether industry can achieve the 2020 vehicle deployment goal of 2.5 million hydrogen-fueled vehicles identified in section 811(a)(4). However, analyses conducted by Oak Ridge National Laboratory indicate that such a deployment scenario would not be achieved without substantial supportive policies and incentives.[9]

The DOE Hydrogen 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 Department established the FreedomCAR and Fuel Partnership (the Partnership),[10] which includes the U.S. Council for Automotive Research (whose members are Ford Motor Company, General Motors Corporation, and Chrysler LLC), five major energy companies (BP, Chevron, ConocoPhillips, ExxonMobil, and Shell), and two electric utilities (Southern California Edison and DTE Energy). The Partnership examines the pre-competitive, high-risk research needed to develop the technologies for deploying vehicles and infrastructure that will reduce the Nation's dependence on imported oil and minimize harmful emissions. In addition, the Department's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project[11] has brought together automobile and energy companies to provide data on the status of hydrogen and fuel cell systems operating in real-world environments and to assess technology readiness. Analyses have been conducted to support the Program's technology validation efforts, to examine a variety of potential deployment scenarios, and to assess the costs and effectiveness of potential policy options.

Hydrogen is a key component in a portfolio of options for powering vehicles that also includes biofuels and plug-in hybrids. To reduce oil use in the transportation sector, the Department is pursuing all of these options and recognizes the synergies in their development. For instance, near-term progress in biofuels production can play a significant role in the longer-term development of biomass-to-hydrogen pathways, and the advanced battery technologies developed for plug-in hybrid vehicles can be incorporated into fuel cell vehicle platforms. Therefore, the Department is working toward expanding the vehicle learning

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[9] 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.

[10] For more information on the Partnership, see: www1.eere.energy.gov/vehiclesandfuels/about/partnerships/freedomcar/index.html.

[11] 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.

demonstrations to include plug-in batteries and biofuels in the vehicle platforms. In fact, a plug-in hybrid fuel cell vehicle was recently added to the current National Hydrogen Learning Demonstration.

The Program employs a number of mechanisms for external review and evaluation. The Department commissioned the National Academies of Science and Engineering (NAS) to review the Hydrogen Program's RD&D plan, and has implemented almost all of the NAS's ensuing recommendations. The NAS also 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 on hydrogen research, development, and demonstration efforts. HTAC submitted the first of its biennial reports to the Secretary on October 26, 2007. In addition, at the request of the House Science Committee, the Government Accountability Office (GAO) reviewed the progress made by the Program. 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),"*[12] was released on February 11, 2008.

The Program's Annual Merit Review and Peer Evaluation Meeting[13] also provides feedback from over 150 technical experts on individual RD&D projects. In addition, the Department has established the Hydrogen and Fuel Cell Interagency Task Force and Interagency Working Group to provide a forum for coordination and cooperation in hydrogen and fuel cell technology research, development, demonstration, and deployment. The Program periodically revises the *Hydrogen Posture Plan* and all sub-program RD&D plans to reflect updates from these reviews and coordination activities, as well as technological progress, programmatic changes, and policy decisions.

[12] *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.

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

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

Since the launch of the Hydrogen Fuel Initiative (HFI) in FY 2004, the Department of Energy (DOE or "the Department") has:

- Pursued (and continues to pursue) a broad range of activities to overcome the technological and non-technological barriers facing the commercialization of hydrogen and fuel cells. These activities include: Hydrogen Production, Delivery, and Storage; Fuel Cells; Manufacturing R&D; Technology Validation; Safety, Codes & Standards; Education; and Systems Analysis. In carrying out these activities, the Department has dedicated approximately $1.2 billion[14] (FY 2004 – FY 2008), including competitively selecting nearly $830 million[15] in projects (nearly $1.2 billion with private sector cost-sharing), subject to appropriations.
- Expanded the Department's partnership with Chrysler, Ford, and General Motors to include major energy companies (ExxonMobil, ConocoPhillips, Chevron, BP, and Shell) and two electric utilities (Southern California Edison and DTE Energy). DOE's partners in this collaboration (known as the FreedomCAR and Fuel Partnership) are helping the Program evaluate research results and establish the technical requirements for hydrogen and fuel cell technology development.[16]
- Established a National Hydrogen Storage Project with four centers of excellence and new independent projects—composed of industry, university, and federal laboratory partners—focused on applied R&D to meet the challenging targets for on-board vehicular hydrogen storage.
- Implemented a systems analysis and integration effort—following a recommendation by the National Academies to integrate all Program elements (hydrogen production, delivery, and storage; fuel cells; safety, codes and standards; and education)—to monitor progress toward technology targets and to conduct the analyses needed to understand costs, define options, evaluate research results, and help balance the Program for the short, medium, and long term.
- Established Program activities to address critical needs in the areas of safety, codes and standards, and education. These activities play an essential role in creating a receptive market environment for hydrogen-based products and systems.

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[14] Congress appropriated $1.159 billion of the $1.267 billion requested by the President for the HFI during FY 2004 – FY 2008. In addition to funding for competitively selected projects in industry, universities, and at the national laboratories, HFI funding included approximately an additional $200 million for R&D at national laboratories and approximately $140 million for congressionally directed projects.

[15] U.S. Department of Energy Hydrogen Program Record # 8001, www.hydrogen.energy.gov/program_records.html. The $830 million figure for competitively selected projects does not include funding that the Program contributed to competitively selected projects through the Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) Program.

[16] 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.

- Launched a manufacturing R&D effort to develop and demonstrate processes and technologies that will reduce the cost of hydrogen production, delivery, storage, and fuel cell systems.
- Established the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC),[17] which advises the Secretary of Energy on the programs and activities conducted under Title VIII of EPACT. HTAC first convened on October 2–3, 2006, and has held seven meetings since then. The committee delivered the first of its biennial reports to the Secretary on October 26, 2007.
- Established the Hydrogen and Fuel Cell Interagency Task Force (ITF), which focuses its 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. The ITF is made up of senior-level agency representatives (at the level of assistant secretary or the functional equivalent) from more than ten agencies. The ITF complements the Interagency Working Group on Hydrogen and Fuel Cells R&D, which meets monthly and was established in 2003 by the Office of Science and Technology Policy under the National Science and Technology Council.
- Conducted five annual reviews of the Program (Annual Hydrogen Program Merit Review and Peer Evaluation).[18] The most recent, held in June 2008, included nearly 300 projects, almost 200 reviewers, and more than 1,000 registered attendees.
- Initiated the International Partnership for the Hydrogen Economy (IPHE),[19] 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.

[17] Hydrogen and Fuel Cell Technical Advisory Committee, www.hydrogen.energy.gov/advisory_htac.html.
[18] Department of Energy Hydrogen Program Annual Merit Reviews, www.hydrogen.energy.gov/annual_review.html.
[19] International Partnership for the Hydrogen Economy, www.iphe.net.

2. Department of Energy Hydrogen Program — Activities under EPACT Title VIII

2.1 Program Overview

The Hydrogen Program is a comprehensive and focused portfolio of activities that address the full 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 Title VIII 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."

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 2.1 provides an overview of the Program's organizational structure.

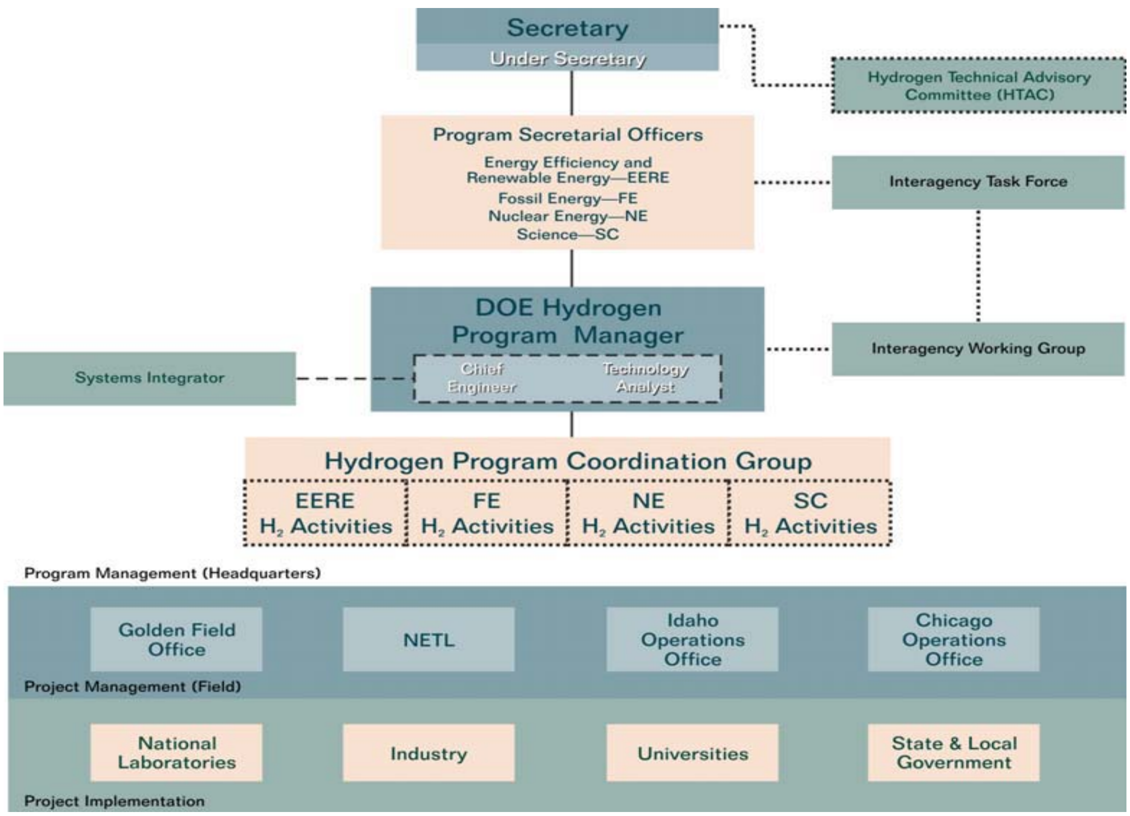

Figure 2.1. *The Hydrogen Program's organizational structure.*

Hydrogen Program activities are documented at a high level in the *Hydrogen Posture Plan;*[20] detailed discussions of the barriers and the current and planned RD&D activities can be found in the hydrogen R&D plans of the individual DOE offices, as follows:

- Office of Energy Efficiency & Renewable Energy (EERE): *HFCIT Multi-Year RD&D Plan*[21]
- Office of Nuclear Energy (NE): *Nuclear Hydrogen R&D Plan*[22]
- Office of Fossil Energy (FE): *Hydrogen from Coal RD&D Plan*[23]
- Office of Science (SC): *Basic Research Needs for the Hydrogen Economy*[24]

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

- The Hydrogen Program's *Annual Merit Review Proceedings*.[25] 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*,[26] which summarizes the year's hydrogen and fuel cell activities and ls for each project.

There are also a number of 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), 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.

