U.S. DEPARTMENT OF
ENERGY

The Department of Energy Hydrogen and Fuel Cells Program Plan

An Integrated Strategic Plan for the
Research, Development, and Demonstration of
Hydrogen and Fuel Cell Technologies

September 2011

The need for clean, sustainable, and domestically produced energy has never been greater. The call for green jobs and U.S. leadership in clean energy, combined with the need to reduce emissions and our growing dependence on imported oil, have come together to form a powerful imperative—one that demands new technologies and new approaches for the way we produce and use energy.

Congress has led the call for the development of clean, domestic sources of energy with the Energy Policy Act of 2005 (EPACT), the Energy Independence and Security Act of 2007, and the American Recovery and Reinvestment Act (Recovery Act). The Department of Energy (DOE) is responding to this challenge, collaborating with industry, academia, and other stakeholders to develop, advance, and enable the widespread use of key energy technologies. As outlined in this document, hydrogen and fuel cells are part of DOE's portfolio of R&D activities for emerging clean energy technologies.

Acknowledgments:
A draft version of this document was posted for public comment on the DOE Fuel Cell Technologies Program's website. The DOE Hydrogen and Fuel Cells Program acknowledges the detailed observations, thoughtful insights, and other valuable comments that were received from a number of groups and individuals, including the Hydrogen and Fuel Cell Technical Advisory Committee, the Fuel Cell and Hydrogen Energy Association, as well as other industry stakeholders and members of the general public.

For more information, contact:

FuelCells@ee.doe.gov

Fuel Cell Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Or visit:

www.hydrogenandfuelcells.energy.gov
www.hydrogen.energy.gov

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The Hydrogen and Fuel Cells Program

An Integral Part of the National Energy Portfolio

In 2010, the National Academies published their review of the Department of Energy's (DOE's) hydrogen, fuel cell, and advanced vehicle technologies activities and reiterated DOE's portfolio approach to light-duty vehicles:

"In the collective opinion of the committee, there are essentially three primary alternative pathways:

- *Improved ICE [internal combustion engine] vehicles coupled with greater use of biofuels,*
- *A shifting of significant portions of transportation energy from petroleum to the grid through the expanded use of PHEVs [plug-in hybrid electric vehicles] and BEVs [battery-electric vehicles], and*
- *The transition to hydrogen as a major transportation fuel utilized in fuel cell electric vehicles.*

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

— The National Academies
Review of the Research Program of the FreedomCAR and Fuel Partnership, Third Report

In April 2009, the Secretary of Energy emphasized the importance of fuel cells within a portfolio of technologies:

"The investments we're making today will help us build a robust fuel cell manufacturing industry in the United States … Developing and deploying the next generation of fuel cells will not only create jobs—it will help our businesses become more energy efficient and productive. We are laying the foundation for a green energy economy."

— Secretary of Energy Steven Chu

In 2008, the U.S. Government Accountability Office presented its report to Congress on DOE's hydrogen and fuel cell activities:

"... [the Department has] made important progress in developing hydrogen technologies in all of its technical areas in both fundamental and applied science. 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."

— U.S. Government Accountability Office report on DOE's hydrogen and fuel cell activities

In 2008, the National Academies completed a report on the resources needed for fuel cell electric vehicles to become competitive in the marketplace:

"Industry- and government-sponsored research programs have made very impressive technical progress … the introduction of fuel cell electric vehicles into the light-duty vehicle fleet is much closer to reality than when the National Research Council last examined the technology in 2004."

— The National Academies
Transitions to Alternative Transportation Technologies—A Focus on Hydrogen

In 2007, the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC), which was established under Section 807 of the Energy Policy Act of 2005 (EPACT), submitted its first biennial report:

"The Committee believes that hydrogen has the significant potential to play an important role in meeting the long term energy needs of the United States because it has the capability to carry energy from any source—fossil, renewable, nuclear—to the points of use with very low environmental footprint. Hydrogen can be produced in a distributed fashion and by using off-peak power or intermittently available renewable energy resources such as sunlight. Hydrogen also has the ability to store this energy during off-peak power periods so that the energy can be made available when and where it is needed."

— Hydrogen and Fuel Cell Technical Advisory Committee
Biennial Report to the Secretary of Energy

Executive Summary

Fuel cells, which convert diverse fuels directly into electricity without combustion, and hydrogen, a zero-carbon fuel that can be produced from renewable resources, are key elements of a broad portfolio for building a competitive, secure, and sustainable clean energy economy. Reducing greenhouse gas emissions 80 percent by 2050 and eliminating dependence on imported fuel will require the use of diverse domestic energy sources and advanced fuels and technologies in all sectors of the economy. It will also require a robust, comprehensive research and development (R&D) portfolio that balances short-term objectives with long-term needs and sustainability.

Benefits and Challenges of Hydrogen and Fuel Cells

Hydrogen and fuel cells offer a broad range of benefits for the environment, for our nation's energy security, and for our domestic economy, including: reduced greenhouse gas emissions; reduced oil consumption; expanded use of renewable power (through use of hydrogen for energy storage and transmission); highly efficient energy conversion; fuel flexibility (use of diverse, domestic fuels, including clean and renewable fuels); reduced air pollution; and highly reliable grid-support. Fuel cells also have numerous advantages that make them appealing for end-users, including: quiet operation, low maintenance needs, and high reliability. In addition to using hydrogen, fuel cells can provide power from a variety of other fuels, including natural gas and renewable fuels such as methanol or biogas.

Hydrogen and fuel cells can provide these benefits and address critical challenges in all energy sectors—commercial, residential, industrial, and transportation—through their use in diverse applications, including: distributed energy and combined-heat-and-power (CHP) systems; backup power systems; systems for storing and transmitting renewable energy; portable power; auxiliary power for trucks, aircraft, rail, and ships; specialty vehicles, such as forklifts; and passenger and freight vehicles, including cars, light trucks, buses, and short-haul trucks.

Widespread use of hydrogen and fuel cells would play a substantial role in overcoming our nation's key energy challenges, including significant reductions in greenhouse gas emissions and oil consumption as well as improvements in air quality. A study by the National Academies has shown that by 2050, fuel cell electric vehicles could provide the largest reduction in emissions and oil consumption of any advanced vehicles. In addition, hydrogen and fuel cells provide a significant economic opportunity for the United States, with various studies projecting up to 900,000 new jobs in the U.S. by 2030–2035. Growing interest and investment among leading world economies, such as Germany, Japan, and South Korea, underscores the global market potential for these technologies and the need for continued investment for industry to remain competitive.

While fuel cells are becoming competitive in a few markets, the range of these markets can be greatly expanded with improvements in durability and performance and reductions in manufacturing cost, as well as advances in technologies for producing, delivering, and storing hydrogen. Successful entry into new markets will also require overcoming certain institutional and economic barriers, such as the need for codes and standards, the lack of public awareness and understanding of the technologies, and the high initial costs and lack of a supply base that many new technologies face in their critical early stages.

Program Strategy and Activities

The Department of Energy's (DOE's) efforts in hydrogen and fuel cells form an integrated program—the DOE Hydrogen and Fuel Cells Program (the Program)—which is coordinated across the Department and includes activities in the offices of Energy Efficiency and Renewable Energy, Science, Nuclear Energy, and Fossil Energy. The Program conducts activities to address the full range of technical and non-technical barriers facing hydrogen and fuel cells. To guide R&D priorities and set program goals, and to clarify where hydrogen and fuel cells can be most beneficial, the Program conducts a comprehensive ***Systems Analysis*** effort. The Program also utilizes an independent ***Systems Integration*** effort to ensure that the various elements of the Program are well coordinated, and that system-level targets are developed, verified, and met. Technical barriers are addressed through activities that span the full spectrum of basic research, pre-competitive applied R&D, and technology validation and demonstration. The Program's R&D strategy maintains an inclusive, technology-neutral approach while conducting focused efforts in specific technical areas and applications. Emphasis on different applications is balanced to enable success in early markets and support the growth of a strong domestic industry, while maintaining progress in longer-term, higher-impact areas. Growth in early markets can help to reduce costs industry-wide, strengthen consumer acceptance, expand the infrastructure, and overcome a variety of logistical challenges. Therefore, the Program aims to achieve advances for a wide variety of applications, with varying time frames for commercial success.

Key areas of research, development, and demonstration (RD&D) include: ***Fuel Cell R&D,*** which seeks to improve the durability, reduce the cost, and improve the performance of fuel cell systems, through advances in fuel cell stack and balance of plant components; ***Hydrogen Fuel R&D***, which focuses on enabling the production of low-cost hydrogen fuel from diverse renewable pathways and addressing key challenges to hydrogen delivery and storage; ***Manufacturing R&D***, which works to develop and demonstrate advanced manufacturing technologies and processes that will reduce the cost of fuel cell systems and hydrogen technologies; ***Technology Validation***, which demonstrates and validates pre-commercial technologies before the deployment phase; and ***Basic Science Research***, which seeks to advance fundamental scientific knowledge and achieve breakthroughs that will enable advancements in applied R&D.

To ensure that advances in the laboratory can be realized in the marketplace, the Program conducts a range of activities to address economic and institutional barriers. The Program seeks to act as a catalyst in the transition from R&D to demonstration and early deployment by integrating real-world technology demonstrations, public outreach and education, and early market deployments into a well-planned timeline. These activities are also closely coordinated with other federal agencies and state and regional efforts. The Program's ***Education and Outreach*** activities aim to increase public awareness and understanding of the technologies, facilitating the implementation of near-term demonstration projects and early market fuel cell installations, while easing the way for long-term market adoption. ***Market Transformation*** activities provide financial and technical assistance for the use of hydrogen and fuel cell systems in early market applications, with the goals of achieving sales volumes that will enable cost reductions through economies of scale, supporting the development of a domestic industry, and providing feedback to testing programs, manufacturers, and potential technology users. The Program also conducts efforts in ***Safety, Codes & Standards*** to develop information resources and best practices to address safety issues, and to provide critical information needed for technically sound codes and standards—these efforts in codes and standards will be ongoing as new technologies emerge and mature.

To address ***infrastructure challenges***, the Program is initiating a coordinated effort to: identify and assess options and scenarios, evaluate the status of the technologies, determine the business case for infrastructure development, and identify potential policies required for commercial viability. The Program aims to play a critical role in fostering the demonstration of technologies for the transition to a more widespread infrastructure. Therefore, the Program's activities and plans also address infrastructure development, including validating innovative approaches to hydrogen infrastructure and supporting early market deployments of fuel cells using hydrogen—these early market deployment projects are addressing many of the logistical and other real-world challenges that will confront fueling stations of the future.

Program Direction, Processes, and Partnerships

The Program supports DOE's mission as described in the *DOE Strategic Plan*, and it addresses the following key goals: Goal 1, catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies; Goal 2, maintain a vibrant U.S. effort in science and engineering as a cornerstone of our economic prosperity with clear leadership in strategic areas; and Goal 4, establish an operational and adaptable framework that combines the best wisdom of all Department stakeholders to maximize mission success. Program activities are coordinated among four DOE offices through the Hydrogen and Fuel Cells Coordination Group, which is led by the Hydrogen and Fuel Cells Program Manager. Program activities are implemented through projects carried out by federal laboratories, universities, non-profit institutions, government agencies, and industry.

The Program engages in several key partnerships that provide valuable stakeholder input, ensuring that its activities will achieve maximum societal, economic, and environmental benefits. These partnerships help to ensure that the RD&D efforts of government, academia, and industry are well coordinated, their diverse capabilities are well integrated, and their resources are effectively utilized. The Program coordinates with the DOE Vehicle Technologies Program to participate in a key strategic partnership—involving automobile manufacturers, energy companies, and utilities—known as U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability). The Program also engages continually with stakeholders through involvement with a number of organizations, including: the Fuel Cell and Hydrogen Energy Association (FCHEA), the California Fuel Cell Partnership, the Hydrogen Utilities Group, and the California Stationary Fuel Cell Collaborative. And, the Program participates in a number of working groups that coordinate activities in specific technology areas. In addition to input received through these groups, the Program regularly solicits input and feedback from stakeholders in the planning of its activities, through various channels, including requests for information and workshops to establish high-level program direction and update technology-specific RD&D plans.

The Program's management strategy for ensuring the most effective use of funds includes development of appropriate targets and milestones, a rigorous competitive-selection process, cost-sharing with private-sector partners, and an extensive peer-review process. Specific targets and milestones for all R&D pathways are developed in close consultation with experts in industry and the research community, and these milestones are regularly updated to reflect changes in the market and industry. Projects are selected on the basis of technical feasibility, high-impact potential, innovation, and overall viability in making progress toward targets. And to ensure that the best projects are selected, the Program places a high priority on the use of competitive solicitations, which allows it to select the best proposals from the most qualified teams, based on the input of independent expert reviewers. The Program also employs a comprehensive approach to managing projects that includes a systematic process for discontinuing certain research pathways ("down-selecting") to focus on the most promising areas. Finally, the Program utilizes diverse channels for external input, including periodic external reviews of the entire Program, regular input from the Hydrogen and Fuel Cell Technical Advisory Committee, and thorough reviews of individual projects at the Annual Merit Review and Peer Evaluation Meeting.

The Program collaborates and coordinates extensively with other efforts at the national, state, and international levels to make the most of the diverse capabilities of these ongoing efforts and to ensure that participating organizations leverage each others' resources to achieve the maximum benefit from their efforts. To facilitate broad interagency coordination, a staff-level Hydrogen and Fuel Cell Interagency Working Group (IWG) has held monthly meetings since 2003. As directed by Section 806 of the Energy Policy Act of 2005, DOE serves as chair of the Hydrogen and Fuel Cell Interagency Task Force (ITF), which includes senior-level representatives from agencies participating in the IWG. The Program's activities with state governments and organizations are key to implementing its overall strategy for real-world demonstrations, public outreach and education, and early market deployments. Several states—particularly California, Connecticut, Hawaii, Ohio, New York, and South Carolina—have major hydrogen and fuel cell programs underway, and the Program is actively involved with all of them. This coordination also enables the Program to evaluate a regionally based strategy, which focuses efforts on certain areas with the highest likelihood of success. The Program also works with many countries around the world that have recognized the importance and potential benefits of hydrogen and fuel cell technologies—through the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), which includes 17 member countries and the European Commission, and the International Energy Agency (IEA) Implementing Agreements, which include more than 25 countries.

The Program's Impact

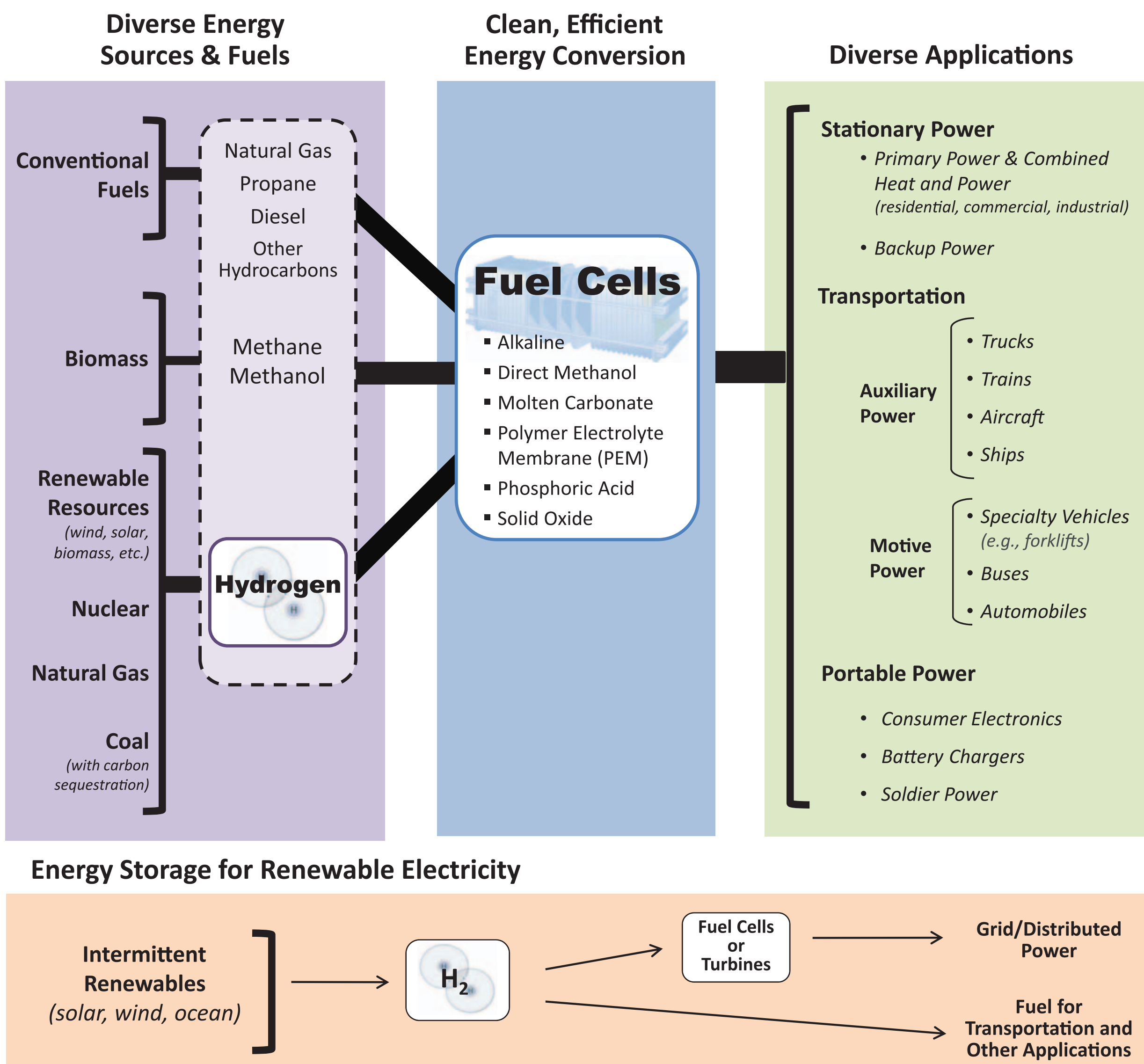
The DOE Hydrogen and Fuel Cells Program has been integral to the important progress in hydrogen and fuel cell technologies in recent years. These advances can be seen in the marketplace today: commercial customers are choosing fuel cells for the benefits they offer, and growing sales and manufacturing volumes for applications such as forklifts and backup power are beginning to lower costs, increase consumer confidence, and grow the domestic supplier base. Hydrogen and fuel cells are also being demonstrated in growing fleets of automobiles, transit buses, and supporting refueling infrastructure. These demonstrations show strong and steady improvements in performance and durability, confirming progress toward commercial viability in these important markets.

By pursuing innovative concepts and promising pathways for R&D, DOE has made significant technological advances; and by working to ease the transition of technologies into the marketplace, DOE has moved hydrogen and fuel cells substantially closer to the crucial role they can play in our energy economy.

Table of Contents

Introduction

Fuel cells can provide power and heat cleanly and efficiently, using diverse domestic fuels, including hydrogen produced from renewable resources, biomass-based fuels, and natural gas. They can be used in a wide range of stationary, transportation, and portable-power applications. Hydrogen can also function as an energy storage medium for renewable electricity, to be used as a fuel for a number of applications or to provide electricity at times of peak demand.



Why Hydrogen and Fuel Cells?

Hydrogen and fuel cells offer a broad range of benefits for the environment, for our energy security, for our domestic economy, and for end-users. These benefits include:

Reducing Greenhouse Gas Emissions

Due to their high efficiency and zero- or near-zero-emissions operation, fuel cells have the potential to reduce greenhouse gas emissions in many applications. Department of Energy (DOE)-funded analyses have shown that fuel cells have the potential to achieve the following reductions in emissions:

- Combined heat and power (CHP) systems: More than 35% to more than 50% reduction in emissions over conventional heat and power sources (with much greater reductions—more than 80%—if biogas is used in the fuel cell)[1]
- Light-duty highway vehicles: More than 55% to more than 90% reduction in emissions over today's gasoline vehicles—even when compared with future hybrid electric vehicles (accounting for projected advances in the technology), fuel cell electric vehicles (FCEVs) using hydrogen from renewables would reduce CO_2 emissions by up to 84%[2]
- Specialty vehicles: More than 35% reduction in emissions over current diesel and battery-powered lift trucks[3]
- Transit buses: Fuel cell buses have demonstrated more than 40% higher fuel economy than diesel internal combustion engine (ICE) buses and more than double the fuel economy of natural gas ICE buses;[4] these very high efficiency improvements could lead to substantial reductions in emissions—even greater reductions in emissions are possible if hydrogen from low- or zero-carbon sources is used.
- Auxiliary power units (APUs): More than 60% reduction in emissions over truck engine idling[5]

Reducing Oil Consumption

Fuel cells offer a virtually petroleum-free way to provide power for applications that are currently responsible for a large portion of the petroleum consumed in the United States today, such as automobiles, buses, backup generators, and auxiliary power generators. DOE analysis has shown that FCEVs using hydrogen can reduce oil consumption in the light-duty vehicle fleet by more than 95% when compared with today's gasoline internal combustion engine vehicles, by more than 85% when compared with advanced hybrid electric vehicles using gasoline or ethanol, and by more than 80% when compared with advanced plug-in hybrid electric vehicles.[6]

[1] Assumes fuel cell CHP with 42% HHV electrical efficiency and 74%HHV overall efficiency; used EPA CHP analysis model at www.epa.gov/chp/basic/calculator.html.

[2] DOE Hydrogen and Fuel Cells Program Record #10001, www.hydrogen.energy.gov_program_records.html. The range of emissions for FCEVs is based on a range of pathways for producing hydrogen, with hydrogen from distributed reforming of natural gas resulting in the most emissions, to hydrogen from biomass gasification resulting in the least.

[3] L.Gaines, et al., "Full Fuel-Cycle Comparison of Forklift Propulsion Systems," Argonne National Laboratory (ANL), October 2008, www.transportation.anl.gov/pdfs/TA/537.pdf. Result cited for battery-powered lift trucks assumes batteries are charged using electricity from conventional combustion-based generators.

[4] "Technology Validation: Fuel Cell Bus Evaluations," *DOE Hydrogen Program 2010 Annual Progress Report*, http://hydrogen.energy.gov/annual_progress.html.

[5] L. Gaines and C. Hartman, "Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks," Center for Transportation Research, ANL, November 2008; since validated experimental data was not available, it was assumed that fuel cell APUs would consume 0.2 gallon/hr, the same as the conventional APU in Gaines' study (current modeling suggests fuel cell APUs would consume even less). This would result in overall CO_2 emissions comparable to those of a diesel ICE APU. Actual CO_2 emissions by fuel cell APUs are likely to be lower, and improvements in the efficiency of diesel reformers and fuel cells will result in further reductions.

[6] DOE Hydrogen and Fuel Cells Program Record #10001, www.hydrogen.energy.gov_program_records.html. The ranges of oil consumption reductions cited all assume that hydrogen from centralized biomass gasification is used; since this is the most petroleum-intensive pathway for hydrogen production (on a "well-to-wheels" basis), potential reductions from other pathways will be even greater. Analysis assumed average projected grid mix in 2030 for all electricity used.

Advancing Renewable Power Using Hydrogen for Energy Storage and Transmission

Hydrogen can be used as a medium for energy storage and transmission, which can facilitate the expansion of renewable power generation. Hydrogen can "store" electrical energy when it is produced through electrolysis using surplus electricity, when generation exceeds demand. This stored energy can be used for other high-value applications—such as CHP systems, passenger vehicles, and buses—or it can be converted back into grid electricity, using fuel cells or turbines, for "peak-power" when demand exceeds generation. Hydrogen can also be moved over large distances through pipelines—potentially at higher efficiency and less expense than conventional long-distance electricity transmission—enabling transmission of energy from renewable generation facilities in remote locations.

Highly Efficient Energy Conversion

Fuel cells directly convert the chemical energy in fuel into electricity, with very high efficiency and without combustion. Fuel cells using hydrogen can achieve nearly 60% efficiency in vehicle systems (more than twice the efficiency of gasoline internal combustion engines). Fuel cells using natural gas or propane can achieve 45% electrical efficiency in stationary power systems, with the potential to achieve more than 70% electrical efficiency in hybrid fuel cell/turbine systems and more than 80% overall efficiency in CHP systems.

Fuel Flexibility—Use of Diverse, Domestic Fuels, Including Clean and Renewable Fuels

Fuel cells can use a diverse variety of fuels, including hydrogen, methanol, methane from biomass, natural gas, propane, and even diesel. Certain renewable, zero- or near-zero-emissions fuels including hydrogen, methanol, and methane from biomass are well suited for use in fuel cells. Hydrogen, in particular, can be produced from diverse and abundant domestic resources through direct conversion of renewable energy such as sunlight and biomass, or through electrolysis using renewable power. Many of these production pathways result in minimal carbon dioxide (CO_2) emissions.

Reducing Air Pollution

Fuel cells emit negligible criteria air pollutants [i.e., carbon monoxide, nitrogen oxides (NOx), ozone, particulate matter (PM), sulfur dioxide, and lead], regardless of the fuel they use. When using hydrogen, fuel cells emit only water.

High Reliability and Grid Support Capabilities

Fuel cells can provide high-quality, reliable power for critical-load applications such as hospitals, data centers, and emergency shelters. They can also be monitored remotely, reducing maintenance time and cost, especially in isolated installations such as telecommunications backup-power sites. Fuel cells can operate as stand-alone systems, without any need to be connected to the grid; this can offer flexibility and energy security. Large-scale fuel cells can also provide grid support to help alleviate transmission issues nearer to the point of use. Fuel cells can also be used in smart grid or microgrid applications, providing an alternative to or an enhancement of traditional electric power systems. Dispersed distributed generation can provide highly reliable electric power, and byproduct heat from fuel cells offers additional benefits for space-, water-, or process-heating needs. While high temperature fuel cells do not have rapid start-up times, polymer electrolyte membrane (PEM) fuel cells offer peaking capabilities with good load-following characteristics.

Suitability for Diverse Applications

Fuel cells can provide power for a wide range of applications, such as: consumer electronics (up to 100 W), homes (1–5 kW), backup power generators (1–5 kW), forklifts (5–20 kW), vehicles (50–125 kW), and centralized power generation (1–200 MW or more).

Quiet Operation

Since a fuel cell stack has no moving parts, it operates quietly and with minimal vibration, unlike traditional combustion engines such as diesel generators. This offers benefits for defense applications that require stealth and low noise signature capabilities, as well as for residential and commercial locations where noise and vibration are undesirable.