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

[21] *Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year RD&D Plan,* U.S. Department of Energy, October 2007, www.eere.energy.gov/hydrogenandfuelcells/mypp.

[22] *Nuclear Hydrogen R&D Plan,* U. S. Department of Energy, March 2004, www.hydrogen.energy.gov/pdfs/nuclear_energy_h2_plan.pdf.

[23] *Hydrogen from Coal RD&D Plan,* U.S. Department of Energy, September 2008, www.fossil.energy.gov/programs/fuels/publications/programplans/H2fromCoalRDDPlan08.pdf.

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

[25] *Department of Energy Hydrogen Program Annual Merit Review Proceedings* (2004 – 2007), www.hydrogen.energy.gov/annual_review.html.

[26] *Department of Energy Hydrogen Program Annual Progress Report* (2004 – 2007), www.hydrogen.energy.gov/annual_progress.html.

2.2 Summary of Program Activities

The core of the Program is a comprehensive and focused RD&D effort, which includes both basic and applied research as well as technology development and demonstration. These RD&D activities are carried out by federal labs, universities, and industry (including car companies, energy companies, large industry developers, and small businesses), and they are designed to advance hydrogen and fuel cell technologies to make them competitive with current technologies in terms of both cost and performance.

The Program's RD&D efforts focus on technologies for light-duty vehicles, distributed power generation, auxiliary power, and portable power applications. While it is through the development of technologies for light-duty vehicles that the Program expects to achieve the most progress toward its goals of reducing oil use and CO_2 emissions, developing economically viable technologies for stationary power applications can contribute to a more efficient, secure, and diversified energy infrastructure. The deployment of stationary and portable power technologies can also play an important role by growing early markets for fuel cells. The growth of these early markets can help to achieve the economies of scale needed for cost reduction and can help build a supply base for many of the same technologies that will be used in vehicles.

In addition to the need for technological advances, significant economic and institutional barriers also exist. These barriers may impede the progress of hydrogen and fuel cell technologies as they move from the technology readiness phase into consumer markets and widespread commercialization. The Department recognizes that technology that meets consumer requirements is necessary, but not sufficient, for industry to move forward with commercialization. Therefore, the Program is also working to help overcome non-technological barriers.

As shown in figure 2.2, the Program conducts the following activities: basic research and applied R&D in hydrogen production, delivery, storage, and fuel cells; manufacturing R&D; technology validation; safety, codes & standards; education; systems integration and analysis; and market transformation. Together, these activities form an integrated effort to overcome the entire range of barriers to the commercialization of hydrogen and fuel cells.

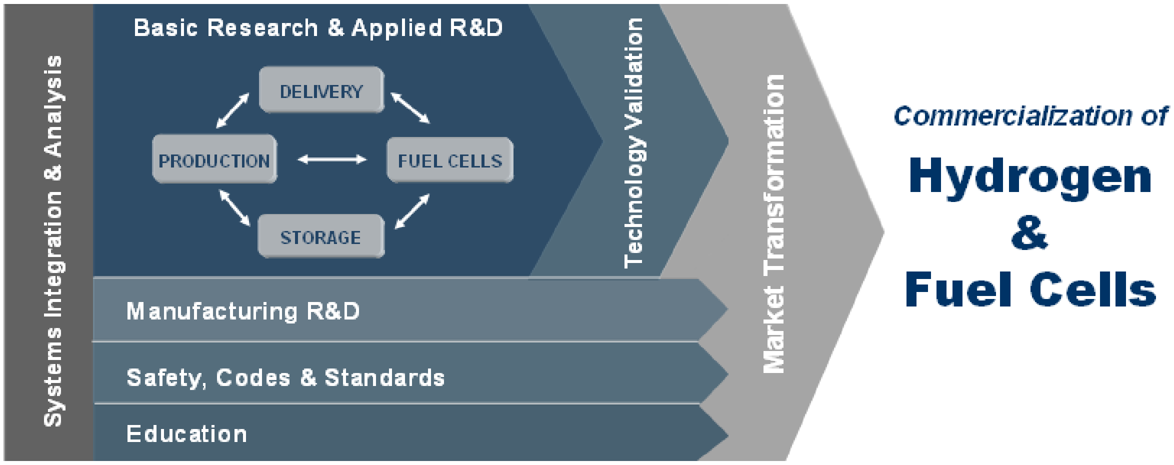

Figure 2.2. *The Program's activities are well integrated and address both technological and non-technological barriers to commercialization.*

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

a. Hydrogen Production & Delivery: The Department is developing lower-cost methods for producing and delivering hydrogen. The ultimate goal is for several different domestic production and delivery pathways to be used, at a variety of scales ranging from large, centralized production to very small, local (distributed) production, depending on what makes the most economic and logistical sense for a given location. 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.[27]

The near-term focus is on developing technologies for distributed production, in which hydrogen is produced at the fueling station, to allow for lower delivery costs. These technologies include natural-gas reforming, renewable liquid reforming, and electrolysis.

The Program is also developing centralized production pathways for the longer term, which will require substantial industry investment to build a delivery infrastructure. These production pathways include: biomass gasification; wind-driven electrolysis; solar and nuclear high-temperature thermochemical water splitting; high-temperature electrolysis; hydrogen-from-coal, with carbon capture and sequestration; and photoelectrochemical and biological production.

To enable these centralized production pathways, the Department is working to overcome the inefficiencies, high costs, and safety concerns associated with delivering hydrogen to the point where it is dispensed. The key objectives for hydrogen delivery R&D are incorporated into the overall $2 to $3 per gge cost target for all production/delivery pathways, with a specific target of $1 per gge for the cost of delivery.

Ongoing and planned research activities in hydrogen delivery include development of: lower-cost and more energy-efficient compression technology, systems for stationary storage and tube trailers, liquefaction technologies, improved pipeline materials, and novel liquid or solid hydrogen carriers.

Since FY 2004, the Program has competitively selected 95 hydrogen production and delivery projects, for a total of $175 million in funding, subject to appropriations ($85 million, over one to four years, for production from renewable sources and natural gas; $82 million, over two to five years, for production from coal; and $7 million, over one to three years, for nuclear-based hydrogen production).[28] An additional $5 million was competitively awarded for hydrogen production and delivery projects through the Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) Program.[29] Renewable hydrogen production R&D and hydrogen delivery R&D will be deferred in FY 2009; however, R&D activities in coal-based and nuclear-based hydrogen production will continue, as will basic science research in areas relevant to hydrogen production.

b. Hydrogen Storage: The Program is developing hydrogen storage systems that are more compact, have higher capacity, and are less costly. The key objective is to enable a driving

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[27] Hydrogen Production and Delivery cost targets are in 2005 dollars.

[28] U.S. Department of Energy Hydrogen Program Record #8001, www.hydrogen.energy.gov/program_records.html.

[29] This $5 million figure does not include funding for SBIR/STTR projects from hydrogen topics submitted by the Fossil Energy Program. These figures were not available at the time this report was written.

range of at least 300 miles for all light-duty vehicle platforms, without reductions in interior space or performance, and without increases in cost.

The principal focus of these efforts is advanced materials having the potential to store hydrogen at lower pressures and near-ambient temperatures, with reduced volume and weight. The Program has identified several materials that have the potential to meet these criteria, while providing higher storage capacities, in three primary areas: metal hydrides, chemical hydrogen storage, and hydrogen sorption.

The Program is also making modest investments in physical storage—pressurized or cryo-compressed tanks—for near-term applications. While this approach provides a viable solution for the early market introduction of hydrogen vehicles—and is currently in use in most existing hydrogen vehicles—it will not meet the Program's ultimate targets, which are intended to enable widespread market penetration.

The Program has created a National Hydrogen Storage Project that 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 2004 to FY 2008, the Program competitively awarded more than $213 million,[30] subject to appropriations, over four to five years for these projects. Over this period, DOE's Office of Basic Energy Sciences (BES) also contributed more than $30 million in funding to the National Hydrogen Storage Project for basic research in hydrogen storage.

c. Fuel Cells: The Program's fuel cell R&D efforts are aimed at reducing the cost and improving the durability of fuel cells. 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.

Since FY 2004, the Program has competitively selected 44 fuel cell projects for $135 million in funding (subject to appropriations) over three to five years.[31] An additional $1 million was competitively awarded for fuel cell projects through the SBIR/STTR Program.

DOE's Office of Fossil Energy (FE) is also 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.

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[30] U.S. Department of Energy Hydrogen Program Record # 8001, www.hydrogen.energy.gov/program_records.html.

[31] Ibid.

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.

In addition to these critical path technologies, BES is also conducting research on hydrogen production technologies including solar hydrogen production, biological processes, design of catalysts at the nanoscale, and membranes for separation and purification.

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 hydrogen production, storage, and use.

Since FY 2005, the Program has competitively selected 134 basic science research projects, for a total funding of $109 million (subject to appropriations).[32]

e. Manufacturing R&D: This effort is aimed at developing and demonstrating processes and technologies that reduce the manufacturing cost of PEM fuel cell systems 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 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. 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. In FY 2008, the Program competitively selected six manufacturing R&D projects for $5 million in funding over two

[32] U.S. Department of Energy Hydrogen Program Record # 8001, www.hydrogen.energy.gov/program_records.html. This includes BES projects only; it does not include projects in the Office of Biological and Environmental Research (also within the Office of Science), which were not formally part of the Hydrogen Fuel Initiative.

years (subject to appropriations). An additional $3 million was competitively awarded for projects in manufacturing R&D through the SBIR/STTR Program.

An updated version of the Hydrogen Program's *Multi-Year Research, Development, and Demonstration Plan,* released in May 2007, includes a section on Manufacturing R&D goals, objectives, technical targets, and schedule milestones. In FY 2009, Manufacturing R&D will be deferred to allow for increased concentration of resources on the critical path challenges of hydrogen storage and fuel cell cost and durability.

f. Technology Validation: To fully assess and validate the results of the Program's R&D efforts, the Department 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[33] (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. In FY 2004, the Department awarded $170 million[34] to the four teams over six years, subject to appropriations. The participating auto and energy companies will have contributed $189 million to this project by the time it is completed.

Technology Validation is an extension of R&D—by providing critical data, it helps identify issues to be addressed in the Program's R&D activities, and it aids in making accurate assessments of the status of the technologies in integrated operating systems. The Learning Demonstration provides data on vehicle range, fuel cell efficiency and durability, and hydrogen quality. Key results from the Learning Demonstration are listed with other Program accomplishments in section 3.1.

Other 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."

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 in all its activities, and these practices and

[33] 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.

[34] U.S. Department of Energy Hydrogen Program Record #8001, www.hydrogen.energy.gov/program_records.html.

lessons-learned are being used to promote the safe use of hydrogen throughout the industry. This work includes the development of leak detection technologies and the creation of comprehensive information resources, such as a best-practices handbook.

To facilitate commercialization of hydrogen 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.

The Program has competitively selected five codes and standards projects for nearly $7 million in funding over one to five years (subject to appropriations).[35]

h. Education: The Department is addressing the knowledge barriers that may impede the acceptance of hydrogen technologies. Overcoming these barriers is critical to enabling the successful implementation of near-term hydrogen demonstration projects and early-market fuel cell installations, as well as the longer-term market adoption and acceptance that are required to realize the full benefits of hydrogen and fuel cell technologies.