Low Maintenance Needs

With fewer moving parts, fuel cells require less maintenance than traditional technologies such as internal combustion engines and other emerging technologies such as microturbines. Compared with batteries, fuel cells are less sensitive to harsh environments and require less space to address maintenance, storage, and environmental disposal needs.

Opportunities for Economic Growth and Leadership in an Emerging High-Tech Sector

The domestic hydrogen and fuel cell industry is poised to become a major high-tech sector, with the potential to help strengthen the domestic economy and provide high-skilled jobs in diverse areas including manufacturing, installation, maintenance, and service. The United States has long been the world leader in hydrogen and fuel cell technologies, but worldwide interest and investment in these technologies are growing.

The DOE Hydrogen and Fuel Cells Program

The DOE Hydrogen and Fuel Cells Program (the Program) conducts comprehensive efforts to overcome the technological, economic, and institutional barriers to the widespread commercialization of hydrogen and fuel cells. The Program is aligned with DOE's strategic vision and goals—its efforts will help to secure U.S. leadership in clean energy technologies and advance U.S. economic competitiveness and scientific innovation.

The Program integrates activities across four DOE offices—Energy Efficiency and Renewable Energy, Science, Fossil Energy, and Nuclear Energy—and works with partners in state and federal agencies, foreign governments, industry, academia, non-profit institutions, and the national laboratories. The Program will also coordinate with other relevant DOE efforts as they develop, such as DOE's Energy Frontier Research Centers, Innovation Hubs, and the Advanced Research Projects Agency-Energy (ARPA-E).

Mission

To enable the widespread commercialization of a portfolio of hydrogen and fuel cell technologies through basic and applied research, technology development and demonstration, and diverse efforts to overcome institutional and market challenges.

Key Goals

The Program's primary goal is to advance hydrogen and fuel cell technologies to be competitive in the marketplace with incumbent and other emerging technologies. Although fuel cells are becoming competitive in a growing number of markets, to achieve widespread commercialization they must enter larger markets and be able to compete in terms of life-cycle cost, performance, durability, and environmental impact. Success in these markets will also depend on non-technical factors, such as user confidence, ease of financing, the availability of codes and standards, and investment in a refueling infrastructure for certain applications.

The Program has defined its key goals based on the technical advances that are needed, which have been identified through discussions with technology developers, the research community, and all relevant stakeholders. These key goals are to develop hydrogen and fuel cell technologies for:

1. Early markets such as stationary power (primary and backup), lift trucks, and portable power—current through the 2014 time frame;
2. Mid-term markets such as residential CHP systems, auxiliary power units, fleets, and buses—in the 2012 to 2017 time frame; and
3. Longer-term markets including main-stream transportation applications with a focus on light-duty vehicles—in the 2015 to 2020 time frame and beyond.

The Program has also set goals for developing technologies for the production, delivery, and storage of hydrogen, which will help spur commercialization of fuel cells and maximize their environmental and energy security benefits. These goals are to 1) reduce the cost of producing hydrogen from renewable resources, nuclear energy, and coal with carbon sequestration, 2) reduce the cost of

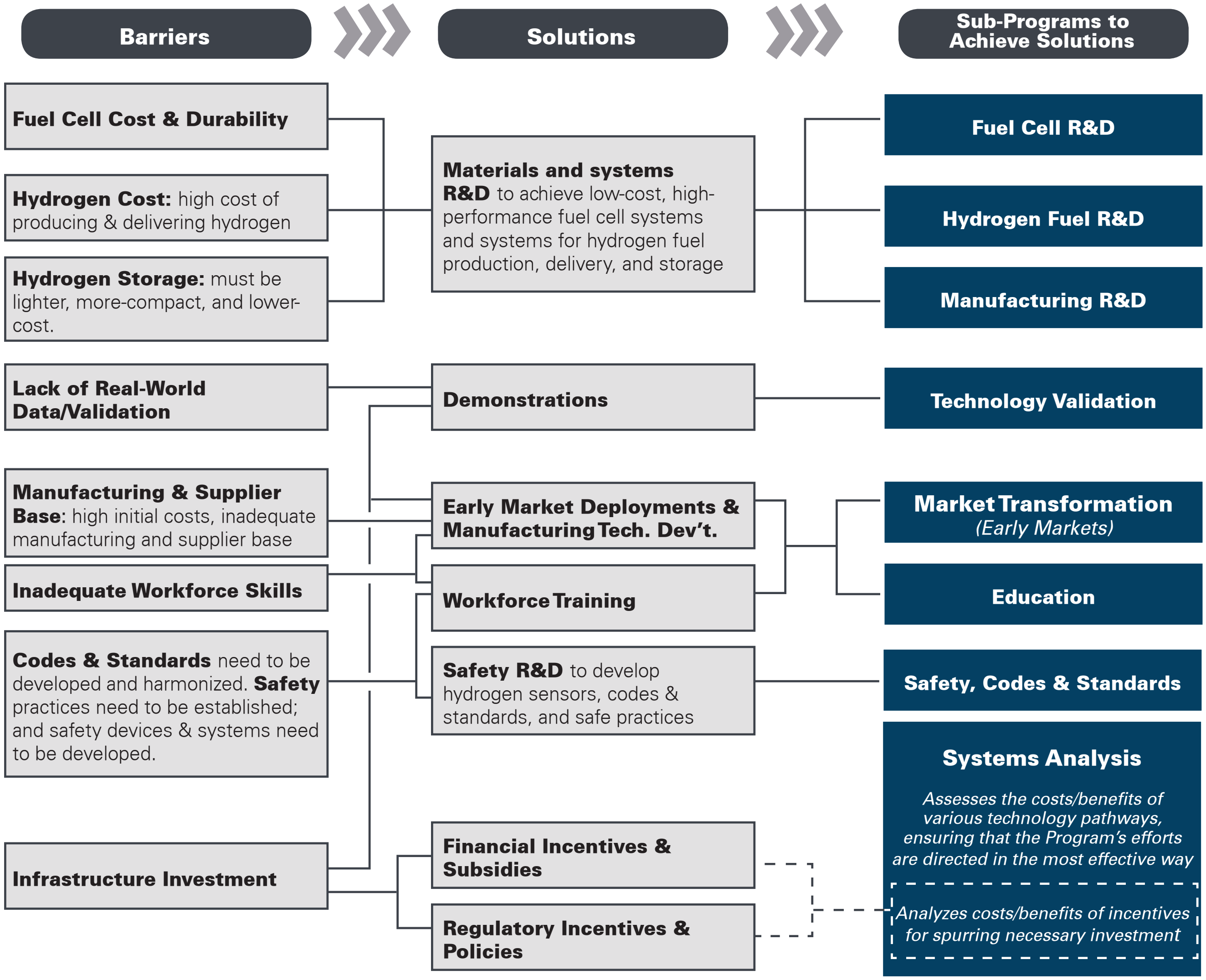


Figure i.1. Program Strategy. The Program integrates diverse efforts to overcome the full range of barriers to the widespread commercialization of hydrogen and fuel cells.

delivering, storing, and dispensing hydrogen, and 3) improve the performance and reduce the cost of hydrogen storage systems.

Achieving the Program's goals will mean that fuel cells will have competitive performance and durability; that it will be technically feasible to manufacture fuel cells at a competitive cost (when produced at volumes commensurate with other technologies in the marketplace); and that it will be possible to produce hydrogen at a competitive cost (assuming high volumes and widespread market penetration). Meeting the Program's cost targets will not guarantee *when* the actual cost of fuel cells or hydrogen technologies will become competitive—this will depend on adequate investment by industry and a commitment to commercialize the technologies and produce hydrogen at sufficient volumes needed to achieve cost reductions. Policies and incentives will also be required to spur the necessary market pull and industry investment.

A full discussion of detailed targets and milestones for all Program activities appears in Chapter 2.

Strategy

The Program's strategy balances an inclusive, technology-neutral approach with focused efforts in specific technical areas and applications (figure i.1). The Program supports activities to broadly advance the state of the art of hydrogen and fuel cell technologies, including basic and applied research common to various types of fuel cells and a wide range of applications. More-focused efforts are pursued for specific applications when technical and market analyses identify markets where fuel cells can provide significant benefits or achieve commercial success that will strengthen and grow the industry.

While certain applications will have a larger impact than others, the Program's portfolio is strategically balanced to enable success in early markets and support the growth of a strong domestic industry, while also maintaining progress in longer-term, higher-impact areas. This balanced approach is based on the fact that growth in any market for fuel cells can support the industry as a whole and hasten its expansion into new markets with additional benefits for society. In this way, all fuel cell applications represent important markets. Therefore, in pursuing its strategy, the Program aims to advance hydrogen and fuel cell technologies for a wide variety of applications, with varying time frames for commercial success. However, the Program does give priority to higher-impact applications, and will continue to prioritize among applications as early markets take hold and evolve.

As hydrogen and fuel cells become competitive in new areas, the resulting increases in market activity will enable significant cost reductions through economies of scale, through development of mass-manufacturing techniques and capacity, and through standardization along the supply chain and within supplier operations. These cost reductions will lead to growth in the number and size of markets where hydrogen and fuel cells are viable. Early successes will also help pave the way for future growth by strengthening consumer acceptance, expanding critical aspects of the refueling infrastructure, and overcoming a variety of logistical and other real-world challenges.

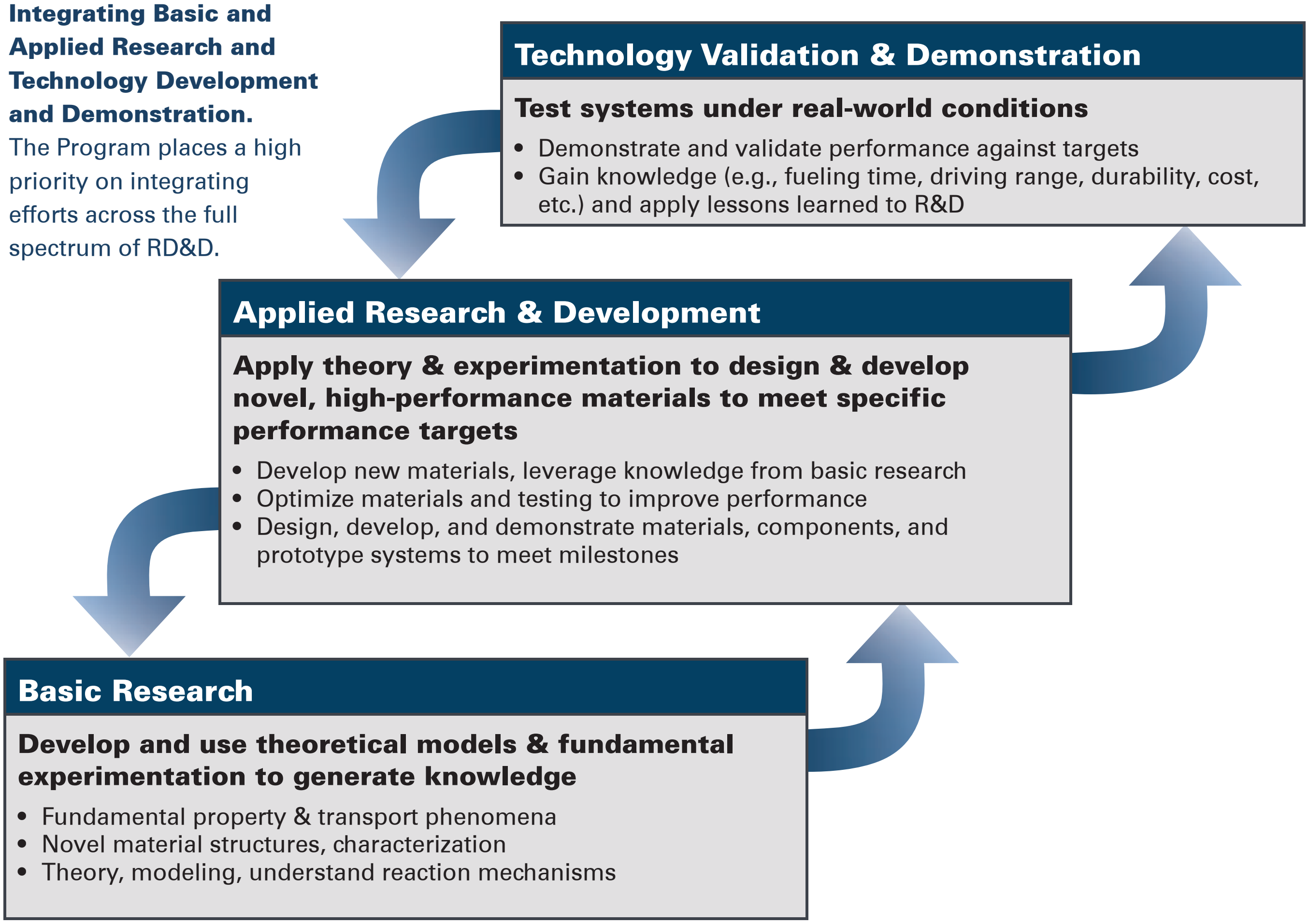
The Program's strategic vision is to achieve key advances in pre-competitive research and development (R&D) that spur further efforts by industry and ultimately lead to successful commercialization. To achieve the necessary technological advances, the Program integrates a full spectrum of research, development, and demonstration (RD&D) activities, including:

- **Basic research** efforts, which use experimentation and theoretical models to uncover the fundamental properties of materials and reaction mechanisms
- **Applied research and technology development** efforts, which employ existing theory and knowledge to design and develop materials, components, and prototype systems to meet performance targets
- **Demonstration and validation of new technologies**, integrated in systems, and operating under "real-world" conditions

Communication and feedback among all these areas (figure i.2) allows the Program to rapidly identify challenges and roadblocks as they emerge and effectively allocate and rebalance resources to optimize R&D efforts.

The Program also aims to act as a catalyst in the transition from R&D to demonstration and early deployment. This is accomplished

Figure i.2. Examples of Integrating Basic and Applied Research and Technology Development and Demonstration. The Program places a high priority on integrating efforts across the full spectrum of RD&D.



through a strategy that integrates real-world demonstrations of technology advancements, public outreach and education, and early market deployments into a well-planned timeline that maximizes their benefits and enables a broader transformation of the marketplace. To further ensure that advances in the laboratory can be realized in the marketplace, the Program works to address economic and institutional challenges facing hydrogen and fuel cells. The Program communicates extensively with stakeholders to identify these challenges, conducts analyses of them where appropriate, and initiates effective measures to overcome them.

The Role of Federal Research, Development, and Demonstration

As shown in figure i.3, the Program's activities are aimed at achieving critical breakthroughs and advancing pre-competitive technologies. Due to the high-risk nature of this research, these areas would not be sufficiently funded by private industry in the absence of government support. As the technologies reach maturity and full commercialization, federal RD&D efforts will transition over to efforts by industry to make ongoing refinements and improvements (figure i.4). A longer-term effort in RD&D for hydrogen fuel technologies is envisioned to enable the fullest realization of the benefits of fuel cell technologies.

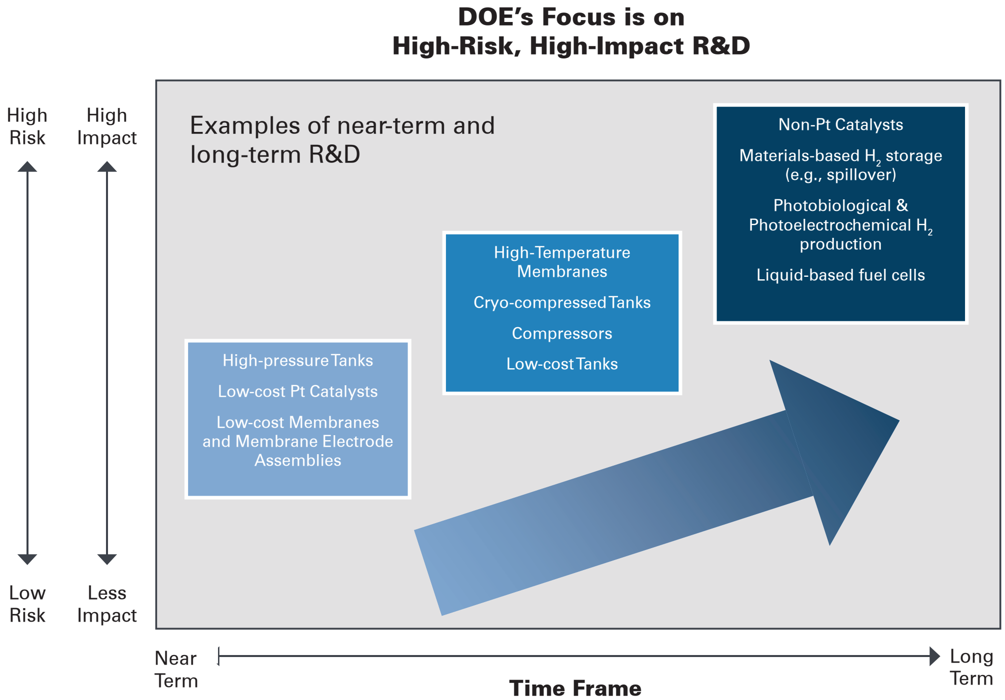


Figure i.3. The Program is focused on high-risk/high-impact R&D.

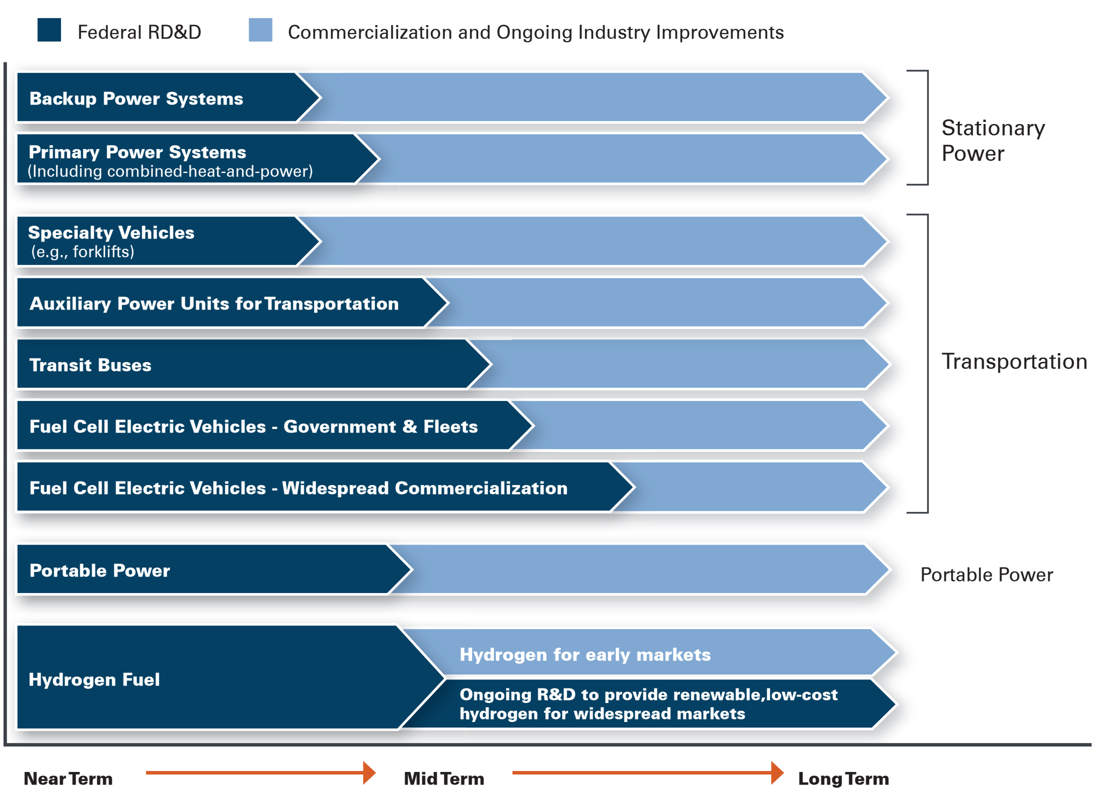


Figure i.4. The Federal Role in RD&D. The Program is pursuing advances in hydrogen and fuel cell technologies in the early stages of development for a variety of applications.

1. Hydrogen and Fuel Cell Applications: *Benefits & Challenges*

Hydrogen and fuel cells can play an important role in our national energy strategy, with the potential for use in a broad range of applications, across virtually all sectors—commercial, industrial, residential, portable, and transportation. This section highlights examples of these applications, the associated benefits, and the remaining challenges.

Commercial Markets & Real-World Demonstrations Today[7]

There are more than 50 commercially available hydrogen and fuel cell products on the market today.

The global market for fuel cells grew to approximately $500 million in 2009.

Approximately 15,000 fuel cells were shipped globally in 2010—more than 40% growth since 2008.

More than 85 megawatts of fuel cells were shipped globally in 2010—more than 50% growth since 2008.

Fuel cells are one of the fastest-growing clean-energy sectors, with 10.3% average annual employment growth from 2003 to 2010.

There are more than 9 million tons of hydrogen produced in the United States today, and more than 1,200 miles of hydrogen pipelines.

In the transportation sector, demonstrations in the United States include:

- More than 200 fuel cell electric vehicles (FCEVs)
- 15 fuel cell buses, with at least 20 more planned
- About 60 hydrogen fueling stations

Looking Forward[7]

Global sales of fuel cells are expected to grow from $598 million in 2010 (projected) to $1.22 billion by 2014.

In 2010–2014, the rate of fuel cell shipments is projected to significantly increase, with annual installed power expected to exceed 1.5 GW by 2014.

Several major car manufacturers—including General Motors, Daimler, Toyota, Honda, and Hyundai—have re-affirmed near-term commercialization goals for FCEVs.

- A survey of automakers estimates deployment of 50,000 FCEVs by 2017 to meet Zero Emission Vehicle mandates.

Germany and Japan have announced aggressive plans for deployments of FCEVs and refueling infrastructure:

- Japan has announced a consortium to enable deployment of 100 hydrogen stations by 2015 and 1,000 stations and 2 million FCEVs by 2025.
- Germany has formed an industry consortium to address hydrogen refueling infrastructure needs.

1.1 Advantages of Hydrogen and Fuel Cells for Diverse Applications

Stationary Power

Stationary fuel cells can be used in a broad range of commercial, industrial, and residential applications and can supplement or even replace power from the electrical grid. These fuel cells can be multi-megawatt systems for large centralized power generation, small units (e.g., one kilowatt) for backup power, or one to a few hundred kilowatt systems for buildings and distributed generation applications, including combined-heat-and-power (CHP) systems (figure 1.1). Examples of key applications include telecommunications sites, office buildings, industrial plants, laboratories, hospitals, data centers, and small businesses, among many others. Because fuel cells can be grid-independent and offer both high reliability and low emissions, they are becoming an attractive option for critical load applications such as data centers, telecommunications towers, emergency response and life support systems, and national defense and homeland security applications. Fuel cell systems can provide intermittent power during periods of high demand and high grid-power cost. High temperature fuel cells have been demonstrated in conjunction with turbines as hybrid systems, achieving electrical efficiencies higher than 60% by using waste heat from the fuel cell to drive other components such as compressors. Fuel cells can also be used to electrochemically separate CO_2 from flue gases in centralized power plants, offering a competitive alternative to conventional approaches to carbon capture.

Distributed Energy Applications and CHP Systems

The advantages of fuel cells for distributed power generation include: elimination of transmission and distribution losses, low emissions, increased reliability, and reduction in bottlenecks and peak demand on the electric grid. They can also provide the very large efficiency improvements inherent in CHP installations, with the potential to use more than 80% of the fuel energy, compared with the 45% to 50% overall efficiency of using electricity from coal or natural gas plants and thermal energy from on-site natural-gas combustion.[8] The lack of criteria pollutant emissions makes fuel cells among the best

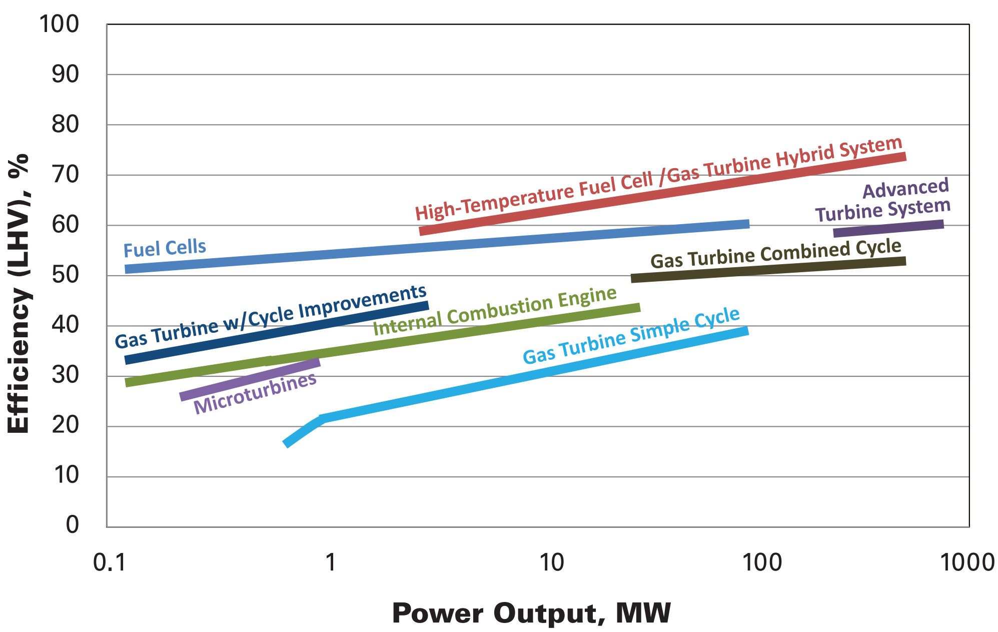


Figure 1.0. Power vs. Efficiency for Stationary Power Technologies. Fuel cells provide very high efficiency for stationary power generation, for a broad range of power output. The highest efficiencies are achieved by high-temperature fuel cell–turbine hybrid systems.[9]

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[7] Sources: *2010 Fuel Cell Technologies Market Report,* DOE, June 2011; *Fuel Cell Technologies Worldwide*, SBI Energy, September 2010; Butler, J., "Green Job Creation in the Fuel Cell Industry: The Next Ten Years," presentation at National Hydrogen Association (NHA) Webinar, March 24, 2010; Hydrogen and Fuel Cells: *The U.S. Market Report*, NHA, March 2010; "U.S. Hydrogen Vehicle Census," Hydrogen Analysis Resource Center, PNNL, accessed September 2, 2011; "U.S. Fuel Cell Bus Projects," NREL, accessed September 30, 2010; "Hydrogen Fueling Station Database," NHA, accessed September 30, 2010; "Automobile Manufacturers Stick up for Electric Vehicles with Fuel Cells," Daimler News, September 9, 2009; California Fuel Cell Partnership, "*Hydrogen Fuel Cell Vehicle and Station Deployment Plan*," April 2010; "Hydrogen Cars Are Still Headed for the Highway," Bloomberg Businessweek, September 22, 2009; Sato, Y., "Overview of Scenario, Roadmap and R&D Projects of Hydrogen and FCEV in Japan," presentation by NEDO, June 4, 2010; *Sizing the Clean Economy: a National and Regional Green Jobs Assessment*, the Brookings Institution, 2011.

[8] *Catalog of CHP Technologies*, U.S. Environmental Protection Agency, December 2008, www.epa.gov/chp/basic/catalog.html.

[9] Adapted from: *Fuel Cell Handbook* (Seventh Edition), EG&G Technical Services, Inc. (for U.S. Department of Energy, Office of Fossil Energy), November 2004, www.netl.doe.gov/technologies/coalpower/fuelcells/seca/pubs/FCHandbook7.pdf.

Figure 1.1. Fuel Cells for CHP Systems. Fuel cells in CHP installations can provide dramatic improvements in efficiency over conventional grid power and on-site natural gas heat.

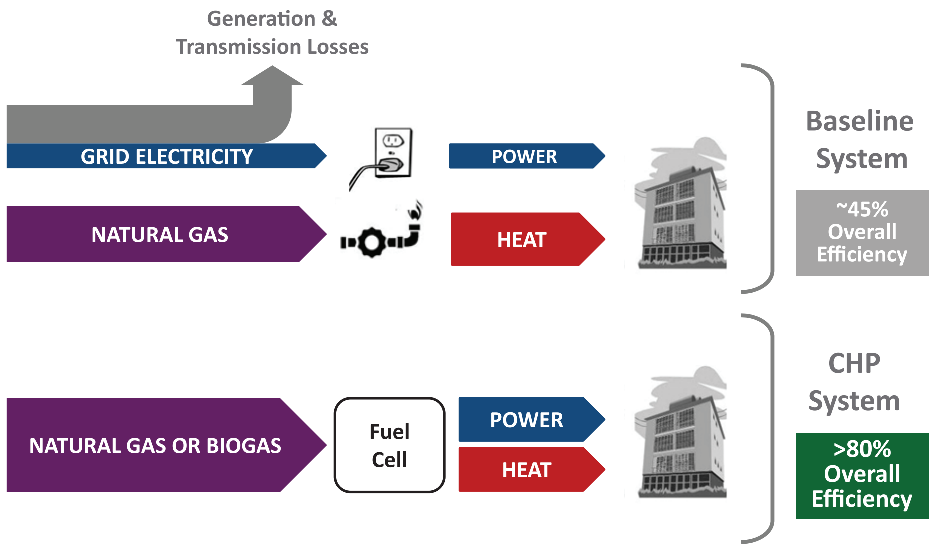
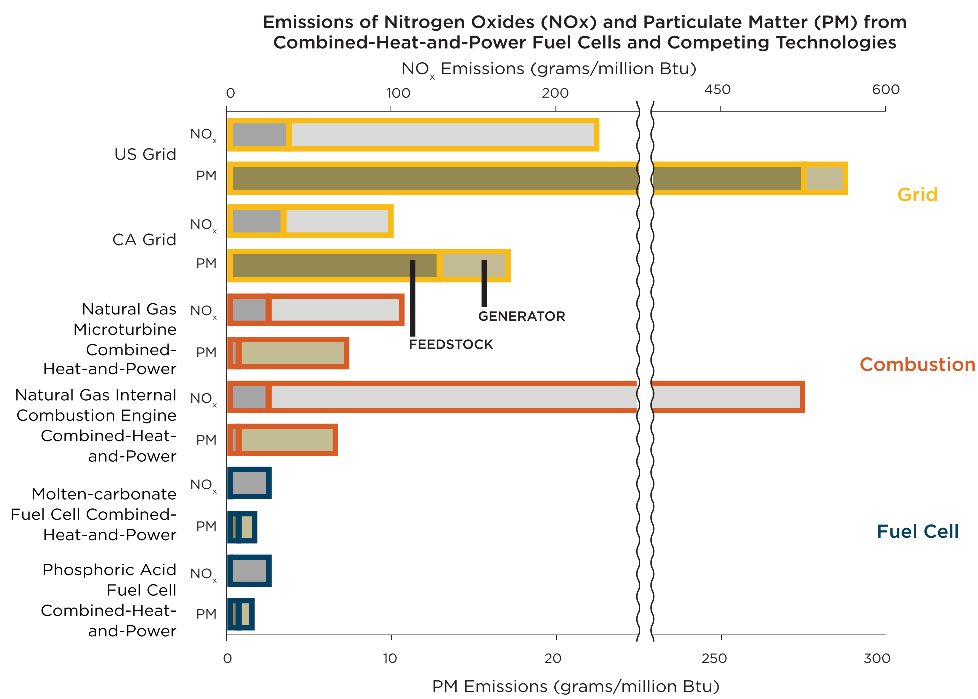
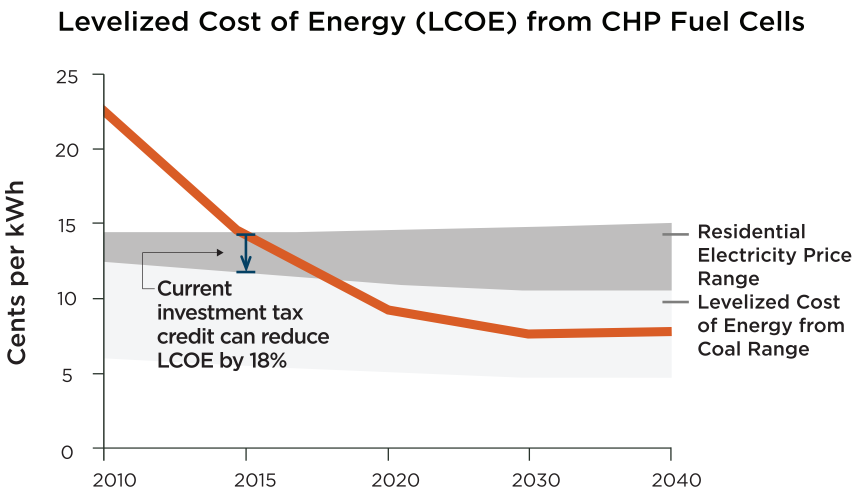


Figure 1.2. Criteria Pollutant Emissions from Generating Heat and Power. Fuel cells emit about 75 – 90% less NOx and about 75 – 80% less particulate matter (PM) than other CHP technologies, on a life-cycle basis. In addition, similar to other CHP technologies, fuel cells can provide more than 50% reduction in CO_2 emissions, when compared with the national grid. "Generator" emissions refer to emissions from the power plant or the CHP system, and "feedstock" emissions refer to the emissions associated with upstream operations, which include the extraction, processing, storage and transportation of fuels.[10]



[10] Wang, MQ; Elgowainy, A; and Han, J. "Life-Cycle Analysis of Criteria Pollutant Emissions from Stationary Fuel Cell Systems," *2010 DOE Hydrogen and Fuel Cells Program Annual Merit Review Proceedings*, U.S. Department of Energy, 2010, www.hydrogen.energy.gov/annual_review10_proceedings.html.



Assumptions	2010	2015	2020	2030	2040
Total Efficiency (HHV)	72.7%	74.8%	78.0%	84.0%	85.2%
CHP Electrical Efficiency (HHV)	39.7%	42.4%	45.1%	46.9%	48.7%
Capital Costs w/o Stack Replacements ($/kWe)	7,200	4,600	2,000	1,000	960
Fixed O&M Costs ($/kWe-yr)	302	204	108	68	67
Variable O&M Costs ($/MWh)	13.7	8.8	3.8	1.9	1.8

Figure 1.3. Example of Levelized Cost of Energy from Fuel Cell CHP Systems.[11] (Note: no carbon costs assumed.)

options for use in nonattainment zones and residential and commercial areas (figure 1.2). Other benefits include their nearly silent and vibration-free operation, ability to use the existing natural gas fuel supply as well as biogas from sources such as wastewater treatment plants and landfill gas facilities, low operation and maintenance requirements, and excellent transient response and load following performance.

Expected advances in CHP fuel cell systems would make them a cost-competitive option for providing light commercial and residential heat and power. While the levelized cost of energy (LCOE) depends on a number of assumptions, figure 1.3 provides an example of the potentially significant reductions in overall LCOE that can be achieved through technology advancements (in terms of both reducing capital cost and improving efficiency) in fuel cell CHP systems.

Backup Power

Fuel cells are emerging as an economically viable option for providing backup power, particularly for telecommunications towers, data centers, hospitals, and communications facilities for emergency services. Compared with batteries, fuel cells offer longer continuous run-times (two- to ten-times longer) and greater durability in harsh outdoor environments under a wide range of temperature conditions. Compared with conventional internal combustion generators, fuel cells are quieter and have low to zero emissions (depending on fuel source). Because fuel cells are modular, backup power systems that use them can be more readily sized to fit a wider variety of sites than those using conventional generators. They also require less maintenance than both generators and batteries.

In a study for DOE, Battelle Memorial Institute found that fuel cells can provide more than 25% savings (when compared with batteries) in the life-cycle costs of specific backup power installations for emergency response radio

[11] Based on analysis conducted by the National Renewable Energy Laboratory and data from *Annual Energy Outlook 2009*, U.S. Energy Information Administration, March 2009, www.eia.gov/oiaf/aeo/pdf/0383(2009).pdf.

towers (excluding additional savings due to existing tax incentives for fuel cells). In the United States, there are currently about 200,000 backup power systems for wireless communications towers.[12] If potential new regulations—requiring longer run-times for these systems—are put in place, fuel cells might be a competitive option for all of these sites. In addition, many developing countries are experiencing explosive growth in new installations of cell phone towers. For example, the number of towers in India is expected to grow from a current base of 240,000 to 450,000 in just three years.[13] As the world's leading supplier of backup-power fuel cells, the United States stands to benefit greatly from growing worldwide demand.

Storage and Transmission of Renewable Energy

Producing hydrogen may provide a cost-effective means of storing and transmitting energy from renewable electricity generation, with minimal or zero emissions. In locations where compressed-air and pumped-hydro energy storage are not feasible (where sufficient underground storage or nearby reservoirs are not available), hydrogen may be a less costly option than other available energy storage technologies. Preliminary analyses have shown that fuel cells using stored hydrogen have the potential to produce electricity for peak demands on a cost-competitive basis with current peak power generation from natural gas combustion engines. Furthermore, because hydrogen is a transportable fuel that can be used in a variety of applications, it can improve the economics of renewable energy generation, providing additional revenue when previously curtailed energy is converted into hydrogen and sold for use in fuel cell electric vehicles, stationary fuel cells, or other applications. Hydrogen can also be transported over large distances through pipelines, which may involve significantly less expense and fewer siting issues than interstate electricity transmission lines. Since many of the renewable resources in the United States are far from the major load centers, a lower-impact, less costly means of energy transmission may be very helpful in enabling increased renewable energy generation. By playing a valuable role in advancing the use of renewable energy, hydrogen can indirectly contribute to the resulting reductions in greenhouse gas emissions, and help to reduce the need for natural gas consumption for peak power generation.

12 "Fuel Cells in Distributed Telecomm Backup," Citigroup Global Markets, August 24, 2005; *Identification and Characterization of Near Term Fuel Cell Markets*, Battelle Memorial Institute, April 2007, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pemfc_econ_2006_report_final_0407.pdf.

13 T. Worthington, "India Telecom Towers, Build 'em High," Reuters, September 1, 2009, http://in.reuters.com/article/idINIndia-42120920090901.

Portable Power

Portable fuel cells are beginning to enter the consumer marketplace, and they are being developed for a range of applications including cell phones, cameras, PDAs, MP3 players, laptop computers, as well as portable generators and battery chargers, which are of particular interest for military applications. Fuel cells can have significant advantages over batteries, including rapid recharging and higher energy density—allowing up to twice the run-time of lithium ion batteries of the same weight and volume. An independent market research firm has estimated that the worldwide market for portable fuel cells could exceed $38 billion by 2017.[14]

Transportation

Auxiliary Power—Trucks, Aircraft, Rail, and Ships

Fuel cells can provide clean, efficient auxiliary power for trucks, recreational vehicles, marine vessels (yachts, commercial ships), airplanes, locomotives, and similar applications that have significant auxiliary power demands.

14 "Fuel Cells for Portable Power Applications," Pike Research, 2011, www.pikeresearch.com.

In many of these applications, the primary motive-power engines are often kept running solely for auxiliary loads. This is an inefficient practice, resulting in significant additional fuel consumption and emissions.

For the approximately 500,000 long-haul Class 7 and Class 8 trucks in the United States, emissions during overnight idling have been estimated to be 10.9 million tons of CO_2 and 190,000 tons of NOx annually.[15] The use of auxiliary power units (APUs) for Class 7–8 heavy trucks to avoid overnight idling of diesel engines could save up to 280 million gallons of fuel per year and avoid more than 92,000 tons of NOx emissions.[16]

Pollution from commercial cargo ships has also become a matter of concern, as these vessels rely almost exclusively on diesel generators for their power while in port. According to the U.S. Environmental Protection Agency (EPA), commercial ships are responsible for more than 15% of the ozone concentration and particulate matter in some port areas. In addition, EPA has stated that marine diesel engines "are significant contributors to air pollution in many of our nation's cities and coastal areas," emitting substantial amounts of NOx and PM.[17] Idling of commercial aircraft engines is also responsible for excessive emissions, as the use of these

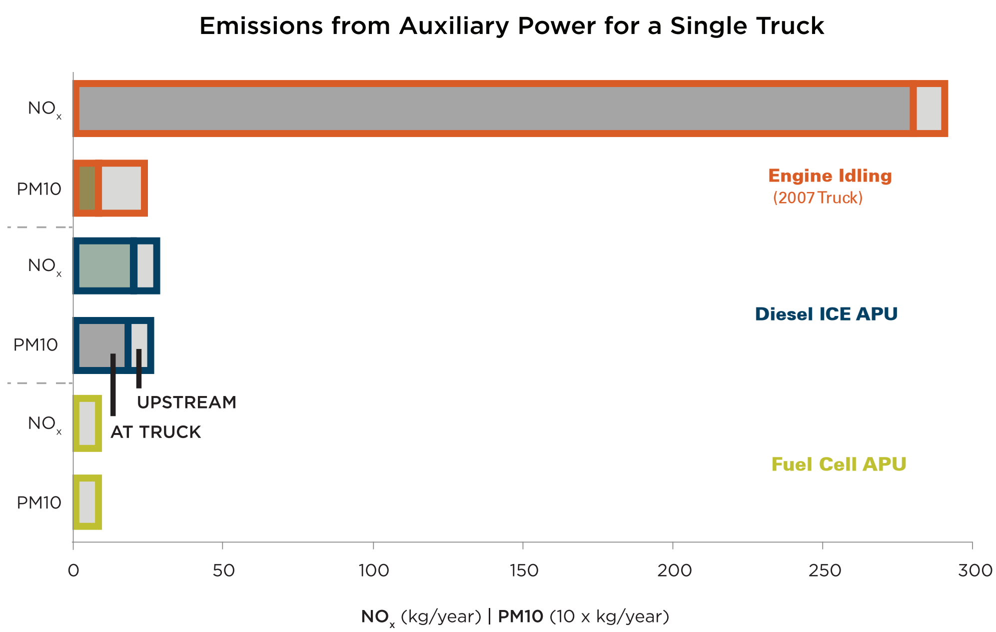


Figure 1.4. Emissions of Criteria Pollutants from Auxiliary Power for Trucks. Fuel cell auxiliary power units (APUs) can achieve significant reductions in criteria pollutant emissions over diesel internal combustion engine APUs and truck engine idling, while still using the truck's existing supply of diesel fuel. A key benefit of fuel cells is that they only emit negligible NOx and particulate matter at the point of use (at the truck) which can have substantial benefits for local air quality. In addition, fuel cell APUs can achieve more than 60% reduction in CO_2 emissions over truck engine idling.[18]

15 N. Lutsey, C. Brodrick, T. Lipman, "Analysis of Potential Fuel Consumption and Emissions Reduction from Fuel Cell Auxiliary Power Units (APUs) in Long Haul Trucks," Elsevier Science Direct, Energy 32, September 2005.

16 L. Gaines and C. Hartman, "Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks," Center for Transportation Research, Argonne National Laboratory, November 2008; and *Idle Reduction Technology: Fleet Preferences Survey*, American Transportation Research Institute (prepared for New York State Energy Research and Development Authority), February 2006.

17 "Ocean-going Vessels," U.S. Environmental Protection Agency website, accessed October 7, 2010, www.epa.gov/otaq/oceanvessels.htm.

18 L. Gaines and C. Hartman, "Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks," Center for Transportation Research, Argonne National Laboratory, November 2008; fuel cell APUs on freight trucks are expected to emit an insignificant amount of criteria pollutants at the truck, even when diesel is assumed to be the input feed to the on-board reformer. The upstream emissions (from activities preceding the use in an APU or truck engine—e.g., crude oil extraction, transportation and refining, diesel transportation, etc.) of diesel are the same for each unit volume used by the fuel cell or by the conventional APU. Furthermore, it was conservatively estimated that a fuel cell APU would consume a similar amount of diesel as an ICE APU, resulting in comparable overall CO_2 emissions. Actual CO_2 emissions by fuel cell APUs are likely to be lower, and improvements in the efficiency of diesel reformers and fuel cells will result in further reductions.

engines at low power settings results in incomplete combustion, which produces carbon monoxide and unburned hydrocarbons.[19]

While aircraft that have APUs rely less on main engine idling, the gas turbine APUs that are used operate at low efficiency and emit criteria pollutants, contributing significantly to local pollution at airports. Additionally, the high auxiliary power loads required during flight operations—up to 500 kW on larger commercial aircraft—are responsible for a significant portion of in-flight emissions. APU fuel cells installed on aircraft can reduce emissions during flight as well as gate and taxiing operations. Analysis of Air Force cargo planes found that the use of fuel cell APUs could result in a 2% to 5% reduction in the total amount of aircraft fuel used by the Air Force,[20] saving 1 million to 3 million barrels of jet fuel and avoiding 900 to 2,200 tons of NOx emissions per year. Fuel cells also produce usable water, which could reduce the amount of water an aircraft needs to carry, reducing overall weight and resulting in further fuel savings.

For providing auxiliary power, fuel cells may be a more attractive alternative to internal combustion engine generators, because they are more efficient and significantly quieter, but they are still able to use the vehicle's existing supply of diesel or jet fuel (in addition to other fuel options that include hydrogen, biofuels, propane, and natural gas). Also, because fuel cells produce no NOx or particulate emissions, they can help improve air quality in areas where there is a high concentration of auxiliary power use—such as airports, truck stops, and ports, and they can be used in EPA-designated nonattainment areas, where emissions restrictions limit the use of internal combustion engine generators. Fuel cells may also offer an attractive alternative to batteries, because they are lighter and do not require long recharge times.

Emissions from idling and auxiliary power are likely to be the subject of increasing regulations in the future. Idling restrictions for heavy-duty highway vehicles have already been enacted in 30 states;[21] in 2008 the EPA adopted new requirements for limiting idling emissions from locomotives;[22] also in 2008, the EPA finalized a three-part program to reduce emissions from marine diesel engines, with rules phasing in from 2008 through 2014;[23] and regulations could also emerge to limit emissions from aircraft while they are on the ground. Fuel cells have the potential to play an important role in all of these applications.

Motive Power — Specialty Vehicles, Light-duty Vehicles, Buses, and Short-haul Trucks

Fuel cells powered by hydrogen and methanol have become a cost-competitive option for some transportation applications. The specialty vehicle market—which includes lift trucks, airport tugs, etc.—has emerged as an area of early commercial success for fuel cells. Specialty vehicles usually require power in the 5- to 20-kW range, and they often operate in indoor facilities where air quality is important and internal combustion engines cannot be used. Lift trucks (including forklifts and pallet trucks) powered by fuel cells are currently in use in commercial applications by several major U.S. companies.

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19 "Safeguarding Our Atmosphere," National Aeronautics and Space Administration Glenn Research Center website, accessed October 7, 2010, www.nasa.gov/centers/glenn/about/fs10grc.html.

20 *DESC Fact Book 2009*, U.S. Defense Logistics Agency, www.desc.dla.mil.

21 Nguyen, T., U.S. Department of Energy, "Market for Fuel Cells as Auxiliary Power Units on Heavy Trucks," *2009 NHA Hydrogen Conference Proceedings*, National Hydrogen Association, www.hydrogenconference.org/proceedings.asp.

22 "Control of Emissions from Idling Locomotives," U.S. Environmental Protection Agency website, accessed October 7, 2010, www.epa.gov/otaq/regs/nonroad/locomotv/420f08014.htm.

23 "Diesel Boats and Ships," U.S. Environmental Protection Agency website, accessed October 7, 2010, www.epa.gov/otaq/marine.htm.

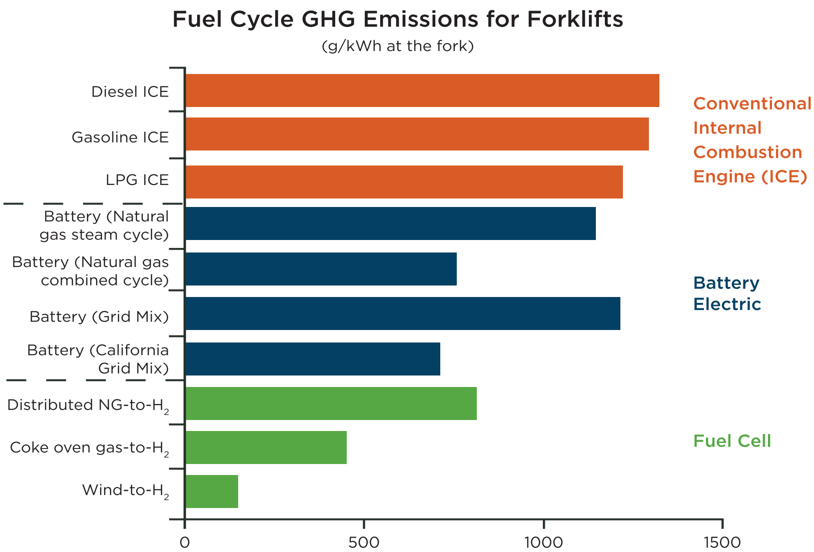


Figure 1.5. Greenhouse Gas Emissions from Forklifts. Specialty vehicles (including forklifts, lift trucks, and others) have become a key early market for fuel cells, where hydrogen and fuel cells can offer substantial reductions in emissions and significant benefits to the end-user in terms of economics and performance.[24]

Fuel cells offer advantages over batteries for specialty vehicles. While both can be used indoors, without emitting any criteria pollutants, fuel cells can increase operational efficiency—and raise productivity—because refueling them takes much less time than changing batteries. While changing forklift batteries can take from 15 to 30 minutes, refueling a fuel cell–powered forklift with hydrogen takes less than three minutes, and fuel cell forklifts using methanol can be refueled even faster. This makes fuel cells a particularly appealing option for continuously used lift trucks running two or three shifts per day, which require multiple battery change-outs and incur significant labor costs. Furthermore, the voltage delivered by a fuel cell is constant as long as fuel is supplied, unlike battery-powered forklifts, which lose power as the batteries are discharged, significantly reducing overall performance and productivity. And, since fuel cells do not require storage space, battery change-out equipment, chargers, or a dedicated area for changing batteries, less space is required. The Battelle study mentioned earlier found that fuel cells used in lift trucks can provide up to 50% savings in life-cycle costs over batteries.[25]

These applications have broader environmental and economic benefits as well. Using fuel cells (powered by hydrogen from natural gas) could reduce the energy consumption of lift trucks by up to 29% and their greenhouse gas emissions by up to 38%, when compared with lift trucks using conventional internal combustion engines. When compared with batteries charged by grid power (average grid mix), the use of fuel cells could reduce the energy consumption of lift trucks by up to 14% and their greenhouse gas emissions by up to 33% (see fig. 1.5). The lift truck market in the United States involves sales of approximately 170,000 units per year and annual revenues of more than $3 billion; it is expected to grow 5% per year through 2013.[26] It is estimated that more than 20,000 U.S. manufacturing jobs would be created if U.S.

[24] *Full Fuel-Cycle Comparison of Forklift Propulsion Systems*, Argonne National Laboratory, October, 2008, www.transportation.anl.gov/pdfs/TA/537.pdf.

[25] *Identification and Characterization of Near Term Direct Hydrogen PEM Fuel Cell Markets,* Batelle Memorial Institute, April 2007, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pemfc_econ_2006_report_final_0407.pdf.

[26] Ibid.

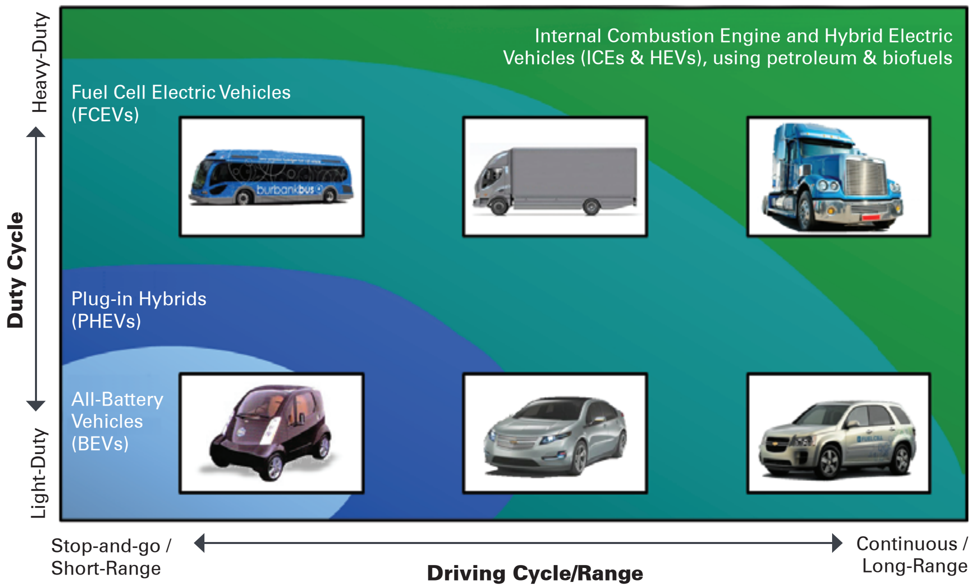


Figure 1.6. Diverse Technologies for Transportation Needs. A diverse portfolio of vehicle technologies will be required to meet the full range of driving cycles and duty cycles in the nation's vehicle fleet. Fuel cells can play a central role, enabling longer driving ranges and heavier duty cycles for certain vehicle types (graphic adapted from General Motors).