These efforts focus on developing educational resources and conducting outreach to increase understanding of the relevant technologies and to address safety concerns. Particular attention is paid to key audiences, such as potential end-users, state and local governments, safety and code officials, local communities, and educators.

Activities include: developing educational materials for state and local government officials and potential end-users; developing and implementing training modules for safety and code officials and emergency responders; educating the general public and key audiences in communities where new hydrogen fueling stations will be installed as part of Technology Validation; and facilitating the expansion of hydrogen and fuel cell programs at educational institutions.

Since FY 2004, the Program has competitively selected 20 education projects for $7.7 million over three to five years (subject to appropriations).[36]

i. Systems Analysis and Systems Integration: The Department 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 energy 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

[35] U.S. Department of Energy Hydrogen Program Record #8001, www.hydrogen.energy.gov/program_records.html.
[36] Ibid.

benefits. Since FY 2005, the Program has competitively selected seven Systems Analysis projects for $8 million in funding (subject to appropriations).[37]

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.

Figure 2.3 shows a listing of competitive solicitations issued by the Hydrogen Program during FY 2004 through FY 2008. Dollar values represent the total announced DOE share of the awards. All awards figures are subject to appropriations, and therefore do not represent actual funding.

[37] U.S. Department of Energy Hydrogen Program Record # 8001, www.hydrogen.energy.gov/program_records.html.

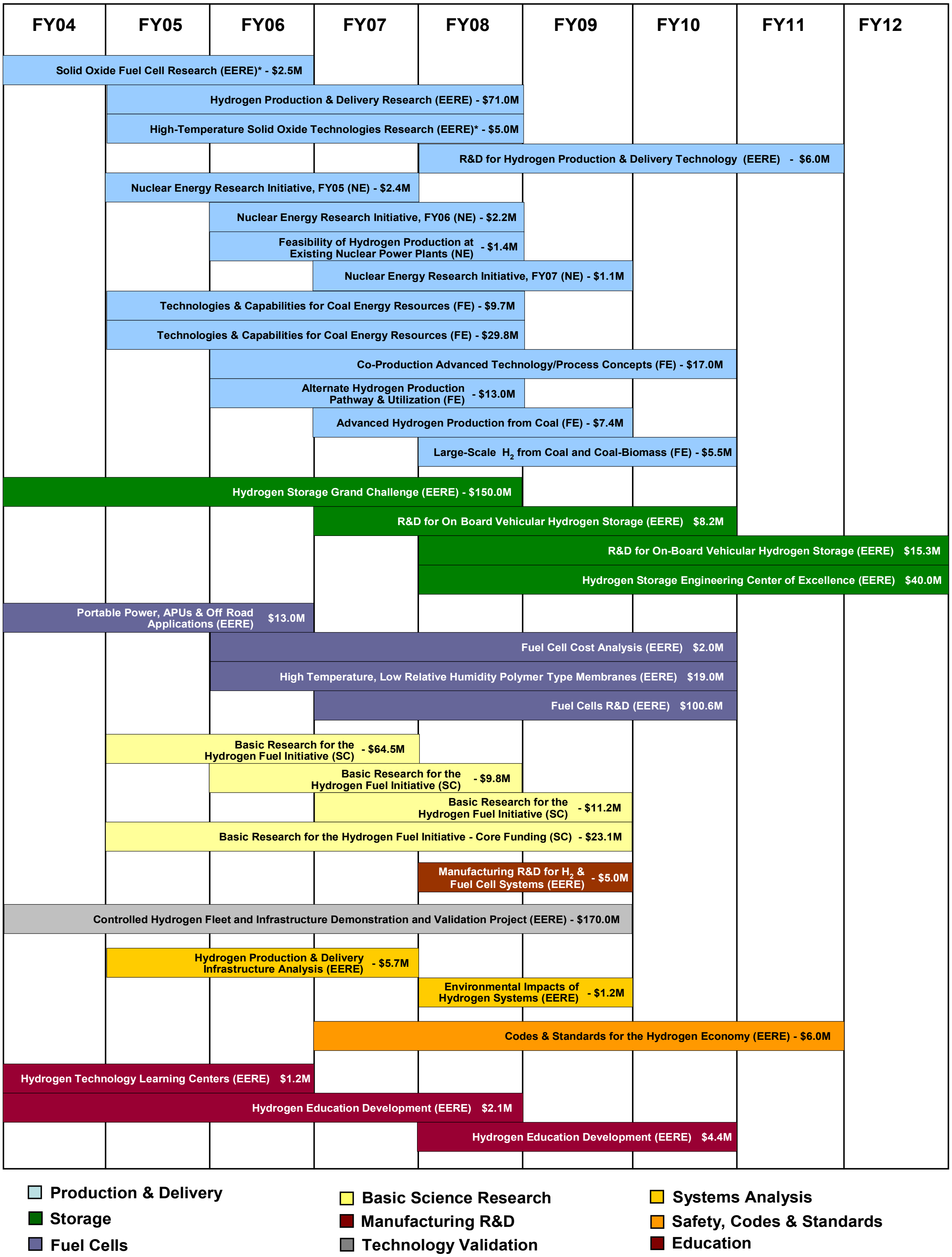

Figure 2.3. *The Hydrogen Program's competitive solicitations issued FY 2004 – FY 2008. Actual funding is subject to award negotiations and annual appropriations.*
*(*These solid oxide technology solicitations in FY 2004 and FY 2005 were congressionally directed; they involved co-production of hydrogen and electricity and reversible fuel cells for hydrogen production.)*

2.2.1 Market Transformation Activities

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 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,*[38] identifies fuel cells to power forklifts and to provide backup power for telecommunications and emergency response as promising near-term opportunities.

Consistent with EPACT section 783, "Federal Procurement of Stationary, Portable, and Micro Fuel Cells," a major focus of the Program's market transformation activities is facilitating hydrogen and fuel cell technology use through federal "early adopters." These projects will 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. The Program has partnered with other federal agencies to provide assistance with the following activities:

- The Defense Logistics Agency's effort to place approximately 100 forklifts at its distribution centers across the country;
- The Department of Defense's planned installation of 18 fuel cell systems that provide backup power to military installations in California and South Carolina;
- The U.S. Postal Service's operation of two fuel cell vehicles in regular mail delivery service;
- The Federal Aviation Administration's planned installation of approximately 25 fuel cell back-up power systems at remote telecommunication towers.

[38] 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.

3. Progress toward Goals

As described in chapter 2 of this report, the Program is conducting activities to address the full 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 Department in achieving deployment goals are addressed.

3.1 Progress toward Program Goals

Since the launch of the Hydrogen Fuel Initiative in fiscal year 2004, the Program has:

- Reduced the cost of hydrogen production from distributed reforming of natural gas at refueling sites from \$5 per gge in 2003 to \$3 per gge in 2006 (see figure 3.1).[39]
- Reduced the cost of producing hydrogen using renewable resources, including distributed reforming of bio-derived liquids (e.g., ethanol, sugars) and electrolysis (see figure 3.1).[40]

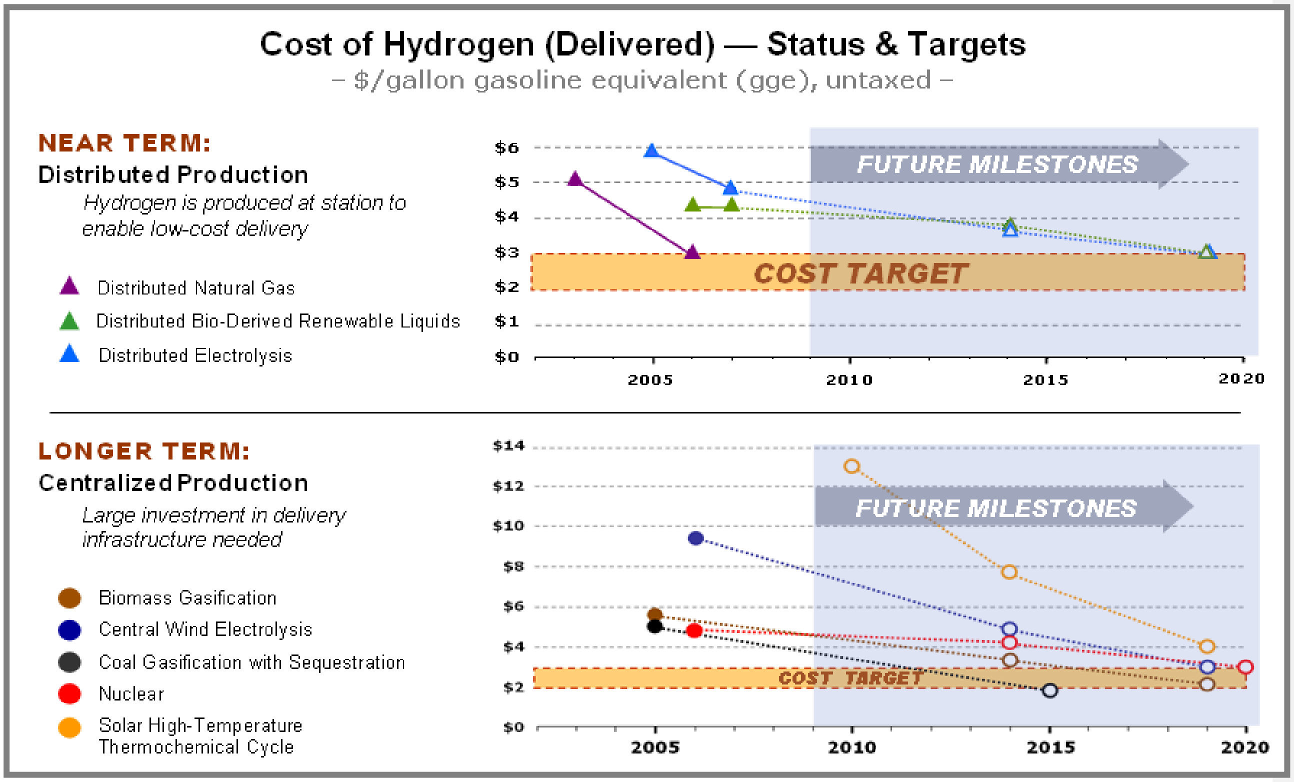

Figure 3.1. *The DOE Hydrogen Program is reducing the cost of producing and delivering hydrogen.*[41]

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[39] *Distributed Hydrogen Production From Natural Gas: Independent Review,* National Renewable Energy Laboratory, October 2006, www.hydrogen.energy.gov/pdfs/40382.pdf.

[40] U.S. Department of Energy Hydrogen Program Record #5040, www.hydrogen.energy.gov/program_records.html; and "Low-Cost, High-Pressure Hydrogen Generator," *2007 Annual Progress Report,* DOE Hydrogen Program, 2007.

[41] The figures for all production and delivery cost status and targets are expressed in 2005 dollars.