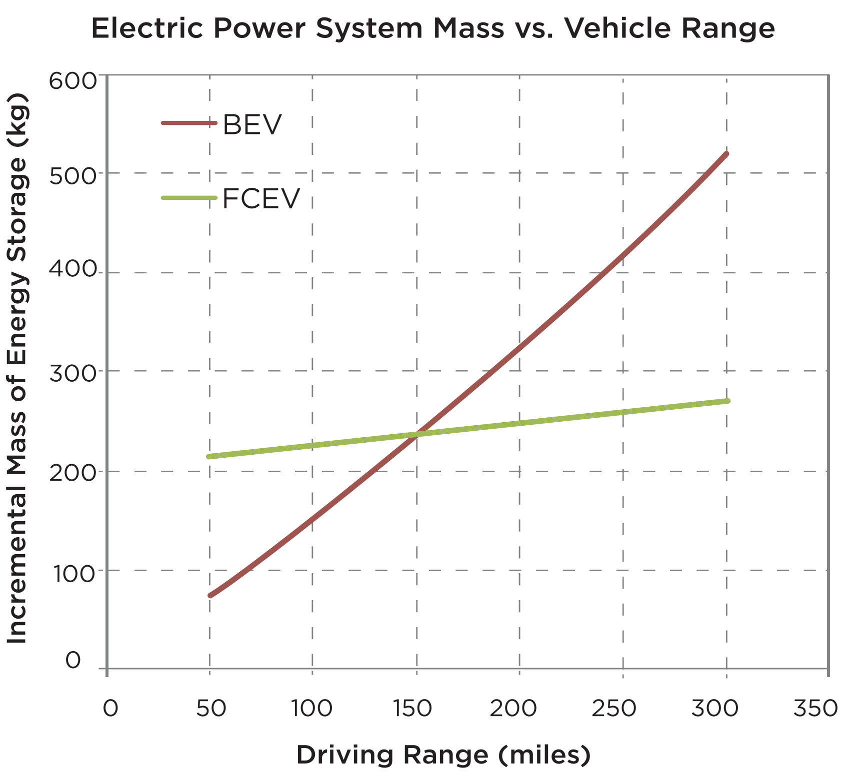


Figure 1.7. Range and Mass of Energy Storage Systems for Battery Electric Vehicles (BEVs) and FCEVs.[27] Battery system mass is preferable for short driving ranges (<150 miles), but FCEVs have much lower system mass (including the fuel cell and hydrogen storage systems) at longer driving ranges.

[27] Mathias, M. (General Motors, Inc.), "Electrification Technology and the Future of the Automobile," 2010 Advanced Energy Conference, November 2010, http://www.aertc.org/conference2010/speakers/AEC%202010%20Session%201/1F%20ESO%20for%20Trans.%20App/Mark%20Mathias/mathias%20presSECURED.pdf

fuel cell manufacturers could capture 50% of the current global market for battery-powered lift trucks.[28] Ongoing improvements in fuel cell technologies will enable industry to further capitalize on the early success in these and other markets for specialty vehicles.

Fuel cells are also being developed for mainstream transportation, where they can be used in a number of applications, including personal vehicles, fleet vehicles (for municipal and commercial use), transit buses, short-haul trucks (such as delivery trucks and drayage trucks for port facilities), and others. Many automobile manufacturers around the world, and several transit bus manufacturers, are developing and demonstrating fuel cell electric vehicles today. The timeline for market readiness varies, but several companies—including Daimler, Toyota, Honda, General Motors, Hyundai, and Proterra—have announced plans to commercialize before 2015.

Due to the unique characteristics (including size, weight, and performance) required for motive-power systems, the type of fuel cell used in vehicles is the polymer electrolyte membrane (PEM) variety, operating on pure hydrogen. In light-duty vehicles, these fuel cells have demonstrated system efficiencies of 53 to 59% (see figure 2.6)—more than twice the efficiency that can be expected from gasoline internal combustion engines (ICEs), and substantially higher than even hybrid electric power systems. In transit buses, fuel cells have demonstrated more than 40% higher fuel economy than diesel ICE buses and more than double the fuel economy of natural gas ICE buses.[29] Fuel cell electric vehicles operate quietly and with all the performance characteristics that are expected of today's vehicles. Most significantly, there are no direct emissions of CO_2 or criteria pollutants at the point of use.

Analysis of complete life-cycle emissions (or "well-to-wheels emissions") conducted using models developed by Argonne National Laboratory indicate that the use of hydrogen fuel cell electric vehicles will produce among the lowest quantities of greenhouse gases per mile of all conventional and alternative vehicle and fuel pathways being developed (figure 1.8a). Even in the case where hydrogen is produced from natural gas (which is likely to be the primary mode of production for the initial introduction of fuel cell electric vehicles), the resulting life-cycle emissions per mile traveled will be about 40% less than those from advanced gasoline internal combustion engine vehicles, 15% less than those from advanced gasoline hybrid electric vehicles, and about 25% less than those from gasoline-powered plug-in hybrids.

When hydrogen is produced from renewable resources (such as biomass, wind, or solar power), nuclear energy, or coal (with carbon sequestration), overall emissions of greenhouse gases and criteria pollutants are minimal. There are some emissions associated with the delivery of hydrogen to the point of use, but these are relatively minor.

[28] Jobs estimate based on preliminary analysis using Argonne National Laboratory's jobs estimation tool and the following: Assuming that battery-powered lift trucks comprise 2/3 of total sales, 50% of the worldwide market would be approximately 247,000 lift trucks per year (based on total worldwide lift-truck shipments of about 740,000 in 2010--source: "Lifts Trucks: Top 20 Lift Truck Suppliers, 2011," Modern Materials Handling, August 1, 2011, www.mmh.com/article/lift_trucks_top_20_lift_truck_suppliers_2011/).

[29] "Technology Validation: Fuel Cell Bus Evaluations," *DOE Hydrogen Program 2010 Annual Progress Report*, http://hydrogen.energy.gov/annual_progress.html.

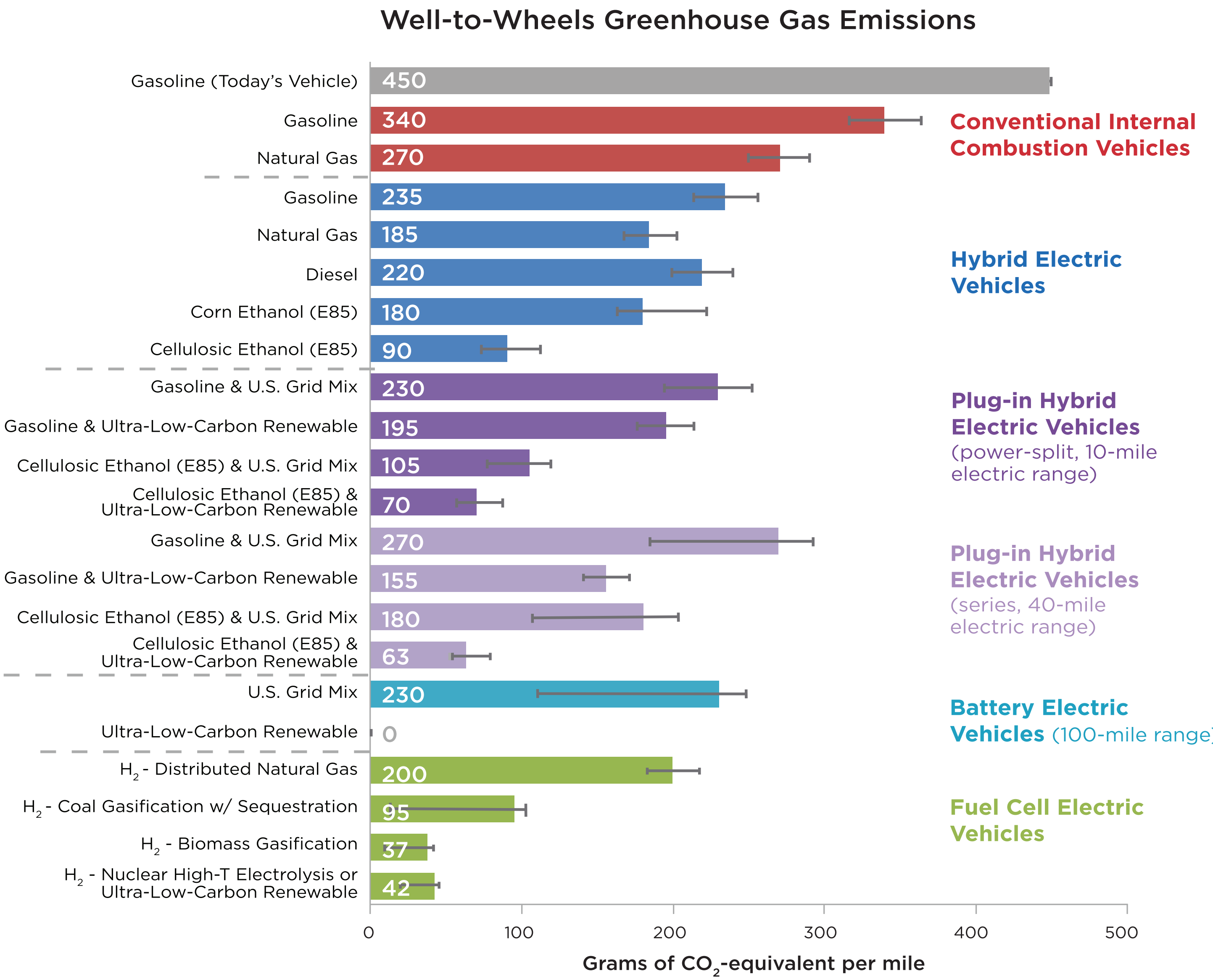


Figure 1.8a. Well-to-Wheels Analysis of Greenhouse Gas Emissions.
Substantial reductions in greenhouse gas emissions are possible through the use of a variety of advanced transportation technologies and fuels, including fuel cell electric vehicles using hydrogen from a variety of sources. Notes: (1) analysis based on a mid-sized car; (2) assumes the state of the technologies expected in 2035–2045; (3) ultra-low-carbon renewable electricity includes wind, solar, etc.; (4) the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning are not accounted for.[30]

[30] DOE Hydrogen and Fuel Cells Program Record #10001, http://hydrogen.energy.gov/program_records.html.

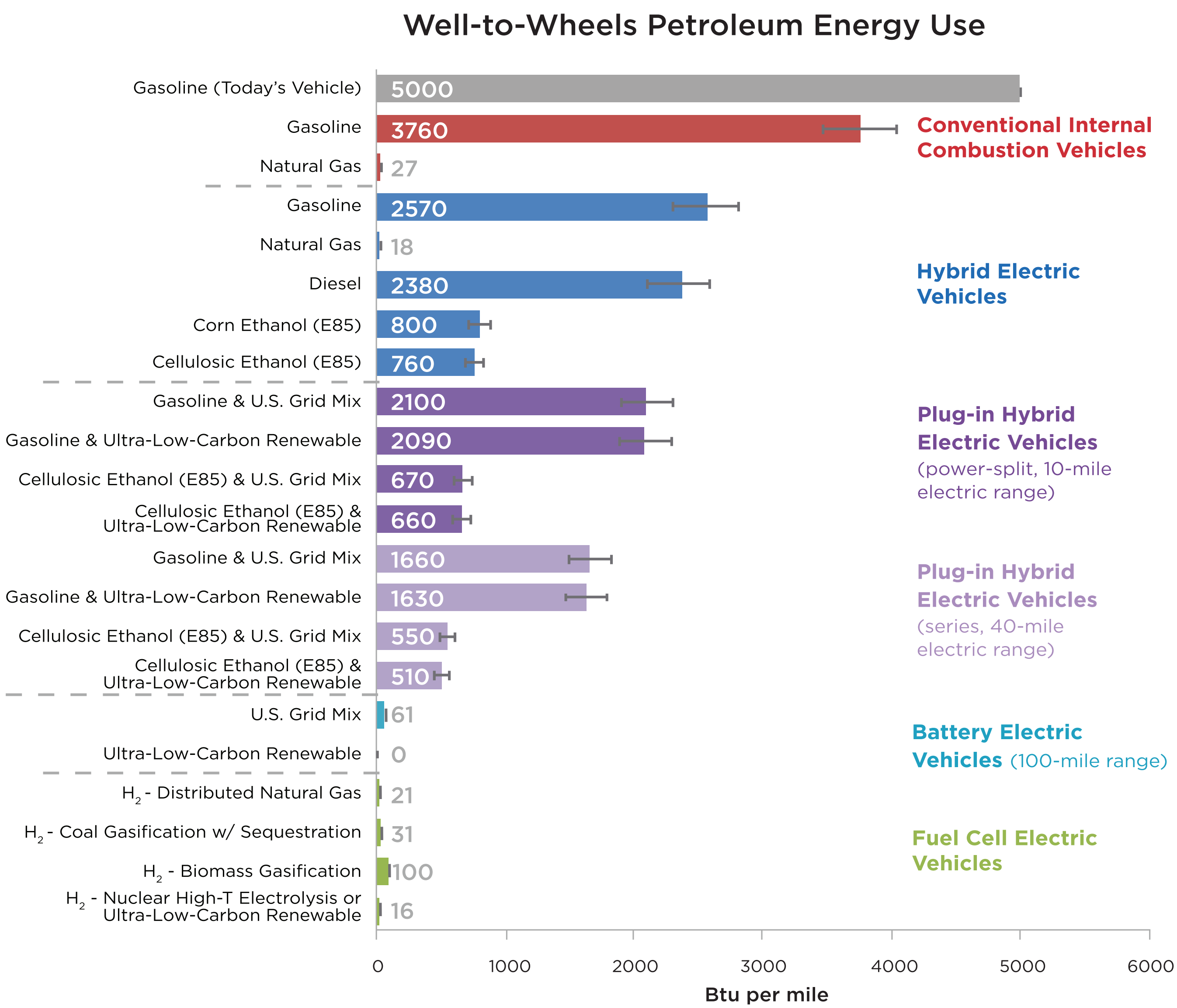


Figure 1.8b. Well-to-Wheels Analysis of Petroleum Use.
Substantial reductions in petroleum consumption are possible through the use of a variety of advanced transportation technologies and fuels, including fuel cell electric vehicles using hydrogen from a variety of sources. Notes: (1) analysis based on a mid-sized car; (2) assumes the state of the technologies expected in 2035–2045; (3) ultra-low-carbon renewable electricity includes wind, solar, etc.; (4) the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning are not accounted for.[31]

[31] DOE Hydrogen and Fuel Cells Program Record #10001, http://hydrogen.energy.gov/program_records.html.

1.2 Potential Impacts of the Widespread Use of Hydrogen and Fuel Cells

Climate Change and Air Quality

The most substantial environmental benefits from fuel cells will come from their use in the stationary power and transportation sectors, where the markets are very large and a significant amount of energy is consumed.

In the stationary power sector, the use of fuel cells in distributed applications can provide reductions in emissions over both distributed and central generation technologies. The high electrical efficiency of fuel cells will enable lower emissions when compared with conventional distributed power technologies such as internal combustion engines or turbines. Emissions reductions can be even more substantial through the use of CHP for distributed energy—which can be greatly expanded by fuel cells, due to their clean and quiet operation. Fuel cells, like other distributed energy technologies, can achieve very high efficiencies when used in CHP systems, far surpassing those of even the most advanced centralized generation facilities. Even greater emissions reductions are possible when fuel cells use biogas, which has near-zero life-cycle emissions.

In addition, hydrogen has the potential to contribute to reducing emissions from stationary power generation, by functioning as an energy storage medium that helps enable the expansion of power generation from intermittent renewable resources, such as wind, solar, and ocean energy. Hydrogen

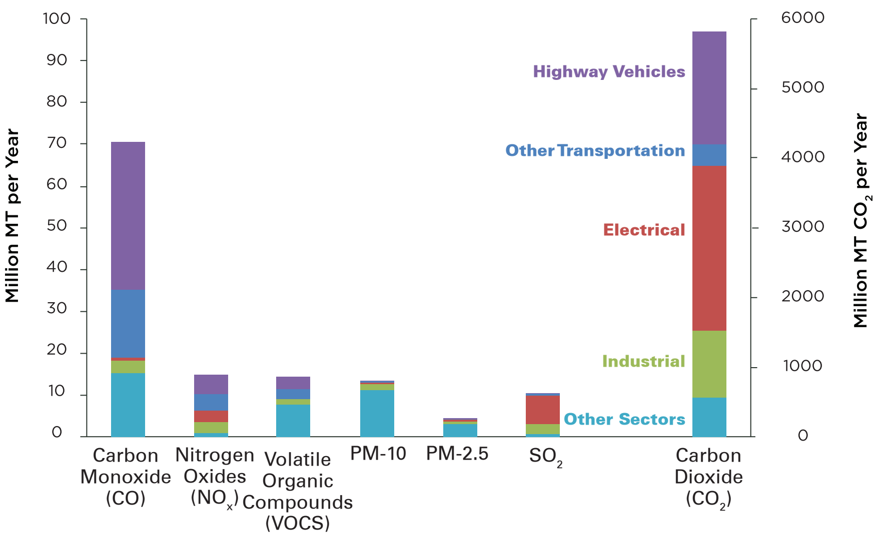
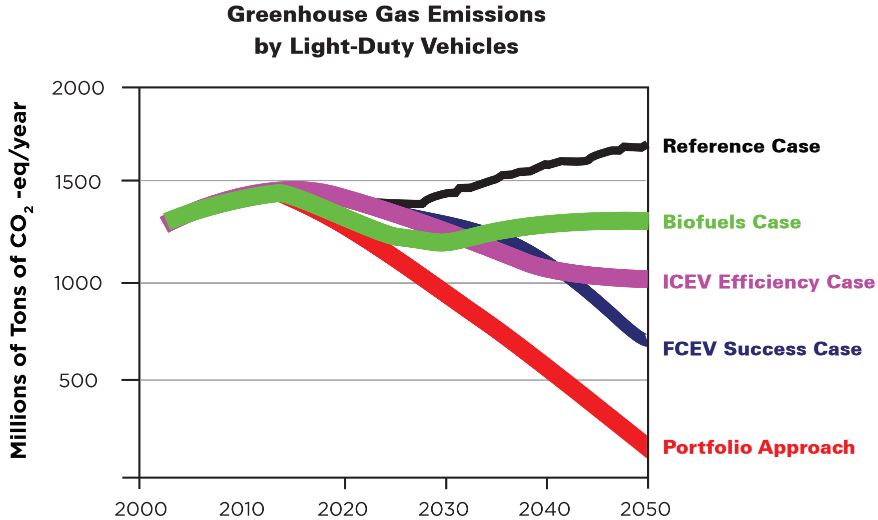


Figure 1.9. Emissions from Fossil Fuels in the United States. Fossil fuels are major contributors to air pollution and greenhouse gas emissions.[32] Fuel cells can convert conventional fossil fuels and low- to zero-carbon renewable fuels into usable energy with significantly reduced emissions.

[32] U.S. Environmental Protection Agency, National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data, 2008, www.epa.gov/ttnchie1/trends/; Energy Information Administration, *Annual Energy Outlook 2010*, Table 18: Carbon Dioxide Emissions by Sector and Source, www.eia.doe.gov/oiaf/aeo/aeoref_tab.html; Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2008*, December 2009, www.eia.doe.gov/oiaf/1605/ggrpt/pdf/0573%282008%29.pdf.

Figure 1.10. Reduced Greenhouse Gas Emissions. Significant reductions in greenhouse gas emissions could be achieved through the use of fuel cells—making substantial gains toward the goal of 80% reduction in CO_2 emissions by 2050. The portfolio approach shown here assumes a significant introduction of fuel cell electric vehicles (FCEVs) to the market, the maximum practical rate of improvements in internal combustion engine vehicle (ICEV) efficiency (including hybrid electric vehicles), and large-scale use of biofuels. Graph adapted from the National Academies report, *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*.[33]



functions as a storage medium when it is produced through electrolysis, using surplus electricity (when generation exceeds demand), and later converted back into electricity using fuel cells or turbines (when demand exceeds generation). In addition to helping balance generation and load, energy storage at the regional level can also increase network stability and power quality and improve frequency regulation. In addition, hydrogen produced by surplus renewable power may also improve the economics of renewable power installations, as these facilities may gain a valuable revenue stream by selling their surplus hydrogen for use in fuel cell electric vehicles, stationary fuel cells, and other applications.

For transportation applications, the greatest impacts will come from the use of fuel cells in light-duty vehicles, which suffer from the least efficient use of energy by any major sector of our economy. The National Academies' 2008 study *Transitions to Alternative Transportation Technologies* found that fuel cell electric vehicles could reduce CO_2 emissions from the light-duty vehicle fleet by 19% in 2035 and 60% (or more than one billion metric tons per year) in 2050.

Furthermore, the same study found that CO_2 emissions from light duty vehicles could be reduced by nearly 60% in 2035 and nearly 90% in 2050 using a portfolio of technologies including fuel cells, improved vehicle efficiency (for internal combustion engines and hybrid systems), and biofuels. Although plug-in hybrid-electric vehicles and biofuels have the potential to achieve impacts sooner than fuel cell electric vehicles, the National Academies have concluded that fuel cells would provide the largest reductions in emissions by 2050, and that no single technology approach could achieve an 80% reduction in CO_2 emissions alone (see figure 1.10).

[33] *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*, National Research Council of the National Academies, 2008, www.nap.edu/catalog.php?record_id=12222; Reference Case is based on the Energy Information Administration's *2008 Annual Energy Outlook* high-oil-price scenario; FCEV Success Case ("Hydrogen Success Case" in the National Academies Report) assumes that development programs are successful and policies are implemented to ensure commercial deployment; ICEV Efficiency Case assumes maximum practical rate of efficiency improvement for ICEVs (including hybrid electric vehicles), resulting in more than doubling in fuel economy by 2050; Biofuels Case assumes large-scale use of biofuels from crop and cellulosic feedstocks, at a maximum practical production rate; Portfolio Approach assumes that all of these advances are pursued simultaneously.

Energy Security

A significant challenge to the nation's energy security is our increasing use of petroleum (figure 1.11). Because more than 70% of our petroleum consumption occurs in the transportation sector[34] (with most of the remainder being used in various industrial processes), this will be where fuel cells will have the most substantial energy security benefits.

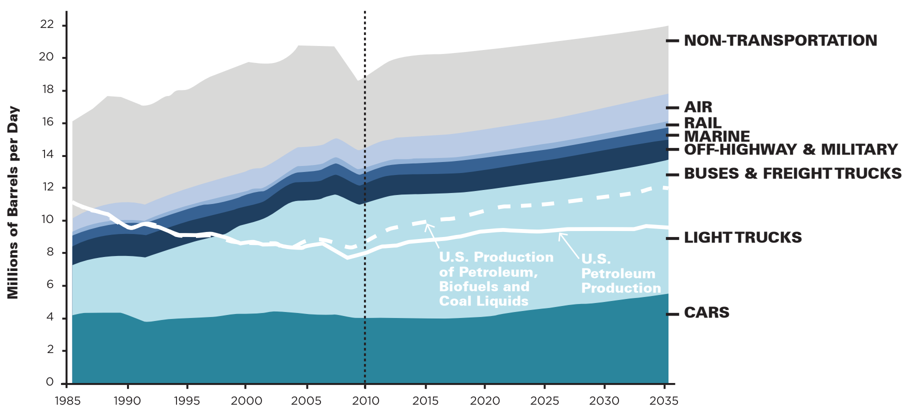


Figure 1.11. America's Widening "Oil Gap." America's reliance on imported oil is the key challenge to our energy security. While oil is used in all sectors and for a wide variety of purposes, the large majority is used for transportation—and a majority of that is used in light-duty passenger vehicles (cars and light trucks).[35]

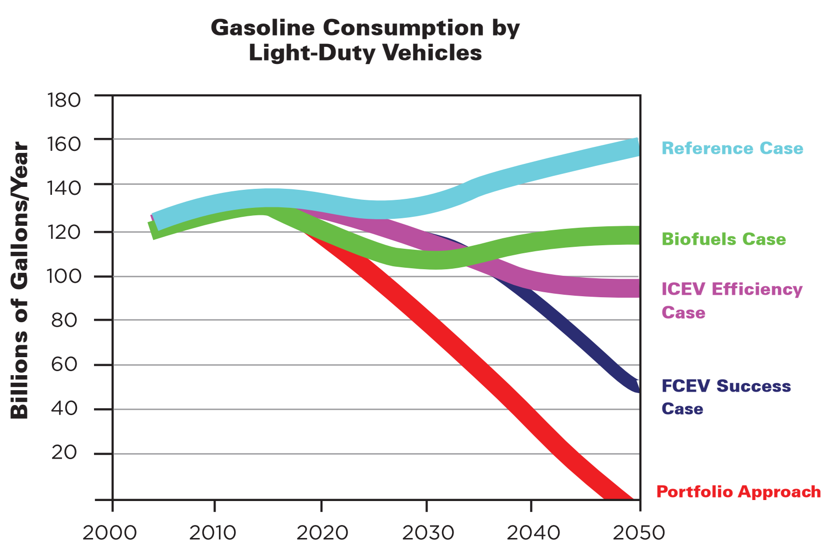


Figure 1.12. Reduced Oil Consumption. Significant reductions in the nation's consumption of oil could be achieved through the use of fuel cells—making substantial gains toward the long-term goal of independence from imported oil. The portfolio approach shown here assumes a significant introduction of fuel cell electric vehicles (FCEVs) to the market, the maximum practical rate of improvements in internal combustion engine vehicle (ICEV) efficiency (including hybrid electric vehicles), and large-scale use of biofuels. Graph adapted from the National Academies report, *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen.*[36]

34 *Annual Energy Review 2009*, Energy Information Administration, August 2010, www.eia.gov/FTPROOT/multifuel/038409.pdf.

35 Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 29, ORNL-6985*, July 2010, http://info.ornl.gov/sites/publications/files/pub24318.pdf; Energy Information Administration, *Annual Energy Outlook*, April 2010, www.eia.doe.gov/oiaf/aeo/pdf/0383(2010).pdf.

36 *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*, National Research Council of the National Academies, 2008, www.nap.edu/catalog.php?record_id=12222; Reference Case is based on the Energy Information Administration's *2008 Annual Energy Outlook* high-oil-price scenario; FCEV Success Case ("Hydrogen Success Case" in the National Academies report) assumes that development programs are successful and policies are implemented to ensure commercial deployment; ICEV Efficiency Case assumes maximum practical rate of efficiency improvement for ICEVs (including hybrid electric vehicles), resulting in more than doubling in fuel economy by 2050; Biofuels Case assumes large-scale use of biofuels from crop and cellulosic feedstocks, at a maximum practical production rate; Portfolio Approach assumes that all of these advances are pursued simultaneously.

The National Academies' *Transitions* study projects that the use of fuel cell electric vehicles could reduce gasoline consumption by 24% (or 34 billion gallons per year) in 2035 and 69% (or 109 billion gallons per year) in 2050. If a portfolio of technologies were employed, gasoline consumption could be reduced nearly 60% by 2035 and 100% by 2050. As with their CO_2 reduction estimates, the National Academies found that fuel cell electric vehicles would provide the largest reductions in gasoline use by 2050, and that no single technology approach could achieve total elimination of gasoline consumption alone.

Economic Competitiveness

International Interest & Investment

Worldwide interest in fuel cell technologies is substantial and growing—this is reflected in a dramatic increase in public and private spending since the mid-1990s. The U.S. government investment of approximately $1.5 billion for fuel cell technology RD&D activities over six years, from fiscal years 2004 to 2009, is on par with investments for similar activities by Japan, the European Commission, and Germany, of approximately $383 million in 2009, $625 million over the next five years, and $744 million over the next eight years, respectively. The Japanese government is investing heavily in fuel cells, spending an average of approximately $295 million annually over the past five years. In addition to research activities, the Japanese Ministry of Economy, Trade and Industry (METI) partnered with industry to demonstrate more than 60 fuel cell electric vehicles and over 3,300 stationary residential fuel cells. In March 2010, Japan announced plans for 1,000 hydrogen stations and 2 million fuel cell electric vehicles by 2025. A consortium of 13 companies was established to focus on a hydrogen infrastructure to support these goals.

In October 2008, the European Commission launched a €1 billion ($1.3 billion), six-year public-private initiative, the Fuel Cell and Hydrogen Joint Technology Initiative, with the

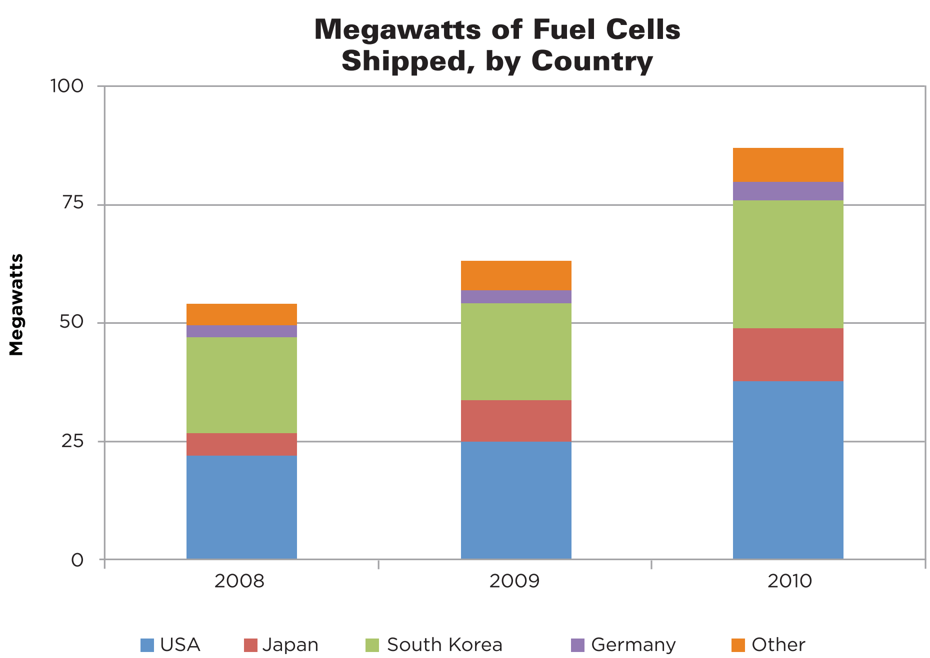


Figure 1.13. Fuel cell shipments, in terms of megawatts, continue to increase (~36% in 2010), and global competition is increasing. U.S. shipments grew by more than 50% in 2010.[37]

[37] *Fuel Cell Technologies Market Report*, U.S. Department of Energy, May 2011, www.hydrogenandfuelcells.energy.gov/pdfs/2010_market_report.pdf.

aim of "making fuel cells and hydrogen one of Europe's leading new strategic energy technologies of the future."[38] And Germany has launched a National Innovation Program on Hydrogen and Fuel Cell Technology, which will invest over $1 billion between 2008 and 2016. Germany has also announced an industry consortium to address hydrogen refueling infrastructure needs. In addition, Korea has announced a strategic plan to become a global leader in fuel cell manufacturing, with key objectives of supplying 20% of global fuel cell shipments and creating 560,000 jobs.[39] The Korean government also announced a program to pay 80% of the cost of residential fuel cells, which would provide a significant boost to Korea's domestic fuel cell industry and increase its capacity to compete in global markets.

Private industry is also making investments to pursue what could ultimately be a major global market for stationary, portable, and automotive fuel cells. A survey of the fuel cell industry conducted by PricewaterhouseCoopers put global R&D spending in the private sector at nearly $830 million and employment at close to 9,000 in 2006 (with just over 60% of "key industry organizations" reporting).[40]

Potential Employment and Market Growth

The potential for long-term employment growth from the widespread use of fuel cells in the United States is substantial. A study commissioned by DOE found that successful widespread market penetration by fuel cells could help to revitalize the manufacturing sector and could add more than 180,000 net new jobs to the U.S. economy by 2020, and more than 675,000 net new jobs by 2035.[41] A separate study, conducted by the American Solar Energy Society to quantify the economic benefits of renewable energy and energy efficiency technologies,[42] found that gross revenues in the U.S. fuel cell and hydrogen industries could reach up to $81 billion/year by 2030, with total employment (direct and indirect) reaching over 900,000—this is based on the most aggressive scenario, which represents what is "technologically and economically feasible." The base-case or "business as usual" case of this study shows these industries achieving about $9 billion/year in gross revenues by 2030, with more than 110,000 new jobs created.

Analyses of the near- to mid-term market for fuel cells also indicate substantial potential growth (a 2011 estimate of fuel cell industry employment by Fuel Cells 2000 indicates more than 13,000 total direct fuel cell industry jobs worldwide, with more than 25,000 associated supply-chain jobs[43]). Fuel Cell Today's 2010 Industry Review predicts that by 2020 the global fuel cell industry could create over 700,000 new jobs in manufacturing, and as many as 300,000 additional jobs in installation, service, and maintenance.[44] And a study conducted by the Connecticut Center for Advanced Technology[45] estimates that the global fuel cell/hydrogen market could reach maturity over the next 10 to 20 years; the

38 "Developing New Energy for the Future: Europe Launches a 1 Billion Euro Project to Get into Pole Position for the Fuel cells and Hydrogen Race," European Commission, October 14, 2008, http://ec.europa.eu/research/fch/pdf/1billioneuro_fch_race_14oct08.pdf.

39 "2010 Hydrogen and Fuel Cell Global Commercialization & Development Update," IPHE, November 2010, www.iphe.net/docs/Resources/IPHE_FINAL_SON_press_quality.pdf.

40 "2007 Worldwide Fuel Cell Industry Survey," PricewaterhouseCoopers, www.fuelcelleurope.org/index.php?m=8&sm=51.

41 "Effects of a Transition to a Hydrogen Economy on Employment in the United States—Report to Congress." U.S. Department of Energy, January 2008, www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf. Key assumptions include: By 2035, fuel cell electric vehicles ramp up to 89% of light-duty vehicle (LDV) sales (60% of stock) and 20% of LDV (7% of stock), for the aggressive and less aggressive scenarios, respectively. By 2035, stationary fuel cells ramp up to 5% and 2% of new electricity demand, for the aggressive and less aggressive scenarios, respectively.

42 "Defining, Estimating, and Forecasting the Renewable Energy and Energy Efficiency Industries in the U.S. and in Colorado," American Solar Energy Society, December 2008, http://ases.org/wordpress/wp-content/uploads/2012/03/CO_Jobs_Final_Report_December2008.pdf.

43 "A Compendium of Job Estimates in the Fuel Cell Industry," Fuel Cells 2000, February 2011, http://fuelcells.org/Fuel_Cell_Industry_Job_Estimates.pdf.

44 "Fuel Cell Industry Could Create 700,000 Green Manufacturing Jobs by 2020," Fuel Cell Today, January 14, 2010, www.fuelcelltoday.com/online/news/articles/2010-01/Fuel-Cell-Industry-Could-Create-700,000-green-manufacturing-jobs-by-2020.

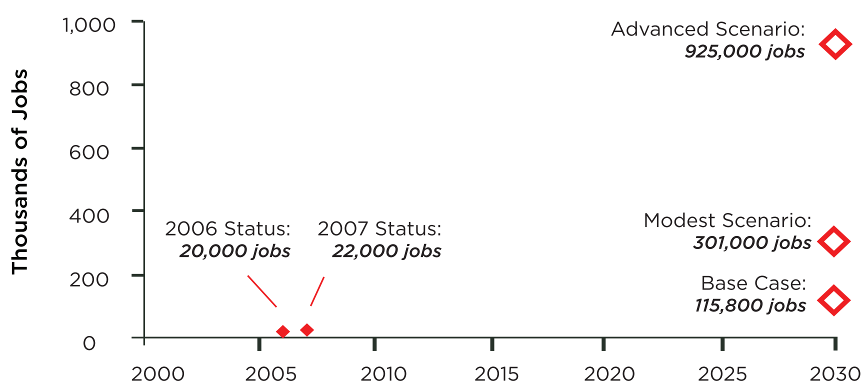
45 *Fuel Cell Economic Development Plan*, Connecticut Center for Advanced Technology, Inc. (produced for the Connecticut Department of Economic and Community Development), January 2008, http://energy.ccat.us/uploads/documents/energy/Fuel_Cell_Plan_1-31-08_DECD.pdf.

report estimates that within this time frame global revenues for the hydrogen and fuel cell markets would reach between $43 billion and $139 billion annually, including the following key market sectors:

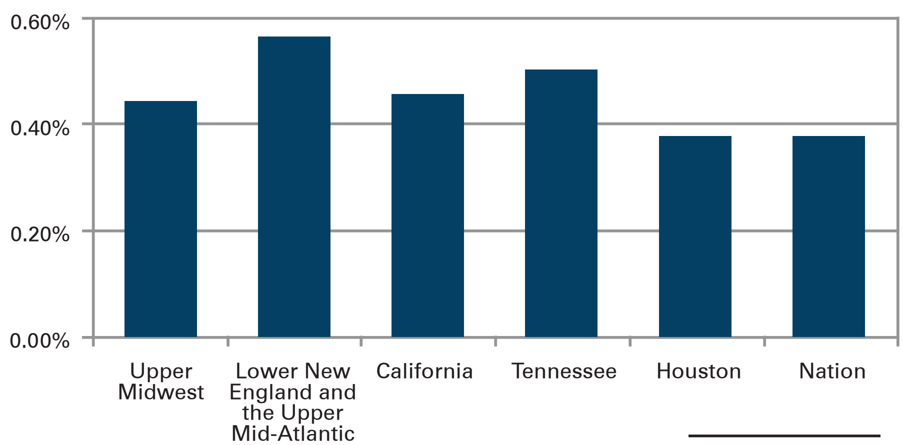
- **$14 billion – $31 billion/year for stationary power**
- **$11 billion/year for portable power**
- **$18 billion – $97 billion/year for transportation**

To achieve such growth and enable U.S. competitiveness, sustained funding is required for RD&D to build and strengthen core competencies in areas such as catalysis, advanced materials, and manufacturing technologies. Investments will also be needed at the university level, to develop human capital, and in industry, to stimulate early markets in order to further develop manufacturing capabilities and help achieve economies of scale.

Total Jobs Created by Hydrogen and Fuel Cell Industries
(includes direct and indirect employment)



Employment Growth Due to Success of Fuel Cell & H_2 Technologies
(as percent of base-case employment in 2050)



Figures 1.14 and 1.15. Employment Growth Due to Hydrogen and Fuel Cell Technologies. Studies by the American Solar Energy Society (ASES) (upper chart) and DOE (bottom chart) show the potential for substantial growth in employment due to the successful widespread commercialization of hydrogen and fuel cells. The ASES study projects up to 925,000 jobs created by 2030 and the DOE study projects up to 675,000 net new jobs by 2035.[46]

[46] "Defining, Estimating, and Forecasting the Renewable Energy and Energy Efficiency Industries in the U.S. and in Colorado," American Solar Energy Society and Management Information Services, Inc., December 2008, http://ases.org/wordpress/wp-content/uploads/2012/03/CO_Jobs_Final_Report_December2008.pdf; and "Effects of a Transition to a Hydrogen Economy on Employment in the United States," U.S. Department of Energy, July 2008, www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf.

1.3 Key Challenges

Although fuel cells are beneficial for many applications, they are currently competitive in only a few markets. The range of these markets can be greatly expanded with improvements in durability and performance and reductions in manufacturing cost, as well as advances in technologies for producing, delivering, and storing hydrogen. Successful entry into new markets will also require overcoming certain institutional and economic barriers, such as the need for codes and standards, the lack of public awareness and understanding of the technologies, and the high initial costs and lack of a supply base that many new technologies face in their critical early stages.

Fuel Cells—The Primary Technical Challenges

The Cost of Manufacturing

To be competitive in all sectors and meet consumer requirements, fuel cells will have to be less expensive than they are today, without compromising performance. Although fuel cells are already becoming cost-competitive in a few applications (on a life-cycle basis), their manufacturing costs will have to come down substantially to enable widespread commercialization. Depending on size and application, stationary fuel cell systems are estimated to cost from $3,000/kW to $7,000/kW

TECHNOLOGY REQUIREMENTS

Fuel Cell Cost & Durability

The cost of fuel cells must be reduced and their durability improved, to be competitive with current technologies. For automotive applications, fuel cells will need to have a durability of 5,000 hours, at a cost of $30/kW. Stationary fuel cell systems will require about 60,000- to 80,000-hour durability, at a capital cost of about $1,000-$1,500/kW, depending on size and application.*

Hydrogen Cost

The cost of producing and delivering hydrogen from zero or near-zero carbon sources must be reduced. Low-cost and environmentally sound CO_2 capture and sequestration technologies must be developed.

Hydrogen Storage Capacity & Cost

Compact, lightweight, and low-cost storage systems must be developed. For vehicles, technologies must enable greater than 300-mile driving range across all vehicle platforms without reducing performance or interior space.

Technology Validation

Technologies must be demonstrated under real-world conditions.

ECONOMIC & INSTITUTIONAL REQUIREMENTS

Safety, Codes & Standards

Data must be collected to enable development of codes & standards; domestic and international codes & standards must be made more consistent; and best-practices for the safe handling and use of hydrogen need to be established.

Hydrogen Supply & Delivery Infrastructure

The high investment risk of developing refueling infrastructure in absence of strong demand must be mitigated.

Manufacturing Cost & Supplier Base

High initial manufacturing costs must be overcome and domestic manufacturing and supplier base must be developed and expanded.

Public Awareness & Acceptance

Public awareness and understanding of the technologies must be strengthened, especially among code and safety officials, policy makers, and potential early adopters.

Market Transformation

A sustained commitment of policies and incentives is required to aid in the growth of early markets; this will help overcome many barriers, including achieving significant cost reductions through economies of scale.

Figure 1.16. The Technology and Economic & Institutional Requirements for Widespread Commercialization of Hydrogen and Fuel Cells. (*Note: These stationary fuel cell costs are for the entire system, including power conditioning systems, batteries, and other auxiliaries.)

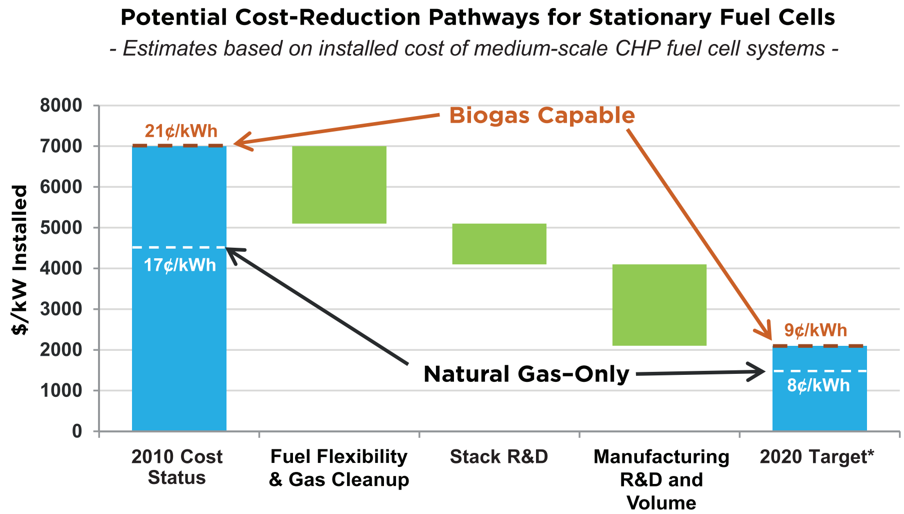


Figure 1.17. Potential Cost Reductions for Stationary Fuel Cells. Costs can be reduced in a number of areas for stationary fuel cells, in order to achieve cost-parity with incumbent technologies. Costs shown here include installation and are based on the entire fuel cell system, including the stack, balance of plant essential for stack operation (e.g., reformer, compressor, etc.), and all other system components, including power conditioning systems, batteries, and other auxiliaries. (*Note: Longer-term targets are under development; these will enable fuel cells to be competitive with other advanced technologies.)

today, and can range as high as $10,000/kW in some cases.[47] Figure 1.17 shows the estimated installed cost of medium-scale CHP fuel cell systems, along with key potential cost reductions that could lead to cost parity with competing technologies. Reducing manufacturing costs will enable fuel cells to be more competitive, without incentives, in a wider range of early markets—for example, the capital cost of stationary fuel cell systems will need to be reduced to about $1,000–$1,500/kW, depending on size and application (note: these costs are for the entire system, including power conditioning systems, batteries, and other auxiliaries).

In the mainstream transportation sector, costs will have to be reduced significantly to compete with internal combustion engines (ICEs). Costs of ICEs for automobiles are much lower than for other applications, due to the very high manufacturing volumes and the associated economies of scale, as well as the efficiencies of well-established supplier bases and distribution networks. Current costs of conventional internal combustion engine transportation power plants are about $30/kW for light-duty vehicles.

Improvements in the technology have already provided significant cost reductions. In particular, the Program has reduced the cost of automotive fuel cells by more than 80% since 2002—lowering the projected high-volume manufacturing cost to about $49/kW in 2011[48] (the 2008 cost-projection of $73/kW, using the same methodology, has been validated by an independent panel, which found $60–$80/kW to be a "valid estimate"). Further advances are needed to achieve a competitive high-volume manufacturing cost. In addition, once these advances are made, to actually reach competitive pricing in the marketplace, sales will have to grow enough to enable higher production rates, and industry will have to make substantial investments to develop

[47] Greene, D., et al., *Status and Outlook for the U.S. Non-Automotive Fuel Cell Industry: Impacts of Government Policies and Assessment of Future Opportunities,* May 2011, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/ornl_non_automotive_fuelcell.pdf; Remick, R. and Wheeler, D., "Molten Carbonate and Phosphoric Acid Stationary Fuel Cells: Overview and Gap Analysis," National Renewable Energy Laboratory, September 2010, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/49072.pdf.

[48] DOE Hydrogen and Fuel Cells Program Records #5005 and #11012, http://hydrogen.energy.gov/program_records.html. The projected cost status is based on an analysis of state-of-the-art components that have been developed through the DOE Program at the laboratory scale. Additional efforts would be needed for integration of components into a complete automotive system that meets durability requirements in real-world conditions.

efficient manufacturing capabilities, high-volume production capacities, and larger, more efficient supply and distribution networks.

Durability

The durability of certain types of fuel cells is approaching levels that will enable viability in some markets, particularly the markets for stationary power. However, to achieve large-scale market penetration, durability will have to be at least 40,000 hours—and in some cases as high as 80,000 hours—for primary-power applications. While some types of stationary fuel cells may be close to meeting these requirements, the highest demonstrated durability of PEM fuel cells, for example, is approximately 20,000 hours. Furthermore, for fuel cell electric vehicles, durability would have to be at least 5,000 hours (or roughly 150,000 miles of driving). Although substantial progress has been made in automotive fuel cells, and a durability of 2,500 hours (~75,000 miles), with less than 10% degradation, has been validated on the road, challenges still remain to achieve the full lifespan of 5,000 hours.

Other Technical Challenges

Some of the other issues relating to fuel cell systems that will have to be addressed concurrently with improvements in cost and durability are: the ability for fuel cells to operate reliably in ambient temperatures of -40°C to +50°C and in conditions of very high or very low relative humidity; higher operating temperatures (for improved co-generation capacity) and improved efficiency for stationary fuel cells; reduced size and weight for auxiliary power fuel cells; higher power density for stationary fuel cells; and higher energy density for portable fuel cells. In addition, to maximize environmental benefits, fuel cell efficiencies should be high and materials and components should be designed to maximize total life-cycle sustainability.

The Technical Challenges Associated with Producing, Delivering, and Storing Hydrogen

To achieve the broadest commercialization of fuel cells, it will be necessary to have an affordable and abundant supply of fuel that can be used in all sectors and for diverse applications. Of all possible fuels for fuel cells, hydrogen can be produced from the most diverse pathways, utilizing the most abundant resources, and it can be used in all fuel cell applications. However, hydrogen also poses the most significant technical challenges, including the high cost of production and delivery and the need for improved performance and lower cost in hydrogen storage systems.

The Cost of Producing and Delivering Hydrogen

While the most significant long-term benefits will come from the use of hydrogen produced from renewable or low-carbon resources, the technologies exist today for hydrogen to be produced from natural gas cost-competitively with gasoline. Projections based on high-volume production indicate that reforming natural gas at the fueling station can provide hydrogen for a cost of close to $3 per gallon gasoline equivalent (or "gge," roughly equal to 1 kg of hydrogen).[49] Even though this is not a long-term solution, fuel cell electric vehicles (FCEVs) using hydrogen produced from natural gas can achieve substantial reductions in CO_2 emissions (>60% in some cases) when compared with vehicles using gasoline (on a "well-to-wheels," or life-cycle, basis).[50]

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49 *Distributed Hydrogen Production from Natural Gas*, National Renewable Energy Laboratory, October 2006, www.hydrogen.energy.gov/pdfs/40382.pdf; assumes widespread deployment of 500 fueling stations per year and production of 1500 kg per day at each station.

50 DOE Hydrogen and Fuel Cells Program Record #10001, http://hydrogen.energy.gov/program_records.html; the use of FCEVs operating on hydrogen produced from natural gas (though reforming at the station) would reduce CO_2 emissions by more than 50% when compared with today's internal combustion engine vehicles (ICEVs); by more than 40% when compared with advanced ICEVs; by about 15% when compared with plug-in hybrid electric vehicles (PHEVs); and by about 15% when compared with advanced hybrid electric vehicles. In addition, FCEVs using hydrogen produced from natural gas would reduce emissions by more than 25% when compared with advanced ICEVs using natural gas.

Cost reduction remains the key technological challenge in the production of hydrogen from zero-carbon sources. Current projections (assuming widespread market penetration and high-volume production) indicate that existing technologies could produce hydrogen at the refueling site from water electrolysis for a cost of $4.90–5.70/kg (including costs of compression, storage, and dispensing); and from wind-powered water electrolysis at a centralized plant for $2.70–3.50/kg (not including costs of delivery, compression, storage, and dispensing).[51] The costs of these production pathways—and others such as solar thermochemical, photoelectrochemical, and biological production, as well as biomass gasification—need to be further reduced.

The costs of technologies for delivering hydrogen—including compression, forecourt storage, and dispensing—also need to be reduced. Using current advanced technologies for pipelines, high-pressure tube trailers, and liquid tanker trucks, delivering hydrogen from a central production facility to a fueling station 60 miles away is projected to cost approximately $2 to $3 per gge (assuming widespread deployments and high-volume production).[52] These costs, and the significant investment in delivery infrastructure that would be needed, can be avoided in the early stages of commercialization by producing hydrogen at the fueling site. However, production at larger, centralized facilities will be required to realize the full benefits of hydrogen produced from diverse renewable pathways and to meet the demands of widespread market penetration.

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

[52] Based on projections using the Hydrogen Delivery Scenario Analysis Model (HDSAM), January 2010, www.hydrogen.energy.gov/h2a_delivery.html. Key assumptions include: hydrogen is delivered to a city with the size and population density of Sacramento, CA; FCEVs have achieved 20% market penetration; there are 147 stations each with a capacity of 1,000 kg/day; and the production plant is located 62 miles from the city gate.

In addition, cost-reductions are also needed for producing and delivering hydrogen for use today, in early markets where manufacturing and production volumes are relatively low, such as forklifts and backup power for cell phone towers. Reducing the total cost of hydrogen and addressing some of the infrastructure challenges faced by these early markets would help these markets to grow, spurring the growth of a refueling infrastructure, which will help to overcome many of the infrastructure challenges faced by the larger transportation markets.

The Challenge of Storing Hydrogen

Full commercialization of fuel cells using hydrogen will also require advances in technologies for storing hydrogen. Developing systems to enable the lightweight, compact, and inexpensive storage of hydrogen will help lower the cost of delivery, allow for smaller footprints of fuel cell installations and refueling sites, and enable longer driving ranges for a wider variety of transportation applications. While hydrogen has the highest energy content per unit weight of any fuel, it has a very low energy content per unit volume—this poses a challenge for storage, because hydrogen requires either very high pressures, low temperatures, or material-based processes to be stored in a compact container. This challenge exists for all fuel cell installations that use hydrogen, but it is most acute in light-duty vehicles, as storage systems for vehicles must operate within stringent size and weight constraints, enable a driving range of more than 300 miles (generally regarded as the minimum for widespread driver acceptance based on the performance of today's gasoline vehicles), and refuel at ambient temperatures and at a rate fast enough to meet drivers' requirements (generally only a few minutes).