- Completed installation and initial testing of a system that directly integrates wind-based electric-power generation and water electrolysis, reducing and simplifying power conditioning between the wind turbine and the electrolyzer and resulting in a significantly reduced hydrogen production cost.
- Improved hydrogen-from-coal technologies, including developing membranes for separation and purification that show the potential, at laboratory scale, to achieve the Program's 2010 technical targets for flux (200 $ft^3/hr/ft^2$).
- Developed and initiated integrated laboratory-scale experiments for producing hydrogen from nuclear power, using both high-temperature electrolysis (operating three 240-cell modules with a target hydrogen-production level of 5,000 liters/hr) and the sulfur-iodine thermochemical cycle using three integrated modules.
- Developed fiber-reinforced polymer (FRP) pipes that can be used for delivery of gaseous hydrogen and show no long-term aging effects 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.
- 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.[41] R&D conducted to modify the performance characteristics of these materials has also resulted in enabling 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).[42]
- 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.[43] System cost remains an issue.
- Reduced the cost of automotive fuel cell systems, based on projections of high-volume manufacturing costs, from $275/kW in 2002 to $73/kW 2008 (see figure 3.2).[44]
- Improved the projected durability of fuel cell systems in vehicles, operating under real-world conditions, from 950 hours in 2006 to 1900 hours in 2008 (see figure 3.3).[45]

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[41] U.S. Department of Energy Hydrogen Program Record #5037, www.hydrogen.energy.gov/program_records.html; and "Hydrogen Storage Sub-Program Overview," *FY 2008 Annual Progress Report,* DOE Hydrogen Program, 2008, www.hydrogen.energy.gov/annual_progress.html.

[42] S. Satyapal, "Hydrogen Storage Sub-Program Overview," *2008 Annual Merit Review Proceedings*, DOE Hydrogen Program, 2008, www.hydrogen.energy.gov/pdfs/review08/5_storage_sunita_satyapal.pdf.

[43] "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.

[44] U.S. Department of Energy Hydrogen Program Records #5005 and #8019, www.hydrogen.energy.gov/program_records.html. The projected costs of $275/kW and $73/kW are based on 2002 and 2008 dollars, respectively.

[45] K. Wipke, "Completed Learning Demonstration Composite Data Products as of December 1, 2006," National Renewable Energy Laboratory, December 2006, slide 5, www.nrel.gov/hydrogen/docs/cdp/41090.ppt; and K. Wipke, et al., "Fall 2008 Composite Data Products," National Renewable Energy Laboratory, September 2008, slide 4, www.nrel.gov/hydrogen/docs/cdp/cdps_fall_2008.ppt.

- Developed a membrane electrode assembly (MEA) with more than 7,300-hour durability in the lab, with voltage cycling. This has the potential to meet the Program's 2010 target of 5,000-hour durability for MEAs in an automotive fuel cell system (see figure 3.4).[46]

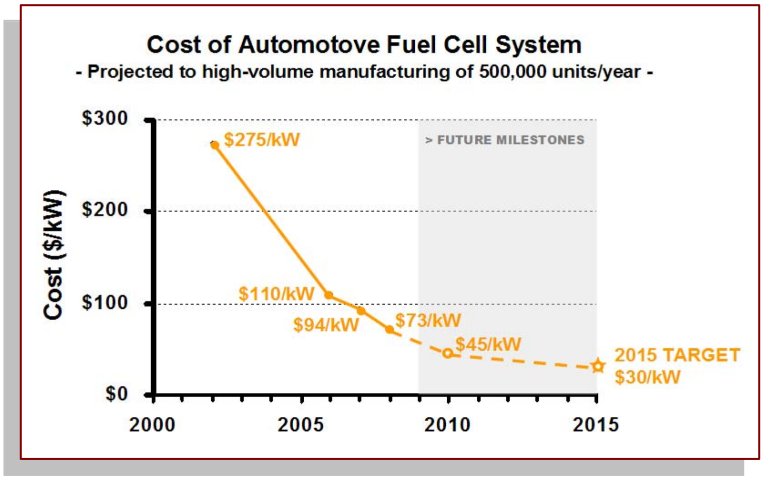

Figure 3.2. *The Program is reducing the high-volume manufacturing cost of automotive fuel cell systems. (Cost estimates are based on dollars for the year the estimate was made; cost targets are based on 2002 dollars.)*

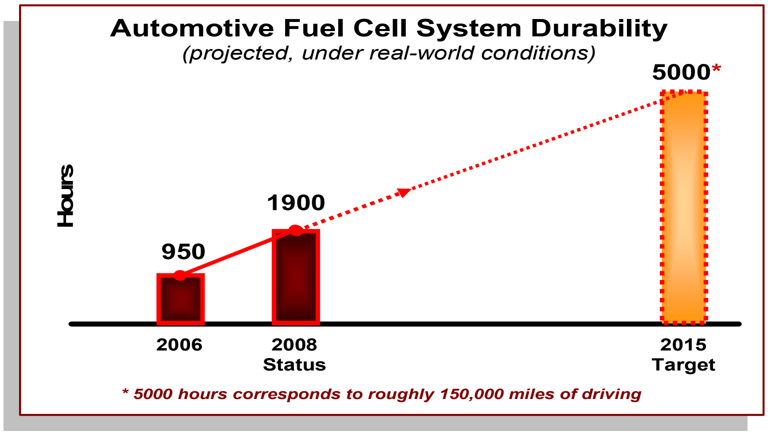

Figure 3.3. *The Program is improving the durability of automotive fuel cells under real-world operating conditions.*

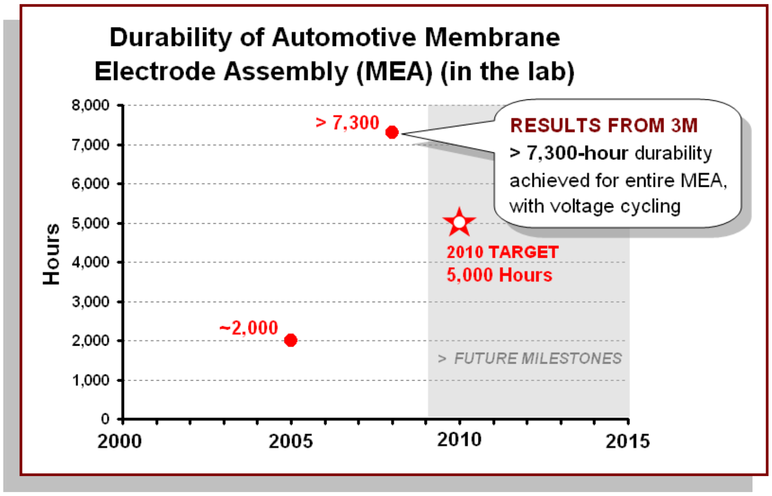

Figure 3.4. *The Program is increasing the durability of critical fuel cell components.*

[46] Nancy Garland, "Fuel Cells" (Overview of Fuel Cell subprogram), *2008 Annual Merit Review Proceedings*, DOE Hydrogen Program, 2008, slide 9, www.hydrogen.energy.gov/pdfs/review08/6_fuel_cells_nancy_garland.pdf.

- Achieved 35 percent efficiency (fuel to electrical energy) in a stationary fuel cell system, meeting the Program's 2008 target.[47]
- Advanced the understanding of the fundamental science related to hydrogen and fuel cells:
  - Performed first-principles calculations to understand how the shape of carbon catalysts on sodium alanate ($NaAlH_4$) affects the electron affinity of the bonding of the molecule, which can then reduce the hydrogen desorption temperature of this hydrogen storage material.
  - Improved understanding of size range and spatial distribution of nano-scale water channels in Nafion® membranes, commonly used in fuel cells to control water and proton transport, using small-angle x-ray scattering (SAXS) in conjunction with nuclear magnetic resonance (NMR) imaging.
  - Created tailored nanorod structures for hydrogen production from solar water splitting that maximize solar absorption and increase the ability to utilize the photocurrent using less expensive catalyst materials.
  - Developed unique and highly efficient hybrid hydrogen generator utilizing a special molecular wire to link a highly efficient biological solar absorber with a robust inorganic catalyst; this unique design increases hydrogen generation efficiency by as much as three orders of magnitude over other hybrid systems.
- Deployed 122 fuel cell vehicles and 16 hydrogen fueling stations in learning demonstrations. 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 58 percent; vehicular fuel cell system projected durability of 1,900 hours (based on data which includes a highest *observed* durability to date of 1,700 hours); and vehicle range of more than 250 miles.[48]
- Collected and analyzed data from the Department of Transportation's Fuel Cell Bus Program. Results from a total of eight fuel cell buses operated in revenue transit service have shown fuel economy improvements of 50 to 80 percent[49] over conventional diesel buses, with ranges of approximately 300 miles. Upcoming projects will add data from as many as 14 new or improved-design fuel cell buses.
- Developed and launched online resources to disseminate hydrogen safety information and facilitate the process of permitting hydrogen installations, including: *The Technical Reference on Hydrogen Compatibility of Materials*; the *Regulators' Guide to Permitting Hydrogen Technologies*; and the Web sites "Hydrogen Safety Best Practices" and "Permitting Hydrogen Facilities."[50]

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[47] Durai Swamy, "Development and Demonstration of a New Generation of High-Efficiency 1 – 10 kW Stationary PEM Fuel Cell System," *2008 Annual Merit Review Proceedings*, DOE Hydrogen Program, 2008, slide 18, www.hydrogen.energy.gov/pdfs/review08/fc_39_swamy.pdf.

[48] K. Wipke, et al., "Controlled Hydrogen Fleet and Infrastructure Demonstration Project, Fall 2008 Composite Data Products," National Renewable Energy Laboratory, September 2008, www.nrel.gov/hydrogen/docs/cdp/cdps_fall_2008.ppt.

[49] L. Eudy, "Fuel Cell Bus Evaluation Results," National Renewable Energy Laboratory, January 2008, www.nrel.gov/hydrogen/pdfs/42665.pdf.

[50] C. San Marchi, *Technical Reference on Hydrogen Compatibility of Materials*, Sandia National Laboratories, January 2005, www.ca.sandia.gov/matlsTechRef/chapters/1401TechRef_Fe9Ni4Co.pdf; *Regulators' Guide to Permitting Hydrogen Technologies,* Pacific Northwest National Laboratory, January 2004, www.pnl.gov/fuelcells/permit_guide.stml; "Hydrogen Safety Best Practices," http://h2bestpractices.org; and "Permitting Hydrogen Facilities," www.hydrogen.energy.gov/permitting/.

- Worked with national and international organizations to provide a sound technical basis for the development of new codes and standards for hydrogen and fuel cell technologies. A key outcome is a National Fire Protection Agency task group's endorsement of the use of quantitative risk assessment in the development of codes for separation distances.
- 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.
- Developed the "Introduction to Hydrogen Safety for First Responders" education program,[51] which has registered nearly 7,000 users since it was launched in January 2007; published a set of early market fact sheets, case studies, and podcasts; partnered with state and state/regional hydrogen and fuel cell initiatives to educate state and local government officials through targeted workshops and on-line training; launched the "Increase Your H2IQ Public Information Program"[52] (includes radio spots, podcasts, print materials, and a MySpace page); and launched middle school and high school curricula and teacher professional-development programs, reaching more than 6,500 teachers since 2004.
- Developed an analytical tool—the H2A model—to address the need for consistent analysis methodology and transparent reporting. The model, which assesses the cost of hydrogen (including a return on capital investment) for a variety of production pathways, is used by the Program and its contractors to evaluate technologies on a common basis, assess technology tradeoffs, and aid systems analysis efforts.
- 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.
- 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 3.5);[53] 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; analysis of early market applications for fuel cells, which shows potential greenhouse gas emissions reductions from fuel cells in early market applications 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; and coal-to-coke hydrogen production analysis that shows current production to be sufficient for approximately one million vehicles per year.[54]
- Conducted scenario analyses to explore the infrastructure and policy requirements of potential market penetration scenarios for fuel cell vehicles. (These analyses are discussed in greater detail in section 3.2.2.)

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

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

[53] U.S. Department of Energy Hydrogen Program Record #9001, www.hydrogen.energy.gov/program_records.html.

[54] Michael Wang, et al., "GREET WTW Analysis of Fuel-Cell Vehicles with Different Hydrogen Production Pathways," *2007 Annual Merit Review Proceedings*, DOE Hydrogen Program, 2007, slide 17, www.hydrogen.energy.gov/pdfs/review07/an_7_wang.pdf.

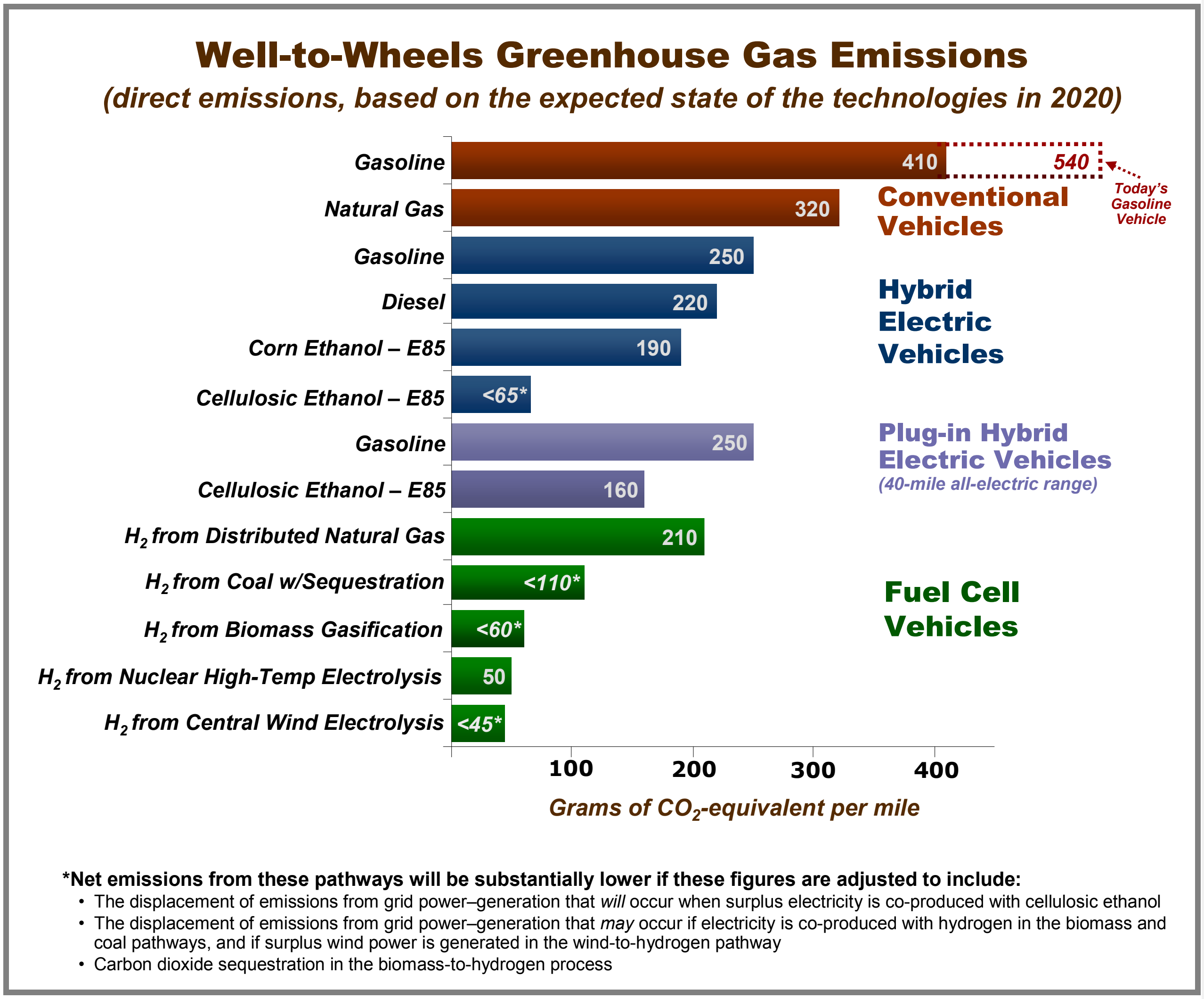

Figure 3.5. *Well-to-wheels analysis shows substantial potential reductions in greenhouse gas emissions through the use of hydrogen from a variety of sources.*[55] *Emissions are expressed in terms of CO_2-equivalent.*

[55] U.S. Department of Energy Hydrogen Program Record #9001, www.hydrogen.energy.gov/program_records.html.

3.2 Progress toward the 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, in DOE's assessment, the cost of fuel cells is still too high and their durability is still too low to enable industry to meet the deployment goal of 100,000 hydrogen-fueled vehicles by 2010, as specified in EPACT section 811(a)(4)(A). Designs for vehicles manufactured in 2010 would need to be determined now, and automakers cannot provide vehicles based on current technology at an affordable cost or with a reasonable warranty. And while fuel cell technology development is currently on track to meet the Program's 2015 technology-readiness targets, it is too early to determine if industry can achieve the 2020 deployment goal of 2.5 million hydrogen-fueled vehicles, as specified in EPACT section 811(a)(4)(B). However, in partnership with the automobile and energy industries, the Program is playing 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. Analysis conducted by Oak Ridge National Laboratory indicates that such a deployment scenario (of 2.5 million vehicles by 2020) would not be achieved without substantial supportive policies and incentives.[56]

3.2.1 Technology Validation Progress: Vehicle and Infrastructure Demonstrations

As mentioned in section 2.2 of this report, the Department'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 122 fuel cell vehicles and 16 hydrogen fueling stations,[57] 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 of the key metrics are shown in table 3.1. It should be noted, however, that most of the vehicles in the Learning Demonstration represent first-generation technology from roughly the period of 2003 to 2004. The lag time between technology development and validation reflects the time needed to move new technology from the laboratory and into full integration in demonstration vehicles. As a result, it will take some time for the more recent advances in materials and component technology—such as the development of fuel cell membranes with more than 5000-hour durability—to be reflected in these results. Second-generation vehicles were introduced into the Learning Demonstration in 2008, enabling the Program to begin assessing the progress from first- to second-generation technology and comparing it with Program targets.

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[56] 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.

[57] K. Wipke, et al, "Controlled Hydrogen Fleet and Infrastructure Demonstration Project, Fall 2008 Composite Data Products," National Renewable Energy Laboratory, September 2008, slides 17 and 24, www.nrel.gov/hydrogen/docs/cdp/cdps_fall_2008.ppt.

	Current Status	Program Targets: Phase 1 – In Progress	Program Targets: Phase 2 –Planned
System Efficiency	53–58%	**2009 Target:** 60%	**2015 Target:** 60%
Fuel Cell System Durability	1,900 hours *(~ 57,000 miles)*	**2009 Target:** 2,000 hours *(~ 60,000 miles)*	**2015 Target:** 5,000 hours *(~150,000 miles)*
Vehicle Range	254 miles	**2009 Target:** 250 miles	**2015 Target:** 300 miles
Fuel Cost	$3/gge *(projected, from distributed natural gas)*[58]	**2009 Target:** $3/gge	**2015 Target:** $2–3/gge
H_2 Quality *(purity)*	99.73–99.999%	**2010 Target:** 99.99%	**2015 Target:** >99.99%
Average Refueling Rate	0.86 kg/min *(in 2008)*	**2007 Target:** 1.0 kg/min	**2012 Target:** 1.67 kg/min

Table 3.1. *Status and targets for the National Hydrogen Learning Demonstration.*[59] *Targets may change due to reductions in funding for FY 2009 and the expansion of the scope of the Technology Validation activity (if it is incorporated into the Vehicle Technologies Program).*

Current demonstration activities in the United States include the following:

- Approximately 180 hydrogen-fueled vehicles are in operation. The overwhelming majority of these are fuel-cell vehicles—only a few are powered by internal-combustion engines. About 120 of these fuel cell vehicles are in California.[60]
- General Motors began deploying 100 fuel cell vehicles for a consumer test market in 2008.[61] Thirty-two of these vehicles will be added to the Department's learning demonstration fleet.
- In July 2008, Honda began leasing fuel cell vehicles to a limited number of retail consumers in Southern California.[62]

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[58] The Program and its partners in the Learning Demonstration Project are currently in the process of assessing demonstrated fuel cost. The projected cost shown here is a result of an independent assessment by the National Renewable Energy Laboratory; *Distributed Hydrogen Production from Natural Gas: Independent Review,* October 2006, www.hydrogen.energy.gov/pdfs/40382.pdf.

[59] K. Wipke, et al., "Controlled Hydrogen Fleet and Infrastructure Demonstration Project, Fall 2008 Composite Data Products," National Renewable Energy Laboratory, September 2008, www.nrel.gov/hydrogen/docs/cdp/cdps_fall_2008.ppt.

[60] "Inventory of Current Fuel Cell and Other Hydrogen-Powered Vehicles," Hydrogen Analysis Resource Center, U.S. Department of Energy, http://hydrogen.pnl.gov/filedownloads/hydrogen/datasheets/Hydrogen_Fueled_Vehicle_%20Census_June%202008.xls, (accessed October 1, 2008).

[61] "How Soon Will You Have a Reasonably Priced Hydrogen Vehicle?" www.chevrolet.com/fuelcell/articles/index.jsp?id=3.

[62] "Honda FCX Clarity Fuel Cell Vehicle Lease Program Begins with First Customer Delivery," Honda Press Release, July 25, 2008, www.hondanews.com/categories/865/releases/4642.

- Several fuel cell bus programs exist in the United States. Currently, 12 hydrogen fuel cell buses are operating in six states, and an additional 26 buses are planned in five states.[63]
- The State of California has 28 hydrogen stations in operation (including six stations associated with the DOE learning demonstration), with plans for 18 more.[64]
- Currently, 61 hydrogen fueling stations are in operation in the United States, with 37 more planned. A complete list of these stations may be found in the National Hydrogen Association's database.[65]

3.2.2 Scenario Analysis

Introducing hydrogen as an energy carrier will involve major changes in the country's vehicle and fueling infrastructure. The associated technical challenges, costs, and risks will be highest 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.