Most of the hydrogen that is used today is stored as a compressed gas or a liquid (liquid storage requires very low, "cryogenic," temperatures), and the majority of the fuel cell electric vehicles in use today in demonstration fleets use high-pressure tanks for onboard storage of hydrogen gas. These storage tanks are more expensive, heavier, and take up more room than conventional fuel tanks. In recent years, automobile manufacturers have been able to increase the capacity of on-board hydrogen storage systems through improvements in overall vehicle architecture and reductions in the size and weight of other system components. These improvements have allowed some vehicles to achieve driving ranges as high as 430 miles[53] on a single fill. However, for the majority of vehicle platforms, current hydrogen storage technology will not provide sufficient driving range to meet consumer expectations.

The challenge of storing hydrogen is not limited only to on-board storage for vehicles. While today's high-pressure tanks may be adequate for some stationary applications, they are typically too expensive and bulky for most sites where a fuel cell would be used. They also add significantly to the cost of using hydrogen for energy storage, limiting the viability of this approach. And, while high-pressure tanks are in use in a variety of early markets, several of these applications, including lift trucks and backup power systems, would benefit from smaller, less-expensive storage vessels. Therefore, improved technologies for hydrogen storage systems will have broad benefits for a variety of fuel cell applications, help to maximize the use of hydrogen as a zero-carbon fuel, and play an important role in expanding early markets for fuel cells.

Crosscutting Technical Challenges

For many of the key technical obstacles facing hydrogen and fuel cells, there are advances that may be necessary or useful in several areas at once. These advances involve overcoming a variety of technical challenges—from expanding the frontiers of basic scientific knowledge, to developing advanced manufacturing technologies and processes, to demonstrating and assessing new technologies in complete systems and under real-world conditions. Breakthroughs in fundamental science—in particular, advances in materials, innovative catalysts and membranes, analytical and characterization tools and techniques, and innovative synthetic techniques—may be useful in the development of all fuel cell systems as well as technologies for hydrogen fuel and infrastructure. For example, advances in membranes and catalysis can be useful both for improving individual fuel cell stack components and for improving technologies for producing hydrogen. Although fundamental breakthroughs in science may not be necessary for successful and large-scale commercialization of fuel cells, any such advances are likely to hasten the pace of progress and ultimately expand the scope of successful commercialization.

All aspects of fuel cell systems, hydrogen production and storage systems, and hydrogen infrastructure will require reduced manufacturing costs. Until now, fuel cells and related technologies have been built at very low volumes, and some types of fuel cells have only been fabricated in laboratories for demonstration purposes—market demand has not yet been sufficient to enable investment in advanced manufacturing. While a large portion of the necessary cost-reductions will come from improvements in the technologies themselves and from industry achieving economies of scale, it is likely that advanced manufacturing techniques and processes will be required to enable manufacturing at competitive cost. Costs may be reduced through advances in areas such as: improved membrane fabrication; online automated measurement tools for characterization,

[53] K. Wipke, et al., "Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions," National Renewable Energy Laboratory and Savannah River National Laboratory, August 2009, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/toyota_fchv-adv_range_verification.pdf.

sampling, and testing; advanced bonding processes for high-temperature membrane electrode assemblies; and analysis to assess manufacturability and potential areas for cost-reduction in new technologies.

Demonstrating and analyzing the performance of new and improved technologies will also be necessary for all fuel cell systems and related technologies. Validation in demonstrations under real-world conditions is an essential extension of R&D. These demonstrations are needed to provide critical data, to identify new technical issues and challenges, and to assess the status of the technologies. To gain the greatest benefits, the performance and durability of all the technologies will need to be demonstrated in complete, integrated systems, involving all necessary advanced technologies, from the fuel cell applications to the technologies for fuel production, delivery, and storage.

Institutional Obstacles and Market Risks

Advancing fuel cell technologies to meet the expectations of the marketplace is necessary, but not sufficient, for successful commercialization. In addition to the need for technological advances, there are also economic and institutional obstacles that may impede the progress of the technologies as industry moves them into commercial markets. Among the more significant institutional challenges are the lack of sufficient codes and standards for many applications, inconsistencies between domestic and international codes and standards, inadequate dissemination of information about the safe use of fuel cells and hydrogen, and the low level of public awareness and understanding of the technologies, particularly among code and safety officials, policy makers, and potential early adopters.

Some of the primary economic challenges and market risks include the following:

- Until sufficient sales volumes materialize, industry will be unable to achieve economies of scale and establish a viable domestic supplier base.
- To reduce costs, industry will have to invest in advanced manufacturing technologies, expand production capacities, and develop efficient supply-chain networks.
- There may not be sufficient national commitment to maintain policy support and financial incentives. (As with other technologies that support key national goals, fuel cells will require incentives during market introduction to overcome the higher initial costs, before economies of scale are achieved.)
- As with any emerging technology, there is fundamental uncertainty about the direction of the market—success in the market cannot be predicted, regardless of how much progress is made in advancing the technologies.
- Liability insurance is expensive, due to the limited track record the technologies have in public use.

The key economic challenge facing the supply of hydrogen is the need for parallel investments in end-user technologies and a delivery infrastructure for hydrogen—commonly referred to as the “chicken-and-egg” dilemma. To a large degree, these undertakings depend on each other for success, so each one faces the risk that the other’s effort will be insufficient. In other words, investments in developing a delivery infrastructure may not pay off if demand does not reach expected levels, and investments in various fuel cell applications may be threatened if the supply of hydrogen is not convenient, user-friendly, and widely accessible.

2. Program Activities, Plans, and Key Milestones

The DOE Hydrogen and Fuel Cells Program is a comprehensive effort coordinated across DOE; the core of the Program consists of activities in basic and applied research as well as technology development and demonstration. These activities will: maintain the rapid pace of progress in fuel cells, expanding the markets in which they can compete; enable the use of lower-cost hydrogen from more diverse and environmentally beneficial sources; enable highly efficient, centralized production of hydrogen by reducing the cost of delivery; and expand the markets for hydrogen-powered fuel cells in several applications by improving hydrogen storage technologies. The Program is also working to reduce institutional and market barriers that may impede the commercialization of these technologies.

As shown in figure 2.0, the Program conducts activities in the following areas: systems analysis; applied R&D of technologies for fuel cells and for the production, delivery, and storage of hydrogen; basic research; manufacturing R&D; technology validation; safety, codes & standards; education; and market transformation. These areas are necessarily interrelated, with developments in one area relying on corresponding developments in others. An integrated

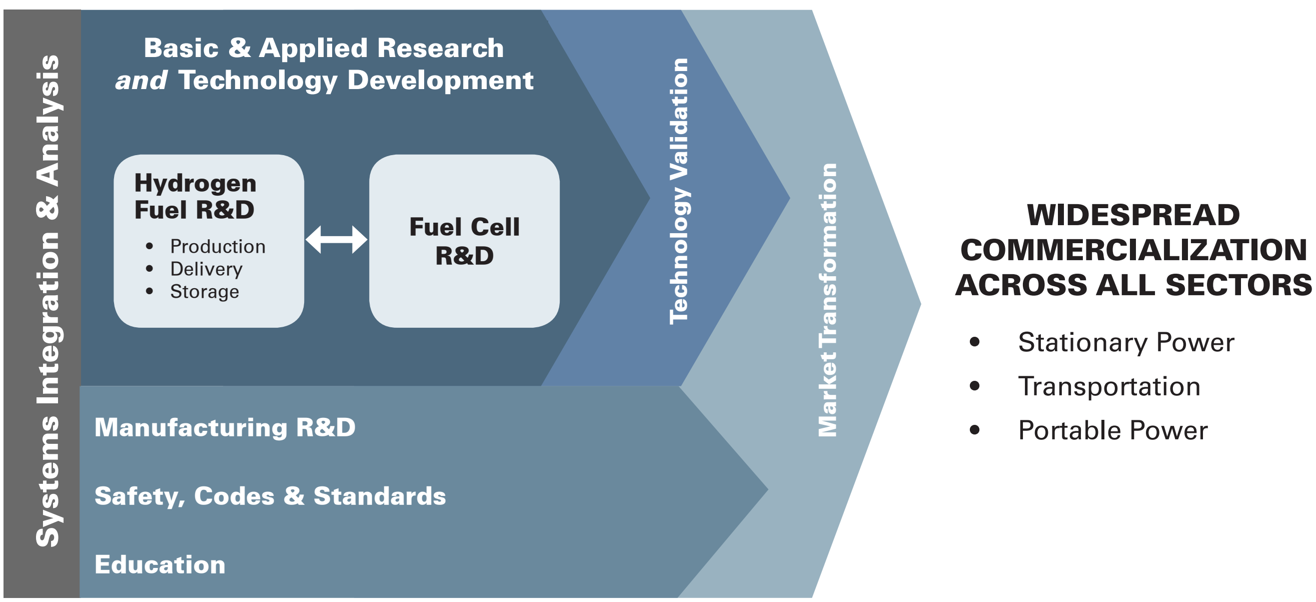


Figure 2.0. Hydrogen and Fuel Cell Program Activities. The Program integrates a range of diverse activities, all leading toward the ultimate goal of widespread commercialization.

approach to RD&D within the Program ensures that common challenges are effectively addressed.

The sections of this chapter outline the key elements of each Program activity—the barriers they address and plans for overcoming them. More-detailed discussions of Program activities and plans can be found in the Office of Energy Efficiency & Renewable Energy's *Fuel Cell Technologies Program Multi-Year RD&D Plan,*[54] the Office of Fossil Energy's *Hydrogen from Coal RD&D Plan,*[55] and the Office of Science's *Basic Research Needs for the Hydrogen Economy.*[56]

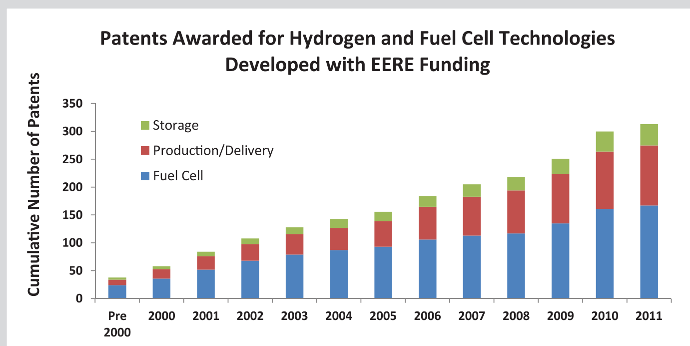
The recent results of Program activities, with information on individual projects, can be found in the *Annual Merit Review Proceedings*,[57] which contains presentations from an annual meeting during which Program-funded projects are reviewed, and in the Program's *Annual Progress Report*,[58] which summarizes each project's activities and accomplishments for the year. Highlights describing recent progress and accomplishments are provided in text boxes in this section.

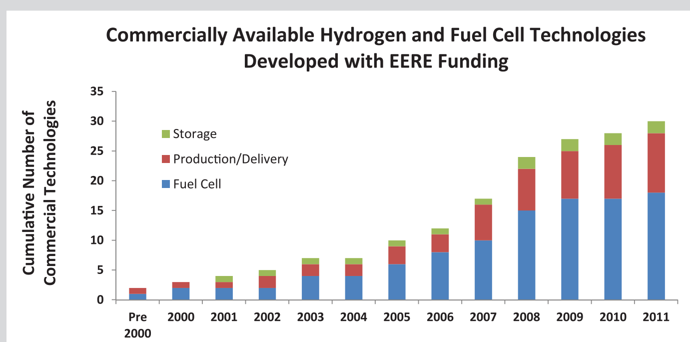
Accelerating the Commercialization of Hydrogen and Fuel Cells

DOE-funded R&D of hydrogen and fuel cell technologies has resulted in more than 300 patents. Thirty technologies developed with Program funding have entered the market—including products from 3M, DuPont, FuelCell Energy, Nuvera, Proton Energy Systems, Plug Power, Quantum, UTC, and many others.[59]

The Program encourages technology transfer through interaction with national labs, industry, universities, and other stakeholders; outcomes are monitored at least annually. Mechanisms for technology transfer include cooperative research and development agreements (CRADAs), and the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs.

DOE continues to track the impact of its funding. For example, $70 million in funding for specific projects was tracked, and this funding was found to have led to more than $200 million in industry revenues and investment.





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

55 *Hydrogen from Coal RD&D Plan*, U.S. Department of Energy, September 2010, http://fossil.energy.gov/programs/fuels/hydrogen/2010_Draft_H2fromCoal_RDD_final.pdf.

56 *Basic Research Needs for the Hydrogen Economy*, U.S. Department of Energy, February 2004, www.science.energy.gov/~/media/bes/pdf/reports/files/nhe_rpt.pdf.

57 *2011 DOE Hydrogen and Fuel Cells Program Annual Merit Review Proceedings*, U.S. Department of Energy, September 2011, www.hydrogen.energy.gov/annual_review11_proceedings.html.

58 *DOE Hydrogen and Fuel Cells Program Annual Progress Report*, U.S. Department of Energy, www.hydrogen.energy.gov/annual_progress.html.

59 *Pathways to Commercial Success: Technologies and Products Supported by the Fuel Cell Technologies Program*, Pacific Northwest National Laboratory, September 2011, www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pathways_2011.pdf.

DOE Progress & Accomplishments

Fuel Cell R&D

- ✓ Reduced the cost of automotive fuel cells (projected to high-volume manufacturing) to $49/kW in 2011—more than 30% reduction in cost since 2008 and more than 80% reduction in cost since 2002
- ✓ More than doubled the durability of automotive fuel cell systems operating under real-world conditions, with more than 2,500-hour durability (about 75,000 miles) that can be demonstrated on the road; membrane durability has exceeded 5,000 hours at the single-cell level, with load cycling and less than 0.2 g/kW of platinum group metal

Hydrogen Production and Delivery

- ✓ Reduced the projected high-volume cost of distributed production of hydrogen from natural gas from $5 to $3/gallon gasoline equivalent (gge)
- ✓ Reduced the cost of electrolyzer stacks by 80% since 2001
- ✓ Reduced the projected high-volume cost of producing hydrogen using renewable resources through several pathways, including distributed electrolysis ($4.90–$5.70/gge), and centralized electrolysis from wind ($2.70–$3.50/gge)
- ✓ Demonstrated a system that directly integrates wind power, solar power, and water electrolysis, reducing and simplifying power conditioning and reducing costs
- ✓ Reduced the projected cost of hydrogen delivery—including 30% reduction in tube-trailer costs, 20% reduction in pipeline costs, and 15% reduction in liquid hydrogen delivery costs

Hydrogen Storage

- ✓ Identified new materials with more than 50% improvement in storage capacity since 2004
- ✓ Developed a novel “cryo-compressed” tank concept that achieved a system gravimetric capacity of 5.4% by weight and a volumetric system capacity of approximately 31 g/L

Manufacturing R&D

- ✓ Reduced the cost of gas diffusion layers by more than 60%
- ✓ Demonstrated the potential for 25% reduction in costs through novel three-layer membrane electrode assembly manufacturing process

Technology Validation

- ✓ Deployed 155 fuel cell electric vehicles and 24 hydrogen fueling stations in learning demonstrations and collected data from 3 million miles of driving, demonstrating up to 59% fuel cell system efficiency (more than double the efficiency of gasoline engines) and refueling times of approximately 5 minutes for 4 kg of hydrogen
- ✓ Validated vehicles with more than 250-mile driving range, and one vehicle capable of 430 miles on a single fill of hydrogen
- ✓ Collected and analyzed data from fuel cell buses, demonstrating fuel economies more than 40% higher than diesel internal combustion engine (ICE) buses and more than 130% higher than natural gas ICE buses
- ✓ Demonstrated combined efficiency of 54% for co-producing hydrogen and power from a stationary fuel cell

Safety, Codes & Standards

- ✓ Conducted safety R&D to provide a sound technical basis for development of critical codes and standards—including the comprehensive hydrogen code, NFPA 2
- ✓ Developed online resources to disseminate best practices and safety information and to facilitate and streamline the permitting process for hydrogen installations
- ✓ Conducted R&D to determine set-back distances and used risk-mitigation approaches to reduce distances by as much as 50%

DOE Progress & Accomplishments (continued)

Education

- ✓ Launched the "Increase Your H2IQ" public information program
- ✓ Disseminated hydrogen and fuel cell course materials to over 8,000 teachers
- ✓ Developed 25 university courses and curriculum modules at five universities

Systems Analysis

- ✓ Completed "well-to-wheels" analysis that shows the potential for significant reductions in emissions and petroleum use through the use of fuel cells in multiple applications

Market Transformation

- ✓ Provided technical assistance, project development, and data collection support to several federal agencies, including assistance with early adoption demonstrations by the Department of Defense, the FAA, and the U.S. Postal Service, involving more than 100 fuel cell systems
- ✓ DOE fuel cell lift truck deployments have led to more than 3,000 additional fuel cell lift truck deployments by industry—***with no DOE funding.***

Recovery Act Update

The Program awarded approximately $42 million in Recovery Act funding to accelerate the commercialization and deployment of fuel cells. With approximately $54 million in cost-share funding from industry participants—for a total of nearly $96 million—this funding is supporting the deployment of nearly 1,000 fuel cell systems in emergency backup power, material handling, and combined-heat-and-power (CHP) applications. As of September 2011:

- ✓ >465 fuel cell powered lift trucks have been deployed;
- ✓ >360 fuel cells have been installed as backup power at cell tower sites; and
- ✓ 75 portable fuel cells as handheld power generators for small consumer electronics are being sent to users as test units.

2.1 Guiding the Program: Systems Analysis and Systems Integration

2.1.1 Systems Analysis

The Program conducts a coordinated, comprehensive effort in modeling and analysis to clarify where hydrogen and fuel cells can be most effective from an economic, environmental, and energy security standpoint, as well as to guide R&D priorities and set program goals. These activities support the Program's decision-making and prioritization process by evaluating technologies and pathways and determining technology gaps, risks, and benefits.

The Systems Analysis function works at all levels of the Program, including technology analysis for specific program elements, policy and infrastructure analysis, and high-level implementation and market analysis. Examples of activities include: pathway analysis for hydrogen production; evaluating impacts of technology advancements on fuel cell cost; feasibility studies of using fuel cells for combined heat, hydrogen, and power (CHHP); analyzing the impacts of hydrogen quality on fuel cell performance and infrastructure; and complete "well-to-wheels" or life-cycle analyses to determine reductions in greenhouse gas emissions and petroleum use. Risk analysis is also performed to determine the effects of certain variables on the probability of meeting the Program's targets and to help identify risk mitigation strategies. Policy analyses include investigating the effects of different policy options and scenarios, infrastructure and resource analysis, vehicle consumer choice analysis, and market penetration studies. Analysis of employment opportunities and needs, manufacturing capability and growth potential, and overall domestic competitiveness are also a critical part of the sub-program's activities.

To perform these analyses, the sub-program utilizes a diverse portfolio of models, including cost models such as H2A, technology performance models such as Autonomie (formerly PSAT, or Powertrain Systems Analysis Toolkit), economic models such as NEMS (National Energy Modeling System) and MARKAL (Market Allocation model), agent-based models, emissions models such as GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), and integrated models such as the Macro-System Model and Hydrogen Demand and Resource Analysis. The Program is dually focused on using established models to address analysis gaps and on enhancing existing models to broaden analysis capabilities.

Plans – Systems Analysis

The Systems Analysis sub-program will continue to address relevant issues, including infrastructure development, resource availability, life-cycle benefits, and domestic competitiveness. Examples of key focus areas include:

Model Development and Validation

- Develop and validate analytical models with real-world data and refine models as required

Technology Analysis and Quantification of Benefits

- Determine the potential for hydrogen as an energy storage medium or energy carrier to optimize the use of intermittent renewables such as wind and solar power
- Quantify the benefits of integrating hydrogen fuel production with stationary fuel cell power generation
- Evaluate the potential for biogas, landfill gas, and stranded hydrogen streams as renewable fuel for stationary fuel cell power generation
- Assess the life-cycle benefits of hydrogen and fuel cells for diverse applications and conduct a rigorous comparison with incumbent and emerging technologies such as gasoline engines and battery electric vehicles

Infrastructure Analysis

- Work with industry and other stakeholders to assess and identify infrastructure scenarios and options for both long-term transportation needs and early market opportunities for hydrogen and fuel cells

Market and Policy Analysis

- Assess opportunities and needs for diverse applications of fuel cells, including the potential for job growth, workforce development needs, manufacturing capacity, and the effects of a federal fuel cell acquisition program on fuel cell costs and market sustainability

2.1.2 Systems Integration

As recommended by the National Academies, the Program established an independent Systems Integration[60] effort to ensure that the various Program elements (such as production, delivery, and storage) are well coordinated, and that system-level targets are developed, verified, and met. The Systems Integration effort is executed by the National Renewable Energy Laboratory, which works closely with the DOE Hydrogen and Fuel Cells Program manager, chief engineer, and technology analyst. Key Systems Integration functions are: to develop and maintain an integrated baseline, linking all the technical, schedule, and cost aspects of the Program; to coordinate independent assessments of the status of various technologies in comparison with the Program's performance and cost targets; to implement configuration-management and change-control processes; and to provide a framework for systematic and comprehensive review of R&D projects.

The Systems Integration function also conducts comprehensive risk analyses to help determine the probability of success for various technology pathways, estimate their technical potential and benefits, and help prioritize R&D efforts. In the assessment process, external subject matter experts estimate the likelihood of achieving different levels of technological advancement based on different levels of Program funding. The results of these analyses are aggregated and compared with the Program's targets to assess the probability of achieving the targets. As a result, sub-programs can develop risk mitigation strategies and update their work-breakdown structures, including cost and schedule estimates. The results are also used in the Office of Energy Efficiency and Renewable Energy's (EERE's) higher-level benefits assessments to estimate the potential effects of the Program's R&D efforts on energy security, the environment, and the economy.

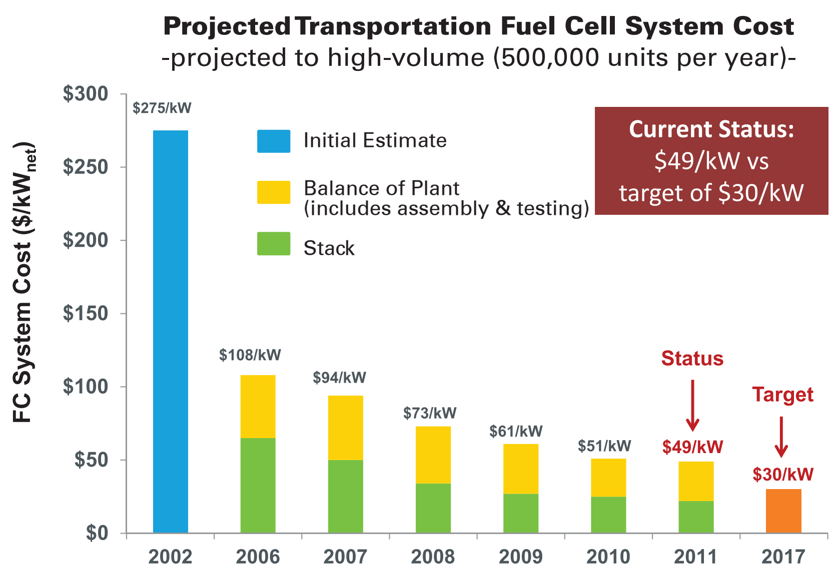
[60] "Systems Integration," DOE Hydrogen and Fuel Cells Program website, accessed October 7, 2010, www.hydrogen.energy.gov/systems_integration.html.

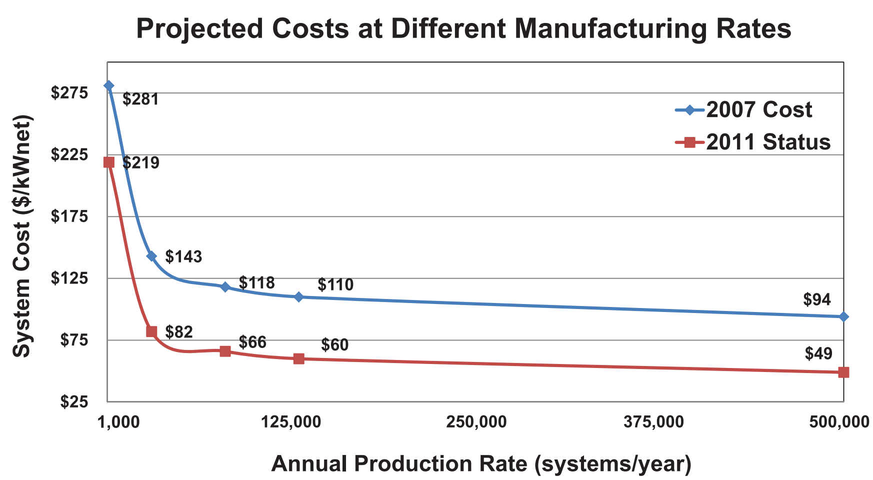
2.2 Advancing the Technologies

2.2.1 Fuel Cell R&D

The Program's efforts in Fuel Cell R&D seek to advance fuel cell technologies that can be used in diverse applications and provide the maximum benefits compared with incumbent or other advanced technologies. The Program focuses on R&D to address both near-term and long-term applications of fuel cells. Near-term applications include distributed power (primary and backup), portable power, auxiliary power units (APUs), material handling equipment, and specialty vehicles. Longer-term applications include light-duty vehicles as well as APUs for aircraft. The portfolio is "technology neutral" in the sense that it covers a range of fuel cell technologies including polymer electrolyte membrane fuel cells (PEMFCs), alkaline fuel cells (AFCs), direct methanol fuel cells (DMFCs), and solid oxide fuel cells (SOFCs). Although molten carbonate fuel cells (MCFCs) and phosphoric acid fuel cells (PAFCs) have been commercially available since the 1990s, further DOE support may be initiated based on R&D required to reduce cost and improve performance. In a parallel effort to the Hydrogen and Fuel Cells Program, the DOE Office of Fossil Energy supports R&D of solid

Figures 2.1 and 2.2. Cost Reductions for Transportation Fuel Cells.[61] Significant cost-reductions have been achieved for transportation fuel cells. Costs shown here are based on an automotive 80-kW PEM fuel cell system, projected to high-volume manufacturing. The top graph shows the results of cost analyses conducted annually by the Program, indicating steady technical progress toward the 2017 target of $30/kW, which will enable fuel cells to be economically competitive with conventional internal combustion engines. The lower graph shows the effect of various annual production volumes on overall fuel cell system cost.





oxide fuel cell technology for megawatt utility-scale, high-temperature stationary fuel cells through the Solid State Energy Conversion Alliance (SECA) Program [see sidebar, "SECA Program," on page 43].