Through workshops with industry, academia, and national laboratories, a set of hydrogen penetration scenarios and transition models were identified and developed.[66] 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."[67]

The analysis examined three vehicle market penetration scenarios identified by industry.[68] These scenarios do not represent a proposed strategy or plan on the part of DOE or industry, nor do they represent a prediction or an indication of what is possible. The market penetration rates used were

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[63] Summary Table of U.S. Fuel Cell Bus Demonstrations, National Renewable Energy Laboratory, www.nrel.gov/hydrogen/docs/us_fcb_projects.xls (accessed October 1, 2008).

[64] Hydrogen Fueling Station Database, National Hydrogen Association (NHA), www.hydrogenassociation.org/general/fuelingSearch.asp (accessed October 1, 2008).

[65] Ibid.

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

[67] *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.

[68] 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.

developed to facilitate analysis of the infrastructure and policy needs that may arise under a variety of scenarios.

- **Scenario 1** – Production of *thousands* of fuel cell vehicles (FCVs) per year by 2015 and *hundreds of thousands* per year by 2019. This option is expected to lead to a market penetration of two million FCVs by 2025.
- **Scenario 2** – Production of *thousands of* FCVs by 2013 and *hundreds of thousands* by 2018. This option is expected to lead to a market penetration of five million FCVs by 2025.
- **Scenario 3** – Production of *thousands of* FCVs by 2013, *hundreds of thousands* by 2018, and *millions* by 2021, such that market penetration is 10 million by 2025. (This scenario was developed by the National Academies for their analysis of hydrogen's potential benefits.)

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 are superior to those in advanced hybrid internal combustion vehicles.
- The highest total annual government expenditure under the policy cases examined was about $6 billion[69]— 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.

[69] In 2004 dollars.

4. Program Funding

The cumulative budget request of $1.267 billion for FY 2004 to FY 2008 has been consistent with the original commitment of $1.2 billion over five years for the Hydrogen Fuel Initiative (see table 4.1). Congress has appropriated a total of $1.159 billion for FY 2004 to FY 2008.

Shortfalls in appropriations available for competitively selected projects in FY 2004 – FY 2008 have affected the funding for planned key activity areas. Figure 6.1 identifies the Program's technology development milestones, including those that have slipped due to these shortfalls.

Activity	Funding ($ in millions)						
	FY 2004 Approp.	FY 2005 Approp.	FY 2006 Approp.	FY 2007 Approp.	FY 2008 Approp.	HFI Five-Year TOTAL	FY 2009 Request
HYDROGEN FUEL INITIATIVE							
EERE Hydrogen	144.9	166.8	153.5	189.5	211.1	**865.8**	177.7
Fossil Energy (FE)	4.9	16.5	21.0	21.5	21.8	**85.7**	11.4
Nuclear Energy (NE)	6.2	8.7	24.1	18.9	9.9	**67.8**	16.6
Science (SC)	0	29.2	32.5	36.4	36.4	**134.5**	60.4
DOE Hydrogen TOTAL	**156.0**	**221.2**	**231.1**	**266.3**	**279.2**	**1,153.8**	**266.1**
Department of Transportation	0.6	0.5	1.4	1.4	1.4	**5.3**	1.4
Hydrogen Fuel Initiative TOTAL	**156.6**	**221.7**	**232.5**	**267.7**	**280.6**	**1,159.1**	**267.5**

Table 4.1. *HFI appropriations, with FY 2009 budget request. The EERE Hydrogen request for FY 2009 includes $146.2 million for the Hydrogen, Fuel Cells and Infrastructure Technologies Program and $31.5 million for the Vehicle Technologies Program. Budget numbers for FY 2004 – FY 2007 do not include SBIR/STTR funding transferred to the Science Appropriation.*

Activity	Funding *($ in millions)*					
	FY 2004 Approp.	FY 2005 Approp.	FY 2006 Approp.	FY 2007 Approp.	FY 2008 Approp.	FY 2009 Request
Hydrogen Production & Delivery	10.1	13.3	8.4	33.7	39.6	0
Hydrogen Storage R&D	13.6	22.4	26.0	33.7	43.5	59.2
Fuel Cell Stack Component R&D	24.6	31.7	30.7	37.1	43.6	62.7
Technology Validation	15.6	26.1	33.3	39.4	29.7	15.0*
Transportation Fuel Cell Systems	7.3	7.3	1.1	7.3	7.9	6.6
Dist. Energy Fuel Cell Systems	7.2	6.8	0.9	7.3	7.6	10.0
Fuel Processor R&D	14.4	9.5	0.6	4.0	3.0	0
Safety, Codes & Standards	5.8	5.8	4.6	13.5	15.9	12.5*
Education	2.4	0	0.5	2.0	3.9	4.0*
Systems Analysis	1.4	3.2	4.8	9.6	11.4	7.7
Manufacturing R&D	0	0	0	1.9	5.0	0
Market Transformation	0	0	0	0	0	0
Technical/Program Mgt. Support	0.4	0.5	0	0	0	0
Congressionally Directed Activities	42.0	40.2	42.5	0	0	0
EERE Hydrogen TOTAL	**144.8**	**166.8**	**153.4**	**189.5**	**211.1**	**177.7**

Table 4.2. *EERE Hydrogen budget, FY 2004 – FY 2009. Budget numbers for FY 2004 – FY 2007 do not include SBIR/STTR funding transferred to the Science Appropriation.*

** The FY 2009 Budget proposes to transfer $31.5 million to the EERE Vehicle Technologies Program ($15 million for Technology Validation; $12.5 million for Safety, Codes and Standards; and $4 million for Education).*

5. External Input, Review, and Evaluation

The Program uses a number of mechanisms for obtaining external input, review, and evaluation. In February 2004, the National Academies of Science and Engineering (NAS) published a review of the Hydrogen Program's RD&D plan and provided recommendations.[70] The NAS also 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 research, development, and demonstration efforts. HTAC submitted the first of its biennial reports to the Secretary on October 26, 2007. The Government Accountability Office (GAO) also reviewed the Program, and released its report on February 11, 2008. In addition to these reviews, the Program receives feedback through its Annual Merit Review and Peer Evaluation Meeting,[71] which involves the participation of more than 150 technical experts reviewing individual RD&D projects.

The Program periodically revises the *Hydrogen Posture Plan* and its RD&D plans to incorporate the recommendations of these reviews, as well as updates based on technological progress, programmatic changes, and policy decisions. The *Hydrogen Posture Plan* is being updated in 2008.

5.1 Reviews and Reports by the National Academies

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

5.1.1 Review of the Hydrogen Program RD&D Plan

In September 2002, the NRC appointed the Committee on Alternatives and Strategies for Future Hydrogen Production and Use to address:

- The current state of technology for producing hydrogen from a variety of energy sources;
- Current and future projected costs, carbon dioxide emissions, and energy efficiencies for hydrogen technologies;
- Scenarios for the potential penetration of hydrogen into the economy and associated impacts on oil imports and carbon dioxide emissions;
- The distribution, storage, and dispensing of hydrogen, with particular emphasis on light-duty vehicles in the transportation sector;
- The Department's RD&D plan for hydrogen.

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[70] *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. The full report is available from: www.nap.edu/catalog/10922.html.

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

The committee's report, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs,*[72] was released in February 2004, providing important recommendations to the Program on RD&D, including directions, priorities, and strategies. Recommendations from this report included suggestions to increase emphasis on exploratory research in critical path technologies, infrastructure (distributed production, delivery methods, and safety), systems analysis, transition planning, and carbon management. Some of the significant actions DOE has taken to address these recommendations are highlighted in section 5.1.4.

5.1.2 Review of the FreedomCAR and Fuel Partnership

In 2005, the NRC's Committee on Review of the FreedomCAR and Fuel Partnership:

- Reviewed the high-level technical goals and timetables for government and industry R&D efforts in the various technical areas being addressed by the Partnership;
- Reviewed and evaluated progress and the Program's direction since the inception of the Partnership toward meeting the Partnership's 2010 technical goals, and examined ongoing research activities and their relevance to meeting the goals of the Partnership;
- Examined and commented on the overall balance and adequacy of the Partnership's research effort and the rate of progress in light of the technical objectives and schedules for each of the major technology areas;
- Examined and commented, as necessary, on the appropriate role for federal involvement in the various technical areas under development;
- Examined and commented on the Partnership's strategy for accomplishing its goals.

The Committee's report, *Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report,*[73] was released in August 2005. This report stated that the Program is well-planned and that it has identified all major hurdles that need to be overcome. The chair of the review committee stated that the Program "is making significant headway." NRC's comments in this report included:

- "The committee believes that research in support of this vision [*the Program's vision of a transformation of automotive technologies and supporting infrastructure*] is justified by the potentially enormous beneficial impact for the nation."
- "The committee is impressed by how well the hydrogen program has progressed."
- "The committee compliments DOE on rapidly implementing most of the recommendations from *The Hydrogen Economy* [NAS's 2004 publication, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*]."
- "The committee is encouraged by the progress the Partnership has made in program management across the many activities and interfaces of the DOE offices and contractors, USCAR, and the energy companies."
- "The committee believes that the setting of priorities needs more emphasis. It appears to the committee that several technical programs may not be contributing solutions to the most critical and important issues."

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[72] The full report is available from: www.nap.edu/catalog/10922.html.

[73] The full report is available from: www.nap.edu/catalog/11406.html.

In 2008, the NRC completed its Phase II Review of the Partnership. This review assessed progress in each of the research and program management areas as well as the responses of program management to recommendations made in the Phase I report. Comments in the Phase II report[74] included:

- "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."
- "... with increased national interest in reducing greenhouse gas emissions, the research efforts of the Partnership are more needed than ever before."
- "There remain many barriers to achieving the objectives of the Partnership. These barriers include cost and performance at the vehicle, system, and component levels. To be overcome, some of these barriers will require invention, and others will require new understanding of the underlying science."
- "The Partnership should reassess the current allocation of funding within the fuel cell program and reallocate as appropriate, in order to prioritize and emphasize the R&D that addresses the most critical barriers. In particular, the Partnership should give membranes, catalysts, electrodes, and modes of operation the highest priority."
- "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."
- "The committee believes that it is time to ... engage in a strategic review in the context of other ongoing domestic and international activities focused on vehicle and fuel technologies."
- "DOE should continue its studies of the transition to hydrogen, extending them to 2030 – 2035, a transition 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 fuel as demand increases substantially, including both forecourt production at the fueling station and centralized production using the most cost effective means of distributing the hydrogen."
- "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."

Some of the significant actions DOE has taken to address the recommendations in these reviews are highlighted in section 5.1.4.

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

5.1.3 Report: "Transitions to Alternative Transportation Technologies—A Focus on Hydrogen"

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.

5.1.4 Recommendations of the National Academies and DOE Actions

Some recommendations from the National Academies and actions taken by the Program include:[75]

- *"Increase R&D in small scale natural gas reforming, electrolysis, and new concepts for distributed hydrogen production systems."* The Program increased R&D of distributed hydrogen production from natural gas, bio-derived liquids, and electrolysis. The Program

[75] 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.

achieved the cost target for hydrogen production from distributed natural gas ($3 per gge) and has reduced the cost of hydrogen from electrolysis from $5.90 per gge to $4.80 per gge.[76]

- *"Establish a comprehensive systems analysis capability to drive technology development decisions relevant to energy, environmental, and economic criteria."* The Program created a Technology Analyst position, hired a senior analyst from industry, and enhanced systems analysis capabilities. These actions enabled evaluations of existing and emerging technologies through multiple pathways utilizing a fact-based analytical framework.

- *"Establish an independent systems integration effort to ensure that the various Program elements (such as production, delivery, and storage) fit together seamlessly."* The Program established a Systems Integration office at DOE's National Renewable Energy Laboratory (NREL) to integrate all Program elements (hydrogen production, delivery, and storage; fuel cells; safety, codes and standards; and education) and to monitor progress toward technology targets. Independent assessments of a number of key targets and milestones have been conducted through the Systems Integration office.

- *"Perform an overall program evaluation, using go/no-go decisions and setting priorities that focus resources on programs that will contribute most to solving the problems critical to the success of the long-term program goals."* The Program regularly reviews and evaluates priorities and makes appropriate adjustments in planning. For example, following a decision to focus more resources on critical priorities, the Department's FY 2009 budget request increased funding for Hydrogen Storage and Fuel Cells, while reducing funding for non-critical areas, such as Manufacturing R&D. In addition, the Program has performed go/no-go decisions for specific technology approaches—e.g., in 2006, the Program decided to discontinue R&D in pure, undoped single-walled carbon nanotubes for vehicular hydrogen storage applications.[77]

- *"Ensure any expanded role for hydrogen produced from fossil fuel has a positive impact on the mitigation of climate change (e.g., develop carbon capture and storage for these technologies)."* The Program has enhanced its coordination with the DOE Office of Fossil Energy and established the Hydrogen Coordination Group to improve the integration, coordination, and balance of activities. The Program has initiated analysis of hydrogen impacts on CO_2 emissions reductions.

- *"Strengthen policy analysis with respect to the hydrogen economy, and better understand the role of government in supporting and facilitating industry investments to bring a transition to the hydrogen economy."* The Program has initiated scenario analyses to assess infrastructure and policy needs to support possible vehicle market penetration scenarios.

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[76] *Distributed Hydrogen Production From Natural Gas: Independent Review,* National Renewable Energy Laboratory, October 2006, www.hydrogen.energy.gov/pdfs/40382.pdf; U.S. Department of Energy Hydrogen Program Record #5040, www.hydrogen.energy.gov/program_records.html; and "Low-Cost, High-Pressure Hydrogen Generator," *2007 Annual Progress Report,* DOE Hydrogen Program, 2007, www.hydrogen.energy.gov/annual_progress.html.

[77] *Go/No-Go Decision: Pure, Undoped Single-Walled Carbon Nanotubes for Vehicular Hydrogen Storage*, U.S. Department of Energy, October 2006, www.hydrogen.energy.gov/pdfs/go_no_go_nanotubes.pdf.

- *"Shift the Program away from some development areas towards exploratory work … Engage universities to play a much bigger role in the research program."* The Program added basic research to its portfolio by integrating DOE's Office of Science (SC) into the Hydrogen Program and creating a line item for basic science research in the Program's budget. The Office of Basic Energy Sciences within SC issued three solicitations and initiated numerous new projects on basic research in hydrogen and fuel cell materials and processes. The Office of Energy Efficiency and Renewable Energy has also initiated exploratory work in the areas of hydrogen storage, biological hydrogen production, non-platinum catalysts, and high-temperature membranes. As a result of these basic and exploratory efforts, university participation in the Program has increased.
- *"Increase emphasis on hydrogen safety to understand how hydrogen systems must be designed, built, and operated differently from today's vehicles and infrastructure."* To provide technical data for hydrogen codes and standards, the Program has increased research in areas such as materials compatibility, hydrogen behavior, and risk assessment. The Program is also developing informational resources and training facilities that will play a critical role in the commercialization of hydrogen energy technologies by helping fill the void of publicly available hydrogen safety data.

5.2 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 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, also known as the *Hydrogen Posture Plan*.

HTAC's first report,[78] submitted to the Secretary in October 2007, commended the Program for using best management practices, such as peer reviews in solicitation processes, assessment of technical progress, individual project selection and monitoring, and overall program management. The committee outlined several positive features of the *Posture Plan*, finding it to be well thought out and comprehensive. The committee's report also identified a number of gaps or areas for improvement in the *Posture Plan*.

HTAC's recommendations include:

- Participation in the Hydrogen and Fuel Cell Interagency Task Force (ITF) should be elevated to at least the functional level of Assistant Secretary or higher, and the ITF should be charged with developing a 'National Hydrogen and Fuel Cells Action Plan' (NHFCAP) to guide interagency cooperation and collaboration;

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[78] "Letter Report to Secretary of Energy Samuel Bodman," Hydrogen and Fuel Cell Technical Advisory Committee, October 2007, www.hydrogen.energy.gov/pdfs/htac_letter_report_attach.pdf.

- Funding for the Program should be increased at least to the $3.275 billion authorized by EPACT for FY 2006 to FY 2010,[79] commensurate with its importance to national security, environmental quality, climate change mitigation, and global technology competitiveness;
- National policies should be developed to overcome market barriers to hydrogen and fuel cell systems during the transition period;
- DOE should continue the Technology Validation activity for fuel cell vehicle and fueling infrastructure technologies and capture the synergistic benefits of including stationary and portable power applications;
- The *Posture Plan* should articulate a process for down-selecting pathways or for directing applied research efforts back to exploratory research efforts when these pathways encounter roadblocks that require major breakthroughs to resolve;
- The *Posture Plan* should be updated to include: a more comprehensive description of the market risks associated with developing hydrogen as an energy carrier; better definition of the government's role in commercialization; a broader vision of how hydrogen fits into the overall energy strategy for the United States; an expansion of the scope beyond the current focus on transportation to include stationary and portable fuel cell power applications; a plan for a DOE leadership role through the ITF to harmonize and expedite efforts to develop consistent codes and standards; and a stronger emphasis on supporting workforce training, public education, and other human capital requirements.

The Department is giving serious consideration to HTAC's recommendations and has already begun implementing several of them. The newly elevated ITF, which includes senior management-level representatives from more than ten agencies, was commissioned on August 1, 2007, and meets semi-annually. DOE is also updating the *Posture Plan* in 2008, and the next edition will address HTAC's recommendations.

In response to HTAC's recommendation about funding levels, DOE has observed that funding across the federal government was approximately $500 million annually in FY 2006 and FY 2007, and totaled more than $2 billion over five years (FY 2003 – FY 2007).[80] Furthermore, the Department's FY 2008 appropriation of $284 million is more than three times the pre-initiative funding levels.

DOE agrees that timely policies and incentives may be needed to stimulate the market for hydrogen and fuel cells. Some incentives are already in place. There is currently a federal tax credit available for 30 percent of the cost of a qualified fuel cell property, up to a maximum of $3000/kW. In addition, hydrogen and fuel cells technologies are eligible for commercialization opportunities through DOE's Loan Guarantee Program, established by EPACT Title VII. The Department also agrees that validation of the complete advanced vehicle and alternative fuel technology portfolio is extremely important for judging commercial readiness. Furthermore, since fuel cell vehicles and "plug-in" hybrid vehicles create a unique energy nexus between transportation and stationary applications, the Department will consider incorporating stationary and portable power applications into future technology validation activities.

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[79] *Energy Policy Act of 2005*, sections 805(h), 805(i), 808(d), 809(c), and 811(c).

[80] U.S. Department of Energy Hydrogen Program Record #8003, www.hydrogen.energy.gov/program_records.html.

DOE further agrees that a disciplined approach to directing research and down-selecting pathways should continue to be an integral part of the research program. The Program employs go/no-go decision points in its applied research projects and has adopted a rigorous approach to project and program management. Future updates of the *Posture Plan* will articulate the process used and address other HTAC recommendations.

5.3 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 the Hydrogen Fuel Initiative (HFI). Specifically, GAO assessed the extent to which federal agencies implementing the HFI have: (1) made progress in meeting the R&D targets of the initiative; (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 under the HFI, 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),"*[81] 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 posture plans and a projection of anticipated R&D funding needs. The Program is updating the *Hydrogen Posture Plan* in 2008 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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[81] *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.

6. Future Activities and Updates to Strategic Plans

The Program's strategic plans have been updated to reflect both technical and programmatic progress and to incorporate inputs from advisory panels. The *Hydrogen Posture Plan*, which outlines the integrated plan of the Program, was issued in 2004, updated in 2006, and is being updated in 2008. The Offices of Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy have updated their hydrogen RD&D plans, which describe the detailed plans for research, development, and demonstration activities for hydrogen and fuel cell technologies through 2015–2020. The EERE RD&D Plan—*Hydrogen, Fuel Cells & Infrastructure Technologies Program's Multi-Year Research, Development, and Demonstration Plan* was first published in draft form in 2003 and updated in 2005 and 2007.

To take advantage of the synergies between FCVs and plug-in hybrids, and within EERE vehicle technology and alternative fuel research, development, and demonstration efforts, the three crosscutting activities currently in the EERE Hydrogen Program—Technology Validation; Safety, Codes and Standards; and Education—are proposed to be moved to EERE's Vehicle Technologies Program in the FY 2009 Budget. Second-generation vehicles were incorporated into the Learning Demonstration in 2008, and the new data acquired will enable the Program to gain understanding of the trajectory from one generation of technology to the next, to better assess which areas will need more attention, and to determine what changes in strategy, if any, will be needed. Synergies with other energy efficient and renewable energy technologies will also be assessed. For example, plug-in hybrid battery technology in combination with fuel cells may offer an alternative vehicle operating strategy.

The Program is also placing greater emphasis on activities that can stimulate early markets for stationary and portable fuel cell applications. These early markets can help to increase sales and manufacturing volumes, which can provide essential cost reductions by enabling economies of scale for many of the same technologies used in fuel cell vehicles and refueling infrastructure. These early 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 6.1. The next edition of the *Hydrogen Posture Plan* will document progress toward goals and the changes in milestones and program strategy.