The primary objectives of Fuel Cell R&D activities are to improve the durability, reduce the cost, and improve the performance (e.g., power, start-up time, and transient response) of fuel cell systems. These advances will require improvements in fuel cell stack and balance of plant (BOP) components. Therefore, Program-sponsored R&D efforts focus on materials, components, and enabling technologies that will contribute to the development of low-cost, reliable fuel cells. High-risk, high-impact approaches that complement industry-sponsored efforts are the primary focus. The Program also sponsors the development of experimental diagnostics and theoretical models to gain a fundamental understanding of reaction mechanisms and optimize material structures and technology configurations. There are different technology needs for different types of fuel cells, and the Program implements a portfolio approach to ensure specific R&D needs are addressed, based on the status of the technology compared to application-driven targets.

Plans – Fuel Cell R&D

The main focus of the Fuel Cell R&D sub-program is to enable competitive cost and performance for multiple applications, including a cost of $30 per kilowatt and a durability of 5,000 hours for automotive fuel cell systems, and a cost of $1,000–$1,500/kW and a durability of 60,000–80,000 hours for stationary systems, depending on size and application. The Program's focus includes additional applications such as: motive power for buses; APUs for heavy-duty trucks, aircraft, or ships; portable power; and residential or light commercial combined heat and power (CHP). Targets for many of these applications are in the EERE Fuel Cell Technologies Program's *Multi-Year RD&D Plan*, and they are periodically updated as required. Examples of key focus areas within the plans of the sub-program include:

Fuel Cell Stack Components

- Reduce or eliminate the platinum group metal (PGM) content of catalysts and develop innovative approaches and components such as gas diffusion layers, durable high-temperature membranes, and low-cost, corrosion resistant bipolar plates to meet cost, durability, and performance targets for PEMFCs
- Develop and optimize membrane electrode assembly (MEA) and stack configuration designs for enhanced performance and durability with optimized components
- Develop membranes with high anionic conductivity and chemical stability to CO_2 as well as low-cost, durable MEAs and components and improved design configurations for AFCs
- Improve DMFC performance and durability while lowering costs, through development of low- and non-PGM catalysts as well as membranes with reduced methanol and water crossover
- Improve performance and durability and reduce cost of high-temperature fuel cells—including MCFCs, PAFCs, small-scale SOFCs, other polymer-phosphoric acid, and similar temperature range fuel cells—through development of better stack components and design configurations

[61] DOE Hydrogen and Fuel Cells Program Records #5005, #8002, #8019, #9012, #10004, #11001, http://hydrogen.energy.gov/program_records.html. The projected cost status is based on an analysis of state-of-the-art components that have been developed and demonstrated through the DOE Program at the laboratory scale. Additional efforts would be needed for integration of components into a complete automotive system that meets durability requirements in real-world conditions.

Independent Assessment of Fuel Cell Cost[62]

To gauge progress toward meeting its targets and to determine future research efforts, the Program conducts annual assessments of the high-volume manufacturing cost of 80-kW PEM fuel cell systems for transportation applications. To date, these cost analyses have been performed by Directed Technologies Inc. (DTI, which has been acquired by Strategic Analysis Inc.) and TIAX LLC. In order to assess the validity of the methodologies used by these contractors and to determine the credibility of their respective fuel cell estimates, in 2008 the Fuel Cell Technologies Program, through the Program's Systems Integration function at the National Renewable Energy Laboratory (NREL), commissioned a qualified panel of experts to conduct an independent review of the two analyses conducted that year.

NREL contracted with fuel cell industry experts who have combined experience of more than 90 years in R&D and manufacturing and more than 60 years specifically in fuel cells. The panel assessed the cost analysis methodology and assessed the impacts on cost resulting from the differences in the PEM system designs examined. They also compared the differences in manufacturing processes and components to determine their influence on cost and formalize any cost differential.

The panel concluded that a range of $60/kW$_{net}$ to $80/kW$_{net}$ is a valid estimation of the potential manufactured cost for an 80-kW$_{net}$ fuel cell system, based on 2008 technology, projected to a manufacturing volume of 500,000 systems per year. They also identified areas of commonality in the DTI and TIAX cost analyses that benefit the Program. In addition, several improvements to the cost analyses efforts were proposed, including improving the clarity of the evaluation processes, imparting greater rigor to the analyses, and quantifying the cost improvements achieved by DOE.

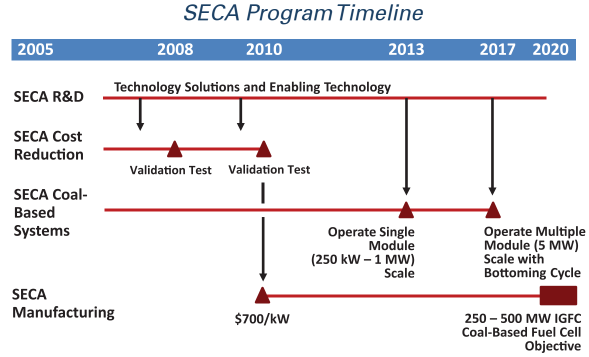
R&D of Large, High-Temperature Fuel Cells

The Solid State Energy Conversion Alliance (SECA), a program within the DOE Office of Fossil Energy, aims to advance solid oxide fuel cell technology for megawatt-scale systems. Since its inception in 2000, SECA has made substantial progress, including a 10X reduction in stack cost and a 5X improvement in stack power density. The Program has also made progress in overcoming the challenges involved in scaling up solid-oxide fuel cells, achieving a 5X increase in cell area and a 25X increase in stack size.

Integrated coal-gasification fuel cell systems utilizing SECA technology offer greater than 99% carbon capture, less than 0.5 parts per million NOx emissions, significantly reduced water requirements, and a coal-to-electricity efficiency as high as 60% on a higher heating value (HHV) basis. The SECA cost goals of $175/kW stacks and $700/kW power blocks (stacks and essential BOP for stack operation) ensure that the cost of electricity to the user will not exceed what is typical today.

The SECA SOFC development effort also provides the technology base for grid-independent distributed generation applications. Fuel cells are an intrinsically modular and hence scalable technology, and high-temperature fuel cells such as SOFCs are capable of utilizing a wide range of fuels (e.g., coal syngas, natural gas, diesel, biogas, etc.) with a relatively high tolerance for contaminants such as sulfur.

SECA Program Timeline



More information on the SECA Program can be found at http://www.seca.doe.gov/.

Figure 2.3. The Solid State Energy Conversion Alliance (SECA), a program within the DOE Office of Fossil Energy, is a parallel effort to the Hydrogen and Fuel Cells Program, aiming to advance solid oxide fuel cell technology for megawatt-scale systems.

Experimental Diagnostics and Fuel Cell Models

- Increase understanding of water transport and management, including freeze tolerance and cold weather operation
- Characterize and analyze fuel cell degradation pathways to help determine mitigation strategies
- Evaluate the impact of fuel and air impurities on fuel cell performance and durability

Fuel Cell BOP, Fuel Processing, Subsystems, and System Integration

- Develop low-cost BOP components for low- and high-temperature systems (air/fuel/thermal) that meet performance and durability requirements
- Develop other subsystems, such as fuel processors, to meet cost, performance, durability, and output fuel quality requirements; this includes fuel flexibility and gas clean up for contaminants from biogas and other fuels
- Optimize subsystems and develop innovative subsystem/system design and integration concepts, including reversible or regenerative fuel cells

Fuel Cell System Analysis

- Continue to update cost and performance analyses based on the latest technology progress, advanced system designs, and optimized configurations for low and high manufacturing volumes; conduct assessment of reversible or regenerative fuel cells

[62] *Fuel Cell System Cost for Transportation—2008 Cost Estimate*, National Renewable Energy Laboratory, May 2009, www.hydrogen.energy.gov/pdfs/45457.pdf.

2.2.2 Hydrogen Fuel R&D

Hydrogen Fuel R&D focuses on materials research and technology development to enable the production of low-cost, carbon-free hydrogen fuel from diverse renewable pathways and to address key challenges to hydrogen delivery and storage. The hydrogen production aspect of these efforts encompasses small-scale hydrogen production through renewable liquids reforming and electrolysis, and large-scale centralized production through biomass gasification, wind- and solar-powered electrolysis, solar-driven high-temperature thermochemical cycles, as well as biological and direct photoelectrochemical pathways. To address hydrogen delivery, this sub-program includes technologies for hydrogen transportation and distribution to the end-user and the refueling-site operations of compression, storage, and dispensing. The hydrogen storage component of this sub-program focuses on the R&D of low-pressure materials-based storage that will enable widespread commercialization of fuel cell systems for diverse applications across the stationary, portable, and transportation sectors. R&D efforts are also conducted to explore advanced conformable and low-cost tank technologies for hydrogen storage systems to meet performance targets. In addition, the project portfolio for Hydrogen Fuel R&D includes combined-heat-hydrogen-and-power (CHHP) systems and energy storage systems for intermittent renewable resources.

2.2.2a Hydrogen Production

The Program is developing methods for producing hydrogen at reduced cost, with emphasis on renewable and low carbon pathways. The ultimate goal is to enable several different domestic production approaches, at a variety of scales ranging from large, centralized production to small, local (distributed) production, that will achieve a cost in the range of $2 to $4 per gallon gasoline

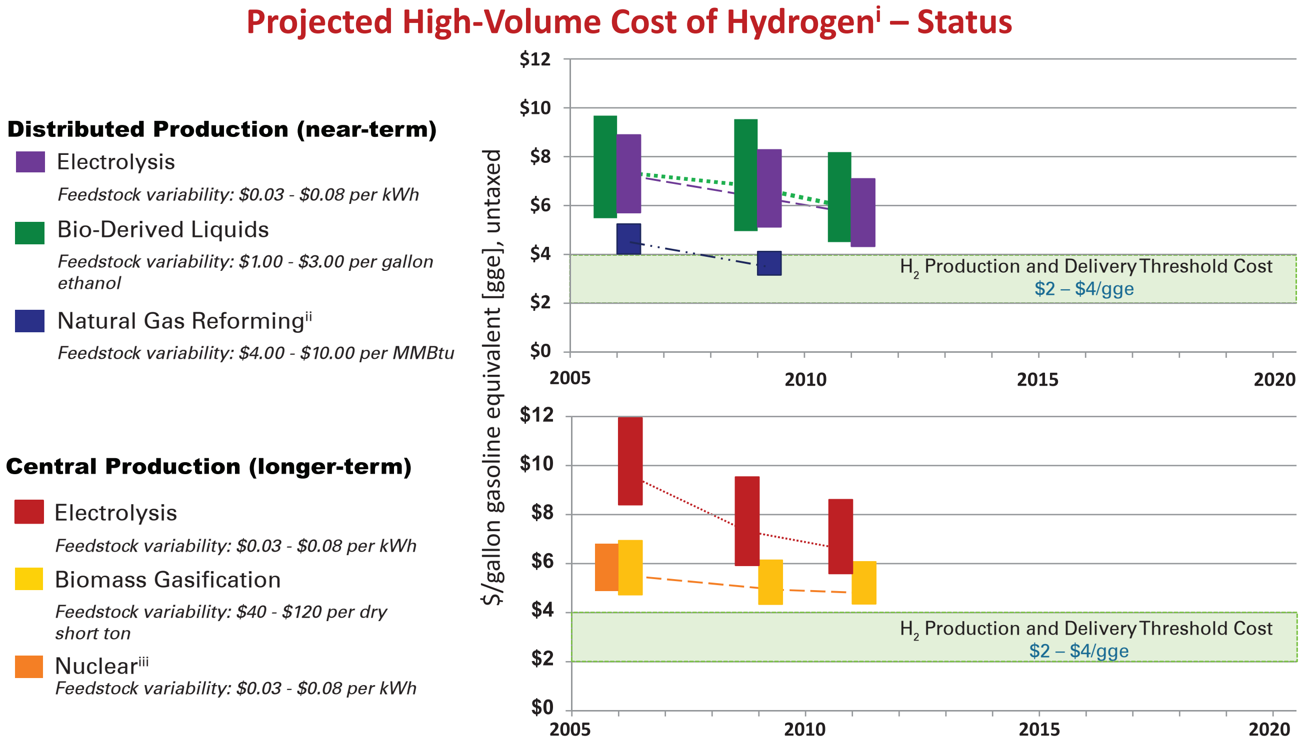


Figure 2.4. Hydrogen Production and Delivery Cost Status. Significant progress has already been made in several hydrogen production pathways. The Hydrogen Threshold Cost represents the cost at which hydrogen fuel cell electric vehicles are projected to become competitive on a cost-per-mile basis with competing vehicles (gasoline hybrid-electric vehicles) in 2020. Notes: (i) Costs shown include all delivery and dispensing costs, but do not include taxes. A cost of $1.80 for forecourt compression, storage, and dispensing is included for distributed technologies, and $2.60 is included as the total cost of delivery (including transportation, compression, storage, and dispensing) for centralized technologies. All delivery costs are based on the *Hydrogen Pathways Technical Report* (NREL, 2009). Projections of distributed costs assume station capacities of 1,500 kg/day, with 500 stations built per year. Projections of centralized production costs assume capacities of ≥ 50,000 kg/day. Cost ranges for each pathway are shown in 2007 dollars, based on high-volume projections from H2A analyses, reflecting variability in major feedstock pricing and a bounded range for capital cost estimates. (ii) DOE funding of natural gas reforming projects was completed in 2009 due to achievement of the threshold cost. Incremental improvements will continue to be made by industry. (iii) High-temperature electrolysis activities are ongoing under the Next Generation Nuclear Plant Program.

equivalent (gge), dispensed and untaxed. This range represents the values at which hydrogen is competitive with gasoline, and it includes consideration of the volatility in the price of gasoline as well as the range of fuel economies possible with fuel cell electric vehicles in comparison with other vehicle options.

The near-term focus in hydrogen production is to develop distributed production technologies, which would be used at fueling stations (or at the point-of-use) to avoid delivery costs and the need for large investments in a delivery infrastructure. These technologies include renewable liquid reforming and electrolysis. DOE cost-shared efforts have already developed technologies for distributed production of hydrogen from natural gas that would enable hydrogen to be produced (at high volumes) at a cost competitive with gasoline, so the Program is no longer conducting research in this area [see sidebar, "Independent Assessment of Hydrogen Cost," on page 46]. However, low-volume cost is still an issue and will be included in future work. The Program is also developing technologies for centralized production for the longer term, including biomass gasification, wind- and solar-driven water electrolysis, solar-based high-temperature thermochemical processes, solar-based photoelectrochemical water splitting, biological hydrogen production, high-temperature electrolysis using nuclear energy, and coal-based production with carbon

Independent Assessment of Hydrogen Cost

Hydrogen Production Cost Estimate Using Water Electrolysis (2009)[63]

In 2009, the Program commissioned an independent review panel to estimate the cost of using water electrolysis to produce hydrogen. The panel examined alkaline and polymer electrolyte membrane water electrolyzers and distributed and centralized hydrogen production scenarios. The panel's review revealed that technology advancements have led to capital cost reductions and improved efficiencies, resulting in reduced electrolysis production costs. The panel estimated the 2009 levelized cost range for state-of-the-art forecourt electrolysis to be $4.90 to $5.70 per kilogram of hydrogen, including compression, storage, and dispensing at 1,500 kg/day. The panel also estimated the 2009 levelized cost range for state-of-the-art centralized electrolysis to be $2.70 to $3.50/kg at 50,000 kg/day. All estimates are based on nth plant assumptions and assume a 10% after-tax internal rate of return.

Distributed Hydrogen Production from Natural Gas (2006)[64]

In 2006, an independent review panel assessed progress toward reducing the cost of distributed production of hydrogen from natural gas. The panel estimated the total cost of delivered and dispensed hydrogen to be approximately $2.75 to $3.50/kg—using 2005 technology and assuming an installation rate of 500 new forecourt units per year and a capacity of 1,500 kg/day.

Competitive Hydrogen Cost[65]

In 2010, the Program conducted a rigorous hydrogen "competitive threshold analysis" to determine the cost at which hydrogen would be competitive with gasoline. The resulting "hydrogen competitive threshold cost," which is independent of the production and delivery pathway, was adjusted from $2.00–$3.00 per gallon of gasoline equivalent (gge) to $2.00–$4.00 per gge. The analysis was based on the Energy Information Administration's 2009 forecast of gasoline cost in 2020, and the fuel economy and incremental vehicle cost of hydrogen fuel cell electric vehicles relative to other advanced vehicle technologies in 2020.

The methodology used ensures that consumers' operating cost (in $/mile) in a hydrogen fuel cell electric vehicle will be equal to or less than a gasoline hybrid electric vehicle in 2020. The new cost range reflects the variability in future fuel efficiency improvement factors, competitive gasoline cost, and vehicle costs, and it includes the cost of delivery (without taxes and expressed in 2007 dollars). These costs will be used to guide the Department's hydrogen and fuel cell R&D activities.

sequestration. These pathways have the potential to utilize abundant, diverse resources in an efficient manner, which will enable supplies of hydrogen to fill the demands for energy in large and growing markets.

Plans – Hydrogen Production

The focus of the sub-program is twofold—addressing both distributed and centralized hydrogen production technologies—with emphasis on hydrogen production from renewable or low-carbon pathways.

Distributed Hydrogen Production

- Develop small-scale technologies for distributed bio-derived liquid reforming, to produce hydrogen from pyrolysis oils and other renewable liquids; R&D goals include:
  - Improved reformer technologies using partial oxidation (or autothermal reforming, steam reforming, or aqueous phase reforming processes) to achieve higher energy efficiency and lower capital costs
  - Development of lower-cost membranes and catalysts that can operate at higher temperatures and pressures
  - Improved system integration to lower the cost of manufacturing
- Reduce capital cost and improve system efficiency and durability for distributed electrolysis systems

Central Hydrogen Production

- Improve technologies for central renewable hydrogen production, including:
  - Component development and systems integration efforts that will reduce capital cost while enabling

63 *Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis—Independent Review*, National Renewable Energy Laboratory, September 2009, www.hydrogen.energy.gov/pdfs/46676.pdf.

64 *Distributed Hydrogen Production from Natural Gas—Independent Review*, National Renewable Energy Laboratory, October 2006, www.hydrogen.energy.gov/pdfs/40382.pdf.

65 DOE Hydrogen and Fuel Cells Program Record #11007, http://hydrogen.energy.gov/program_records.html.

electrolyzers to operate more efficiently from inherently intermittent power derived from wind and solar sources
- Process development of solar-driven high-temperature thermochemical water splitting cycles to enable integrated laboratory-scale studies followed by demonstrations utilizing solar-based heat
- Materials identification and system development of photoelectrochemical systems
- System optimization for thermochemical conversion of biomass
- Increased efficiency and productivity of biological hydrogen production systems
- Development of a near-zero atmospheric emission coal plant producing hydrogen and power, with carbon sequestration

2.2.2b Hydrogen Delivery

To enable the use of hydrogen produced from highly efficient centralized facilities, technologies will have to be developed to lower the cost of delivery to the station. There are also costs associated with compression, storage, and dispensing that will affect the final cost of hydrogen produced at both central and distributed sites. The cost of delivery technologies for central and distributed hydrogen production pathways will affect the final cost of hydrogen and determine the level of infrastructure investment required to enable its widespread use. The Program is pursuing advances in existing technologies for hydrogen delivery and developing new technologies to reduce delivery costs. These efforts make extensive use of systems analysis of delivery alternatives, which shows the total cost advantages and disadvantages of the alternative approaches for transporting hydrogen over long distances.

Plans – Hydrogen Delivery

The Program will continue R&D to enable safe, low-cost hydrogen delivery, focusing on:

Process Technologies: Compression, Liquefaction, and Dispensing

- Develop more reliable, lower-cost, higher-efficiency compression technology (low-pressure/high-throughput for pipelines and high-pressure/low-throughput for stations)
- Develop more energy-efficient and lower-cost liquefaction technology
- Develop low-cost high-pressure gas and liquid dispensing technologies that ensure safe, reliable, and complete tank fills

Materials Development

- Improve pipeline materials to resolve hydrogen embrittlement concerns and to reduce capital costs
- Evaluate fiber reinforced polymer (FRP) pipelines for long-term in-ground durability, flaw tolerance, and off-normal usage and develop a performance database for design codification with standards development organizations
- Develop lower-cost gaseous hydrogen tank technology and systems for stationary storage and tube trailers

Delivery Analysis Tools

- Update and validate Hydrogen Delivery Scenario Analysis models to focus on research areas needing the most effort to ensure efficient use of R&D funds

2.2.2c Hydrogen Storage

The Program is developing technologies to enable the lightweight, compact, and inexpensive storage of hydrogen. These technologies will help lower delivery costs, allow for smaller footprints of fueling sites and fuel cell installations, and enable achievement of performance and cost targets for a wide range of early market and transportation applications.

To address the critical challenge of hydrogen storage for transportation, stationary, and portable applications, the Program will continue with its overarching strategy to conduct R&D of materials-based technologies with the potential for long-term impact. The R&D strategy includes independent projects and the Hydrogen Storage Engineering Center of Excellence, which addresses the engineering challenges of materials-based hydrogen storage systems and includes teams of competitively selected university, industry, and federal laboratory partners.

Hydrogen storage efforts for light-duty vehicles focus on applied, target-oriented research of materials systems including high-capacity metal hydrides, chemical hydrogen storage carriers, and high-surface-area adsorbents with the potential to meet the 2015 technical goal of reaching a storage density of 1.8 kWh/kg (5.5% hydrogen by weight) and 1.3 kWh/L (40 g/L). Research is continuing to address advanced materials concepts with the potential to meet the "ultimate" DOE targets of 2.5 kWh/kg (7.5% hydrogen by weight) gravimetric capacity and 2.3 kWh/L (70 g/L) volumetric capacity, based on the goal of enabling significant market penetration across all vehicle platforms. The Program is also pursuing advances in physical storage—i.e., pressurized or cryo-compressed

Ammonia's Potential as a Hydrogen Carrier[66]

Ammonia has a number of favorable attributes as a potential hydrogen carrier, including its high capacity for hydrogen storage (hydrogen makes up 17.6 percent of ammonia, by weight), its relative ease of transport, and its relatively widespread availability. However, high temperatures (e.g., > 500°C) and significant energy input are required to release hydrogen from ammonia, and the large reactor mass and volume for on-board fuel processing make it an unattractive option for vehicular hydrogen storage. Other concerns include safety and toxicity, both actual and perceived, as well as the inability of PEM fuel cells to tolerate trace levels of ammonia along with the hydrogen. However, ammonia could still play a role in energy storage, or as a hydrogen carrier that would be reformed at the station. The Program plans to conduct an independent assessment with a diverse group of technical experts to evaluate the potential for ammonia in specific applications, along with an assessment of the cost and energy impact benefits compared with competing technologies.

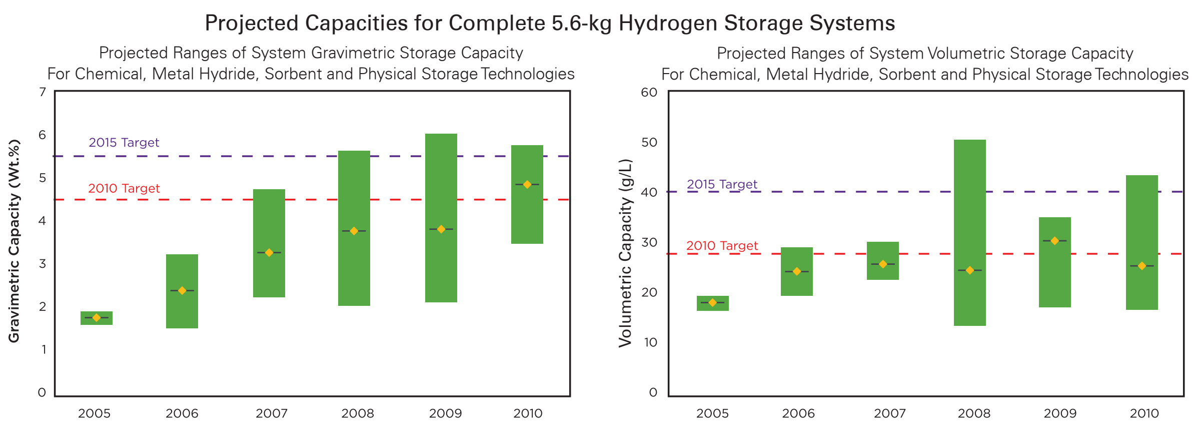


Figure 2.5. Projected Capacities for Hydrogen Storage Systems. The Program is making progress toward targets for improved hydrogen storage capacity. Advanced storage technologies will enable extended driving ranges across all vehicle platforms and will provide benefits for hydrogen delivery and off-board storage at fueling stations and stationary fuel cell installations. The green bars indicate the range of storage capacities for technologies evaluated in a given year, and the yellow dots represent the average for that year.

66 G. Thomas and G. Parks, "Potential Roles of Ammonia in a Hydrogen Economy," U.S. Department of Energy, April 2006, www.hydrogen.energy.gov/pdfs/nh3_paper.pdf.

tanks, for nearer-term applications. Independent testing to validate materials performance and systems analysis for assessment of emerging technologies are an integral part of the Program's R&D efforts. Figure 2.5 shows progress in hydrogen storage capacities compared with targets.

Hydrogen storage remains one of the most technically challenging barriers to the widespread commercialization of fuel cell electric vehicles. In addressing this challenge, the Program has established a goal of developing technologies that will allow for a driving range of more than 300 miles (~500 km) while meeting the packaging, cost, safety, and performance requirements of current and future vehicle markets. While some automakers have demonstrated progress with prototype and concept vehicles that can travel more than 300 miles on a single fill (including one vehicle that was independently validated at 430 miles), this driving range must be achievable across different vehicle platforms, without compromising space and performance, and at a competitive cost.