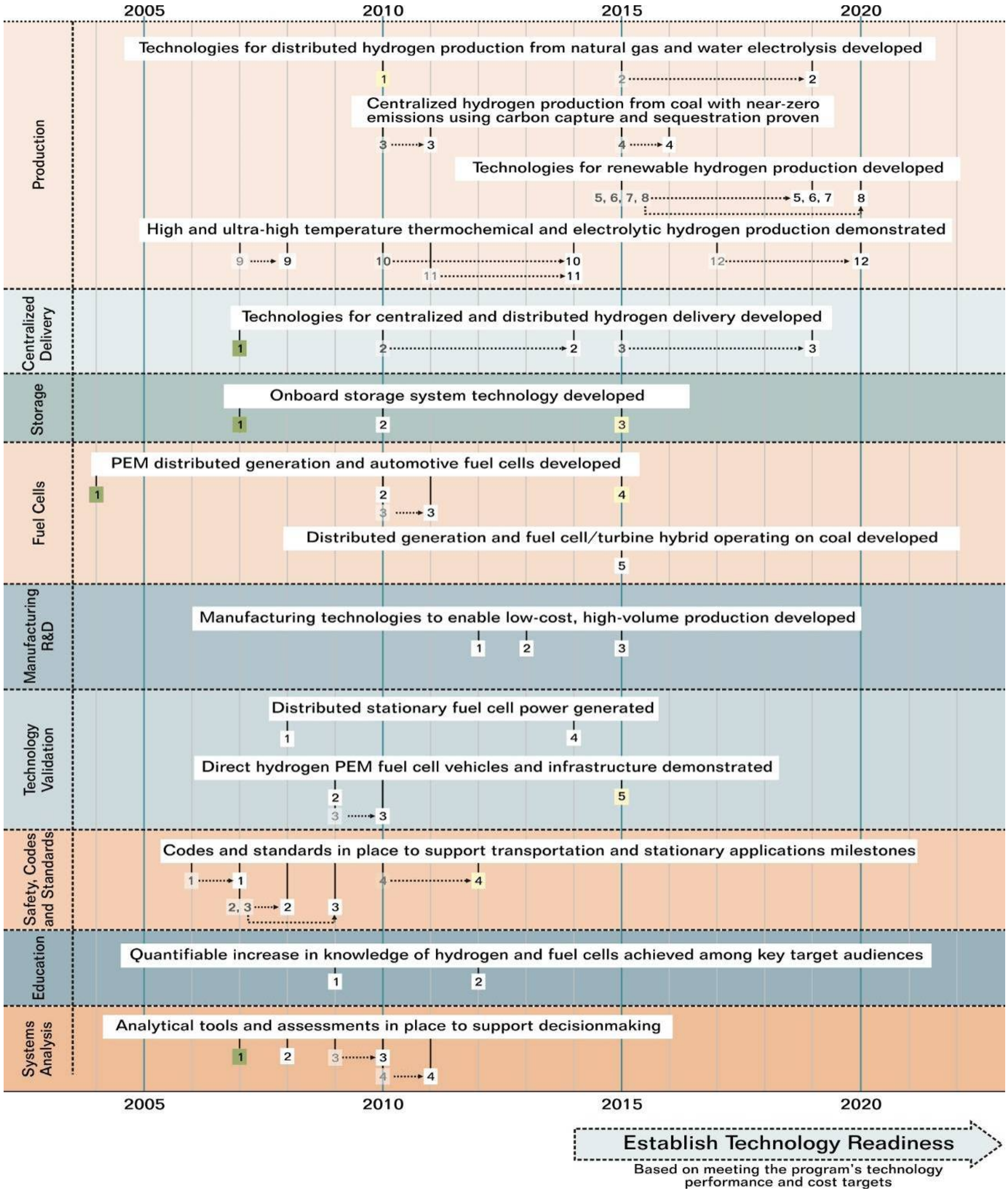

Figure 6.1: Technology Development Timeline: Milestones and Decision Points. *Critical path R&D will enable technology readiness for fuel cell vehicles in 2015. R&D in stationary and portable fuel cell technologies will expand the availability of fuel cells for clean power generation and help grow the early markets for hydrogen and fuel cells—which will reduce cost through economies of scale and help to overcome institutional and societal barriers. Longer-term R&D of hydrogen production and delivery technologies will be necessary for supplying hydrogen in quantities sufficient for widespread commercialization of fuel cells for vehicles and for stationary power generation. Milestones that have been met are shown in green, and milestones for critical path R&D are shown in yellow.*

Production Milestones*

Distributed Natural Gas and Electrolysis

1. 2010: Develop technology to produce hydrogen from natural gas at a refueling station that projects to a cost of $2.50/gge for hydrogen. (At the pump, untaxed, at 5,000 psig)
2. 2015 ➔ 2019: Develop technology to produce hydrogen utilizing distributed electrolysis that projects to a cost of <$3.00/gge. (At the pump, untaxed, at 10,000 psig)

Central Coal[e, f]

3. 2010 ➔ 2011: Develop pre-engineering membrane separation modules and reactors for hydrogen production that meet membrane cost target of $150-200/ft^2
4. 2015 ➔ 2016: Prove the feasability of a near-zero atmospheric emissions coal plant producing hydrogen and power with carbon capture and sequestration at a 25% cost reduction compared to current coal-based technology

Renewable Resources

5. 2015 ➔ 2019: Develop technology to produce hydrogen through distributed reforming of renewable liquid fuels at a refueling station that projects to a cost of <$3.00/gge for hydrogen (At the pump, untaxed, at 10,000 psig)
6. 2015 ➔ 2019: Develop technology for central hydrogen production integrating wind electricity production and electrolysis that projects to a cost of <$2.00/gge at the plant gate (<$3.00/gge delivered)
7. 2015 ➔ 2019: Develop technology for central hydrogen production from biomass gasification that projects to a cost of <$1.10/gge at the plant gate (<$2.10/gge delivered)
8. 2015 ➔ 2020: Demonstrate laboratory-scale photobiological water splitting system to produce hydrogen at an energy efficiency of 5% (solar-to-hydrogen); demonstrate laboratory-scale photoelectrochemical water splitting system to produce hydrogen at an energy efficiency of 10% (solar-to-hydrogen)

High-Temperature Thermochemical and Electrolytic

9. 2007 ➔ 2008: Operate laboratory-scale thermochemical and electrolytic processes to determine the feasibility of coupling them with a nuclear reactor
10. 2010 ➔ 2014: Laboratory-scale demonstration of solar-driven high-temperature thermochemical and electrolytic hydrogen production that projects to a cost $6.00/gge ($7.00/gge delivered)
11. 2011 ➔ 2014: Pilot-scale demonstration of thermochemical and electrolytic hydrogen production system for use with nuclear reactors that projects to a cost of $4.00/gge ($5.00/gge delivered)
12. 2017 ➔ 2020: Engineering-scale demonstration of thermochemical and electrolytic hydrogen production system for use with nuclear reactors that projects to a cost less than $3.50/gge ($4.50/gge delivered)

Storage Milestones

1. 2007: Down-select hydrogen storage options with potential to meet 2010 targets
2. 2010: Develop and verify onboard storage systems achieving 4.5% by weight capacity and 900 watt-hours/liter energy density at a cost of $19.00/kWh of stored energy
3. 2015: Develop and verify onboard storage systems achieving 5.5% by weight capacity,1,300 watt-hours/liter, and $15.00/kWh

Manufacturing R&D Milestones

1. 2012: Develop continuous in-line measurement for MEA fabrication
2. 2013: Demonstrate pilot scale processes for assembling fuel cell stacks
3. 2015: Develop fabrication and assembly processes for high-pressure hydrogen storage technologies that can achieve a cost of $2/kWh

Technology Validation Milestones

1. 2008: Validate stationary fuel cell system that co-produces hydrogen and electricity at 20,000 hours durability with 40% efficiency at a cost of $1500/kW or less
2. 2009: Validate fuel cell vehicles achieving a 250-mile range and $3.00/gge of hydrogen at multiple sites
3. 2009 ➔ 2011: Validate fuel cell vehicles achieving 2,000 hours of durability at multiple sites
4. 2014: Validate stationary fuel cell system that co-produces hydrogen and electricity at 40,000 hours durability with 40% efficiency at a cost of $750/kW or less
5. 2015: Validate PEM fuel cells on operational vehicles in different climatic conditions that achieve 5,000 hours durability (service life of vehicle) and a 300-mile range that can be produced for $45/kW when produced in quantities of 500,000

Education Milestones

1. 2009: Increase knowledge of hydrogen and fuel cells among state and local government officials and students by 10% and the public and potential end users by 15% (compared to a 2004 baseline)
2. 2012: Increase knowledge of hydrogen and fuel cells among state and local government officials and students by 20% and the public and potential end users by 30% (compared to a 2004 baseline)

Fuel Cell Milestones

1. 2004: Decision to discontinue onboard fuel processing R&D based on inability to achieve <0.5 minute start time and <2 MJ start energy for a 50-kW system
2. 2010: Develop direct hydrogen polymer electrolyte membrane automotive fuel cell operating at 60% peak efficiency, 220 W/L density, 325 W/kg specific power at a cost of $45/kW (high-volume production)
3. 2010 ➔ 2011: Distributed stationary generation natural gas/propane 5-250 kW fuel cell go/no-go decision based on ability to achieve: 40% electrical efficiency, 40,000 hours durability (equivalent to service life between major overhauls), at a cost of less than $750/kW
4. 2015: Develop polymer electrolyte membrane automotive fuel cell system meeting cost of $30/kW (based on high-volume manufacturing) and demonstrating 5,000-hour durability with cycling
5. 2015: Develop fuel cell/turbine hybrid operating on coal meeting cost of $400/kW with a HHV efficiency of 50% with carbon sequestration

Safety, Codes and Standards Milestones

1. 2006 ➔ 2007: Facilitate publishing domestic and international hydrogen quality standards and publish initial set of basic safety training materials
2. 2007 ➔ 2008: Publish initial best practices manual for hydrogen safety
3. 2007 ➔ 2009: Education program for safety and code officials in place
4. 2010 ➔ 2012: Initial set of technical codes and standards in place to support demonstrations, commercialization decisions, and regulatory standards

Centralized Delivery Milestones

1. 2007: Define the criteria for a cost-effective hydrogen fuel delivery infrastructure for supporting the introduction and long-term use of hydrogen for transportation and stationary power
2. 2010 ➔ 2014: Develop technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of use in vehicles or stationary power units to <$1.70/gge of hydrogen
3. 2015 ➔ 2019: Develop technologies to reduce the cost of hydrogen fuel delivery from the point of production to the point of use in vehicles or stationary power units to <$1.00/gge of hydrogen

Systems Analysis Milestones

1. 2007: Complete technoeconomic analysis of current production technologies
2. 2008: Develop a macro-system model of the hydrogen fuel infrastructure to support the transportation system
3. 2009 ➔ 2010: Complete assessment of hydrogen quality requirements for production, delivery, storage and fuel cell pathway
4. 2010 ➔ 2011: Develop electricity infrastructure module for the macro-system model

** The hydrogen cost milestones are not yet normalized across the Hydrogen Program. The Program is in the process of normalizing the criteria used to determine the cost goals using the "H2A" modeling tool. "Projects to" refers to the estimated cost at high-volume, commercial-scale production.*

Figure 6.1 (cont'd): Legend for Technology Development Timeline. *Arrows indicate where milestones have slipped due to budget shortfalls. Milestones that have been met are shown in green, and milestones for critical path R&D are shown in yellow.*