Plans – Hydrogen Storage

In addition to ongoing efforts to discover new materials for high-capacity storage for light-duty vehicles, the Program will address R&D needs and priorities for hydrogen storage for stationary and portable fuel cell applications. R&D efforts are needed to increase filling and discharge rates, improve pressure and temperature management, and achieve cost-effective packaging into integrated systems for stationary and mobile applications. Additional work is needed for larger-scale material production and handling methods. Cost also remains an issue with technologies for compressed and cryo-compressed hydrogen storage. Ongoing and planned hydrogen storage R&D activities include the following:

Materials Development

- Identify and develop innovative hydrogen storage approaches, utilizing both theory/modeling and experimental approaches, including:
  - Reversible storage materials that can be easily recharged onboard for vehicular applications, such as high-capacity adsorbents, advanced metal hydrides, and potentially reversible chemical hydrides
  - Chemical hydrides or carriers that must be regenerated off-board, including addressing regeneration energy and cost issues

Tank Technologies

- Optimize and validate high-pressure, cryogenic, and cryo-compressed tanks as near-term approaches, with a focus on cost reduction and capacity improvement
- Leverage other DOE and interagency efforts to reduce carbon fiber cost for high-pressure tanks

Engineering Science, Analysis, and Crosscutting R&D

- Develop and validate models for components and subsystems applicable to materials-based storage approaches
- Conduct systems analyses to identify potential configurations and approaches based on material properties and performance requirements
- Research and develop approaches to improve conformability of storage systems
- Conduct crosscutting research in materials testing, materials reactivity, and safety; guide material selection and risk mitigation strategies
- Identify performance targets for hydrogen storage for key early market, stationary, and portable fuel cell applications
- Coordinate with the Delivery sub-program on storage-delivery interface issues, such as dispensing technologies

2.3 Driving Progress through Crosscutting Efforts

2.3.1 Manufacturing R&D

As part of the Program's comprehensive strategy, the Manufacturing R&D sub-program was initiated to develop and demonstrate manufacturing processes and technologies that will reduce the costs of manufacturing fuel cell systems and systems for producing, storing, and delivering hydrogen. Advanced manufacturing technologies and processes will be required to move hydrogen and fuel cells from laboratory-scale production into high-volume manufacturing, and they can provide critical support to industry, spurring the growth of a strong domestic supplier base.

Plans – Manufacturing R&D

The Manufacturing R&D sub-program plan focuses on innovative and cost-effective manufacturing processes and technologies, with specific examples as follows:

Diagnostics to Reduce Cost and Improve Quality

- Develop real-time, online measurement tools to reduce or eliminate costly ex-situ characterization, sampling, and testing; examples include process control tools to produce high-volume, low-cost gas diffusion layers (GDLs) to six sigma quality standards
- Develop a high-volume manufacturing leak-test process to reduce labor costs and achieve more-robust, automated testing with increased speed

Innovative Process Development and Performance Correlation

- Develop novel, robust, ultrasonic bonding processes for high-temperature MEAs to greatly reduce MEA-pressing cycle time
- Develop and demonstrate an innovative precision fiber placement and commercial filament winding, with some adaptations of high-speed "dry winding" methodology for high-pressure carbon composite tanks
- Demonstrate digital fabrication of fuel cell components, with particular emphasis on catalyst coated membranes, using printing technology
- Determine relationships between manufacturing processes, GDL product properties, and fuel cell performance, to direct process control strategies and establish process specifications to increase flexibility and quality
- Develop and demonstrate innovative manufacturing process improvements to enable high-volume production of high-temperature fuel cells specifically designed for CHP applications

2.3.2 Technology Validation

The Technology Validation sub-program conducts real-world demonstrations, along with data collection and analysis, of pre-commercial hydrogen and fuel cell technologies. These demonstrations involve multiple types of fuel cells and a variety of systems, including stationary power installations, hydrogen fueling infrastructure, fuel cell electric vehicles, and systems that integrate power generation with renewable fuel production. Technology Validation is an extension of R&D—by providing critical data (figure 2.6), this sub-program helps identify issues to be addressed in the Program's R&D efforts, such as component or system engineering issues that may not be evident in laboratory tests. This aids in measuring progress and making accurate assessments of the status of the technologies in integrated systems, operating under real-world conditions.

	Current Status *(demonstrated by Technology Validation)*	Program Targets: Phase 1 — In Progress	Ultimate Targets
System Efficiency	53 – 59%	60%	60%
Fuel Cell System Durability	2,500 hours *(~75,000 miles)*	2,000 hours *(~60,000 miles)*	5,000 hours *(~150,000 miles)*
Vehicle Range	up to 254 miles	250 miles	300 miles
Fuel Cost	$7.70 – $10.30/gge *(projected, from on-site natural gas reforming)** $10.00 – $12.90/gge *(projected, from on-site electrolysis)**	$3/gge**	$2 – 4/gge**
Refueling Rate	0.77 kg/min	1.0 kg/min	1.67 kg/min

** Projections are based on estimates of costs provided by project partners, projected to a production rate of 1,500 kg/day in an early market rollout—they do not include significant cost-reductions that would result from deployments of fueling stations in a more mature market. For widespread market penetration (assuming a build-out rate of 500 fueling stations per year), DOE independent panels estimated the cost of producing hydrogen to be: $2.75–3.00/kg using distributed natural gas reforming (2006) and $4.90–5.70/kg using distributed electrolysis (2009).*
*** Hydrogen cost targets assume a production rate of 1,500 kg/day at each station and a build-out rate of 500 stations per year.*

Figure 2.6. Status and Targets for Technology Validation of Vehicles and Infrastructure.[67]

[67] K. Wipke, et al., "Controlled Hydrogen Fleet and Infrastructure Analysis," *2010 DOE Hydrogen and Fuel Cells Program Annual Merit Review Proceedings*, U.S. Department of Energy, 2010, www.hydrogen.energy.gov/pdfs/review10/tv001_wipke_2010_o_web.pdf.

Technology Validation is also a key element of the Program's strategy for moving laboratory successes into commercial markets. The Program's technology validation activities, along with its early market deployments and public outreach and education activities, form an integrated timeline to achieve the maximum impact in stimulating the marketplace and overcoming initial market barriers. The sub-program's activities support commercial acceptance of the technologies by providing high-visibility demonstrations, early infrastructure, and both economic and performance data, which help to better determine market and investment risks. The Program ensures that its Technology Validation projects are strategically located where there is the greatest potential for immediate impact in terms of raising the visibility of the technologies among key potential end-users. Projects are also chosen for applications where potential operators, customers, and installers are likely to gain the most from the user-experience and real-world operational data that these projects provide. These demonstration projects also provide valuable lessons-learned for safety and code officials, as well as first-responders, and they are closely coordinated with the Education and Safety, Codes and Standards sub-programs.

To leverage state and local efforts, the Program coordinates its demonstrations closely with related state activities. For example, a combined-hydrogen-heat-and-power (CHHP) demonstration project in Fountain Valley, California, is being jointly funded by the Program, the California Air Resources Board, and the South Coast Air Quality Management District. This project will demonstrate an innovative approach to hydrogen infrastructure (through the use of a high-temperature stationary fuel cell that co-produces hydrogen, heat, and electricity), while providing hydrogen for demonstrations in the area being conducted by automobile manufacturers and the state of California.

Plans – Technology Validation

The sub-program will continue validating the status of the technologies and obtaining data to guide R&D for diverse applications. In addition to coordinating with the Education sub-program on training and outreach, the Technology Validation sub-program will conduct customer acceptance and perceptions studies to gather feedback and monitor user perceptions. The sub-program will focus on the following areas and associated activities:

Transportation Applications

- Through real-world operation, validate fuel cell electric vehicle performance, including a driving range of at least 300 miles between fill-ups and fuel cell durability of at least 5,000 hours (equivalent to 150,000 miles); validate fuel quality; and demonstrate innovative technologies for hydrogen fueling infrastructure
- Continue coordination with the U.S. Department of Transportation (DOT) to analyze data from fuel cell bus demonstrations and identify remaining challenges to guide R&D efforts—upcoming projects will add data from new or improved-design fuel cell buses
- Coordinate with Systems Analysis and R&D sub-programs to define future validation efforts for other transportation applications such as APUs for aircraft, heavy-duty trucks, ships, and rail

Stationary Applications

- Validate renewable energy station concepts to co-produce hydrogen and electricity, including CHHP (trigeneration) approaches using waste biogas
- Define and validate approaches for using hydrogen as a medium for energy storage and transmission, for use with intermittent and/or remotely sited renewable power generation
- Validate stationary fuel cells (e.g., residential and light-commercial CHP systems)

2.3.3 Basic Science Research

The Program includes hydrogen and fuel cell–related activities in the Basic Energy Sciences (BES) program, within the DOE Office of Science. These activities seek to advance fundamental scientific knowledge and spur revolutionary advances, and they have the potential to contribute significantly to the Program's applied R&D efforts. This basic research is primarily crosscutting in nature, as any progress is likely to bring advances that are not isolated to just one area of fuel cells, hydrogen, or infrastructure technologies. 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 technologies for fuel cells and for the production, delivery, and storage of hydrogen.

The BES program supports fundamental scientific research addressing critical challenges related to fuel cells and the production and storage of hydrogen. This program employs both experimental and theoretical components for maximum impact, in five critical basic research areas:

- Novel materials for hydrogen storage
- Membranes for separation, purification, and ion transport
- Design of catalysts at the nanoscale
- Bio-inspired materials and processes
- Solar hydrogen production

For more information on how basic research can help overcome some of the critical technical advances needed in the areas of hydrogen and fuel cells, see the report, *Basic Science Needs for the Hydrogen Economy*, at: www.science.energy.gov/~/media/bes/pdf/reports/files/nhe_rpt.pdf.

In August 2009, the BES program established 46 Energy Frontier Research Centers (EFRCs). These integrated, multi-investigator centers are conducting fundamental research focusing on one or more of several "grand challenges" recently identified in major strategic planning efforts by the scientific community. The Program will coordinate with the EFRCs in research areas with the potential to provide advances relevant to hydrogen and fuel cell technologies.

In addition, the Program coordinates with the Biological and Environmental Research (BER) program, also within the DOE Office of Science. The BER program includes activities supporting fundamental research on biological systems involved in hydrogen production by microorganisms. The BER program's hydrogen research focuses on:

- Understanding metabolic and regulatory networks involved in biological hydrogen production
- Development of a wider range of model hydrogen-producing organisms
- Identification of novel genes, enzymes, and biochemical pathways relevant to hydrogen metabolism

The aim of BER-supported research is to provide integrative, systems-level understanding of hydrogen metabolism by phototrophic and fermentative microbes and to enable directed metabolic engineering approaches for enhancing hydrogen production.

2.4 Overcoming Institutional and Economic Barriers

2.4.1 Safety, Codes & Standards

The Safety, Codes and Standards sub-program supports R&D that provides critical data required for the development of technically sound codes and standards, which will be needed for the widespread commercialization and safe deployment of hydrogen and fuel cell technologies. For example, DOE-funded R&D provided critical data to develop validated hydrogen ignition and dispersion models at relevant temperatures and pressures. Data such as these enabled an update to the hydrogen bulk storage separation distances used in key codes (e.g., NFPA 52 and NFPA 2). As a result, required separation distances were reduced by as much as 50% in some instances.[68] The sub-program also identifies risk management measures to reduce the risk and mitigate the consequences of potential incidents that could hinder the commercialization of these technologies.

These activities promote collaborative efforts among government, industry, standards development organizations (SDOs), universities, and national laboratories in an effort to harmonize regulations, codes, and standards (RCSs) both domestically and internationally. Because the development of safety codes and product standards is not a static event but a continuing process, the Program's efforts will continue as technologies mature.

In addition to activities supporting codes and standards development, the sub-program conducts safety activities focused on development of information resources and best practices. The sub-program utilizes extensive external stakeholder input from automobile manufacturers and the energy, insurance, and aerospace sectors, as well as the fire protection community and academia, to enhance and create safety knowledge tools for emergency responders and authorities having jurisdiction. Continual availability of safety knowledge tools, distributed via an array of media outlets to reach the largest number of safety personnel possible, is a sub-program priority. The sub-program also supports the development and implementation of best practices and procedures to ensure safety in the operation, handling, and use of hydrogen and fuel cell technologies in all Program-funded projects.

Plans – Safety, Codes & Standards

Ongoing and planned Safety, Codes and Standards activities and goals include:

Safety R&D

- Ensure that safety is a critical priority in research, technology development, and market deployment
- Promote widespread sharing of safety-related information, procedures, and lessons-learned with first responders, authorities having jurisdiction (AHJs), and other stakeholders
- Understand and mitigate risk to facilitate the safe use of hydrogen and fuel cell technologies and improve insurability
- Conduct R&D to provide critical data needed to define requirements in codes and standards

[68] "NFPA 2: Hydrogen Technologies Code," National Fire Protection Association, 2011, www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=2.

Support of Codes and Standards Development

- Conduct research to support the development of codes and standards and facilitate international harmonization of codes and standards, including fuel quality standards
- Support and facilitate the promulgation of essential codes and standards by 2015 to support the widespread commercialization and market entry of hydrogen and fuel cell technologies
- Support and facilitate the completion of all essential domestic and international RCSs by 2020
- Support and facilitate the development of the Phase I Global Technical Regulations (GTRs) for hydrogen-fueled vehicles under the United Nations Economic Commission for Europe, World Forum for Harmonization of Vehicle Regulations and Working Party on Pollution and Energy Program (ECE-WP29/GRPE) by 2012 and Phase II by 2015
- Develop appropriate test methodologies, such as for measuring hydrogen cycling effects, and component testing for certification; and coordinate with nationally recognized accredited testing facilities
- Complete critical assessment of indoor refueling and system operation, and recommend relevant code modifications

2.4.2 Education and Outreach

The Program conducts education and public outreach activities to increase public awareness and understanding of hydrogen and fuel cells, with particular emphasis on addressing key audiences. The sub-program has identified and prioritized its audiences based on their roles in the use of hydrogen and fuel cell technologies in the near term. These audiences include safety and code officials, potential end-users and early adopters, and state and local government representatives. Educational materials and programs have been designed specifically for these groups, along with more general materials and programs for the public at large. To address longer-term educational needs, the sub-program is also developing materials for schools and universities, which are the source of future researchers, scientists, engineers, technicians, and technology users.

The Program's near-term education and outreach efforts are closely coordinated with its demonstration and early market deployment activities—as well as state and regional hydrogen and fuel cell initiatives—as part of a comprehensive strategy to transform success in the laboratory into success in the marketplace. By coordinating its efforts with existing hydrogen and fuel cell demonstrations and deployments, the Education sub-program is able to capitalize on the interest generated by these activities to reach a broader and more engaged audience, as well as the most likely early adopters. In addition, by providing valuable information to key players, education and outreach activities help to facilitate the implementation of these projects and contribute to their success. Integrating education and outreach into demonstration and deployment activities is one way that the Program lays the groundwork for additional early market deployments and helps ensure that these activities lead to genuine transformation of the marketplace, ultimately leading to long-term market adoption and acceptance.

Plans – Education & Outreach

Ongoing and planned education and outreach efforts include the following:

Educational Materials and Information Resources

- Develop and deploy Web-based training for a range of audiences including code officials and first responders

- Develop case studies and fact sheets that document technology deployment experiences, benefits, and lessons-learned
- Conduct activities to raise public awareness, with an emphasis on outreach in communities where demonstration and deployment projects are located or planned

Workforce Development

- Facilitate the expansion of hydrogen and fuel cell programs at educational institutions and coordinate activities within DOE and other agencies to ensure appropriate training material is available
- In coordination with the Systems Analysis sub-program, complete analysis to identify domestic employment and workforce development opportunities for early market hydrogen and fuel cell applications

2.4.3 Market Transformation

The Market Transformation sub-program identifies strategic opportunities to grow early markets for hydrogen and fuel cells, and it directly assists in the deployment of commercial and near-commercial hydrogen and fuel cell systems. Market Transformation activities make up a key final phase in the Program's comprehensive strategic timeline for moving technologies from the laboratory to self-sustaining commercialization in the marketplace. As such, these activities are closely coordinated and integrated with the Program's demonstration and education and outreach efforts.

The primary goal of Market Transformation is to increase sales volumes in key early markets, where a modest amount of new orders may have a significant impact on reducing costs through economies of scale. This approach is

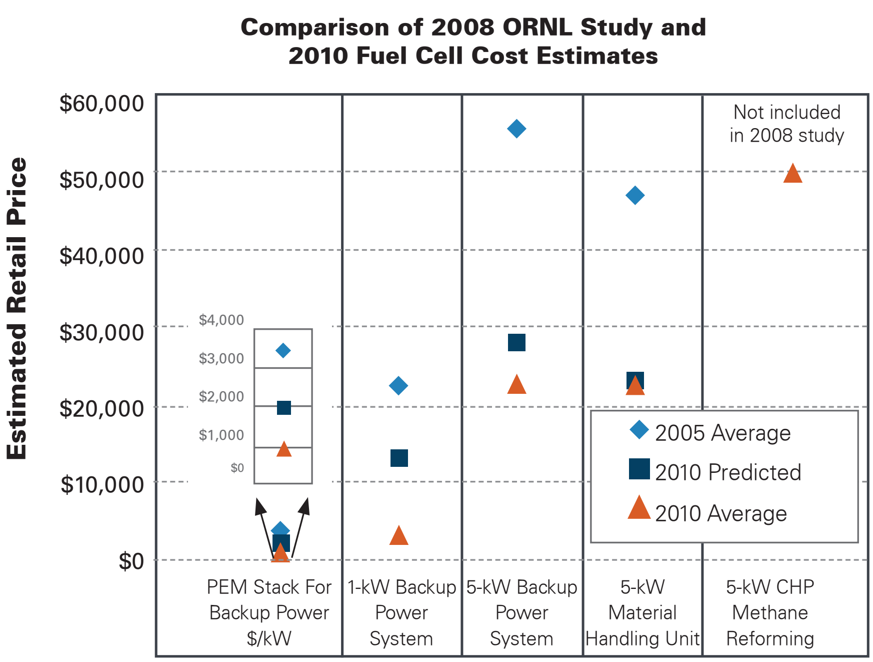


Figure 2.7. Cost Reductions in Early Market Fuel Cells. A 2008 study by Oak Ridge National Laboratory[69] assessed the average cost (in 2005) of fuel cells for early markets and then predicted what these costs would be in 2010, based on a model that included economies of scale and technology progress. An updated 2011 study by the same group has estimated the average 2010 cost, which was shown to be equal to or even lower than the predictions.

aligned with national laboratory and market research studies that outline necessary deployment measures to reach the Program's goals. For example, Oak Ridge National Laboratory developed a model to estimate reductions in the costs of certain types of fuel cells due to sales in early markets—they have since found that, in most cases, costs have fallen more significantly than the model predicted, as shown in figure 2.7.

Early market sales will also stimulate further market activity by supporting the growth of a domestic industry, overcoming some of the logistical and other non-technical challenges associated with adoption of a new technology, and establishing key elements of the infrastructure that will be essential for later market growth. In addition to their direct positive impact on the market, these deployments will provide valuable data on the performance of the technologies in real-world operation, lessons-learned from early adopters, and information that will be used to validate the benefits of the technologies.

The Program's early market deployment efforts are primarily focused on identifying opportunities for purchases of fuel cells by federal agencies and facilitating those purchases through technical and financial support.[70] The sub-program actively collaborates with other agencies to facilitate federal deployment of hydrogen and fuel cells in key early markets, including specialty vehicles, backup/remote power, portable power, primary power for critical applications, and renewable hydrogen production (including the use of hydrogen for energy storage). These federal agency partnerships are supported by the Hydrogen and Fuel Cell Interagency Working Group and the Hydrogen and Fuel Cell Interagency Task Force (establishment of the Task Force was mandated by the Energy Policy Act of 2005). To date, the Program has collaborated on deployment projects with several agencies, including the FAA, the National Parks Service, and the Department of Defense (DOD). Substantial opportunities for further collaboration were created with a memorandum of understanding (MOU) between DOE and DOD, signed in July 2010. In addition to the interagency activities the Program is involved in, DOE also provided $42 million of funding from the American Recovery and Reinvestment Act to industry partners, to support the deployment of up to 1,000 fuel cells, primarily in forklifts and backup power systems. DOE's partners in these deployments include several major companies, such as Sprint, AT&T, FedEx, Whole Foods, Sysco, Wegmans, and Coca-Cola. The Program will continue to support efforts initiated by the Recovery Act and will continue to provide valuable data from these projects to industry stakeholders.

The Market Transformation sub-program also coordinates with regional, state, and local activities involving hydrogen and fuel cells (for more information on coordination with states, see section 3.3.2). In some cases, early deployment projects involve collaboration with federal agencies and state or regional organizations. For example, in Hawaii the Program is working with the Hawaii Natural Energy Institute and DOD on a project involving demonstrations of renewable hydrogen production (from wind and geothermal energy) and early market deployments of stationary fuel cells and hydrogen-powered internal combustion engine buses. By pursuing such opportunities for broad collaboration, the Program seeks to maximize the benefits of all the resources committed by its various partners. And by concentrating deployments in strategic areas, involving key early market applications, the

[69] D. Greene and K.G. Duleep, "Bootstrapping a Sustainable North American PEM Fuel Cell Industry: Could a Federal Acquisition Program Make a Difference?" Oak Ridge National Laboratory, October 2008, http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2008_183.pdf.

[70] These efforts are consistent with federal early adoption provisions provided in the Energy Policy Act of 2005.

Program strives to achieve a "critical mass" of activity that will lead to a self-sustaining market for the technologies.

Plans – Market Transformation

Market Transformation activities will encourage higher-volume purchases of hydrogen and fuel cell technologies to help reduce non-technical barriers and support domestic industry growth. Ongoing and planned activities include the following:

- Collect and analyze data from cost-shared projects to provide important third-party test data
- Collaborate with DOD, other federal agencies, as well as state and local governments, to increase deployments of market-ready applications, both domestically and abroad
- Deploy fuel cell systems that co-produce hydrogen and electricity, including combined-heat-hydrogen-and-power (CHHP) systems using biogas from waste streams
- Enable and maximize use of intermittent renewable energy resources by using hydrogen for energy storage and fuel cells to generate electricity
- Continue to facilitate deployments through project management and feasibility analyses

2.4.4 Infrastructure

To address one of the key challenges to widespread commercialization of hydrogen and fuel cell technologies, particularly in the transportation sector, the Program is initiating a coordinated effort to: identify and assess hydrogen infrastructure options and scenarios; evaluate the status of technologies compared with their performance and cost targets; determine the business case for infrastructure development; and identify potential policies required for commercial viability. Based on these assessments, plans will be developed to co-fund projects that demonstrate innovative solutions to the infrastructure challenge, such as the use of bio-gas from waste streams as a feedstock for hydrogen (this was explored in a DOE-DOD workshop on opportunities in waste-to-energy), along with other novel ideas. These efforts are conducted in close coordination with other key players through several partnerships—including the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and the California Fuel Cell Partnership—and in consultation with the Hydrogen and Fuel Cell Technical Advisory Committee. A major aspect of these efforts is to gather and apply lessons learned from various regions and technologies, including

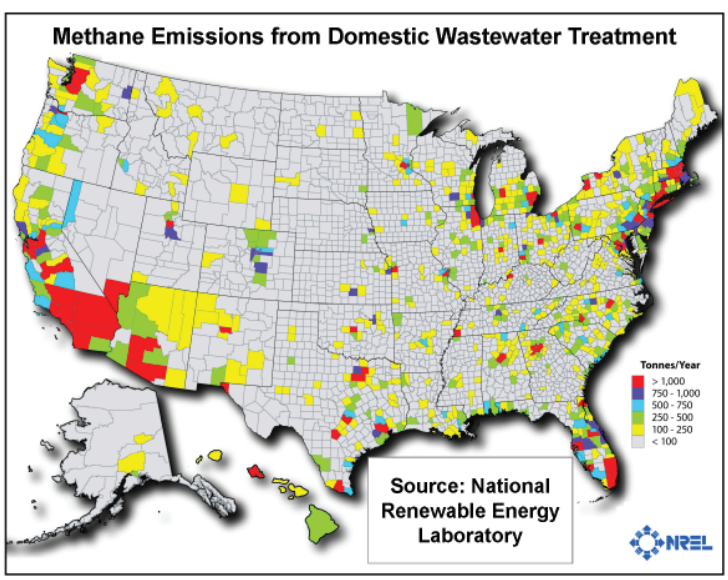


Figure 2.8. Energy from Waste. Another focus area for Market Transformation is waste-to-energy, which is one of the key areas for potential collaboration identified in the 2010 MOU between DOE and DOD. Because waste streams are concentrated near areas of high population density and energy demand (as shown in this map), they can be useful and convenient sources of fuel for CHP and CHHP installations, and they can provide an early-market source of hydrogen. This is especially true of military installations, where there is typically a significant waste-steam, a high population density, and diverse energy demands. The proximity of waste-to-energy sources to major population centers makes this approach a promising option for establishing a supply of hydrogen for the early phases of FCEV commercialization.

international stakeholders who have already established industry-led consortia to develop infrastructure.

While the Program's R&D approach includes longer-term plans for renewable hydrogen production using a variety of efficient, centralized processes, the near-term approach focuses on lower-cost options such as distributed, on-site hydrogen production from natural gas, which can utilize much of the existing infrastructure, or hydrogen produced using biogas from waste streams. The Program will continue validating infrastructure technologies as needed, through the Technology Validation sub-program, with emphasis on innovative ways to provide hydrogen for transportation applications in the first phases of commercialization.

The Market Transformation sub-program will also continue to address infrastructure challenges and apply lessons-learned from existing deployments in early market applications. Commercial customers who utilize hydrogen infrastructure today are tackling logistical and other real-world problems that will also be faced by operators of fuel cell electric vehicles, buses, and the public fueling stations of the future. For example, across the country, existing fleets of lift trucks are performing thousands of refuelings per week. And major companies, including FedEx Freight, Whole Foods, Wegmans, Coca-Cola, Sprint, AT&T, and Sysco, have committed to the use of hydrogen through their participation in DOE's Recovery Act projects. To make these operations work, participants have had to address a myriad of challenges related to hydrogen infrastructure—including siting, zoning, supply, and pricing issues.

As early market infrastructure challenges are overcome through technology improvements, cost-reductions, the growth and development of the supply-chain, improved institutional processes, or simply the accumulated wisdom of user-experience, there will be significant long-term benefits that will aid in the transition to a more widespread infrastructure. In the longer term, large-scale establishment of hydrogen infrastructure will likely involve partnerships among industry, DOE, and other agencies, such as DOT, and will include coordination on state activities in key areas, such as the infrastructure plans in California and Hawaii that are currently underway.

2.5 Key Milestones

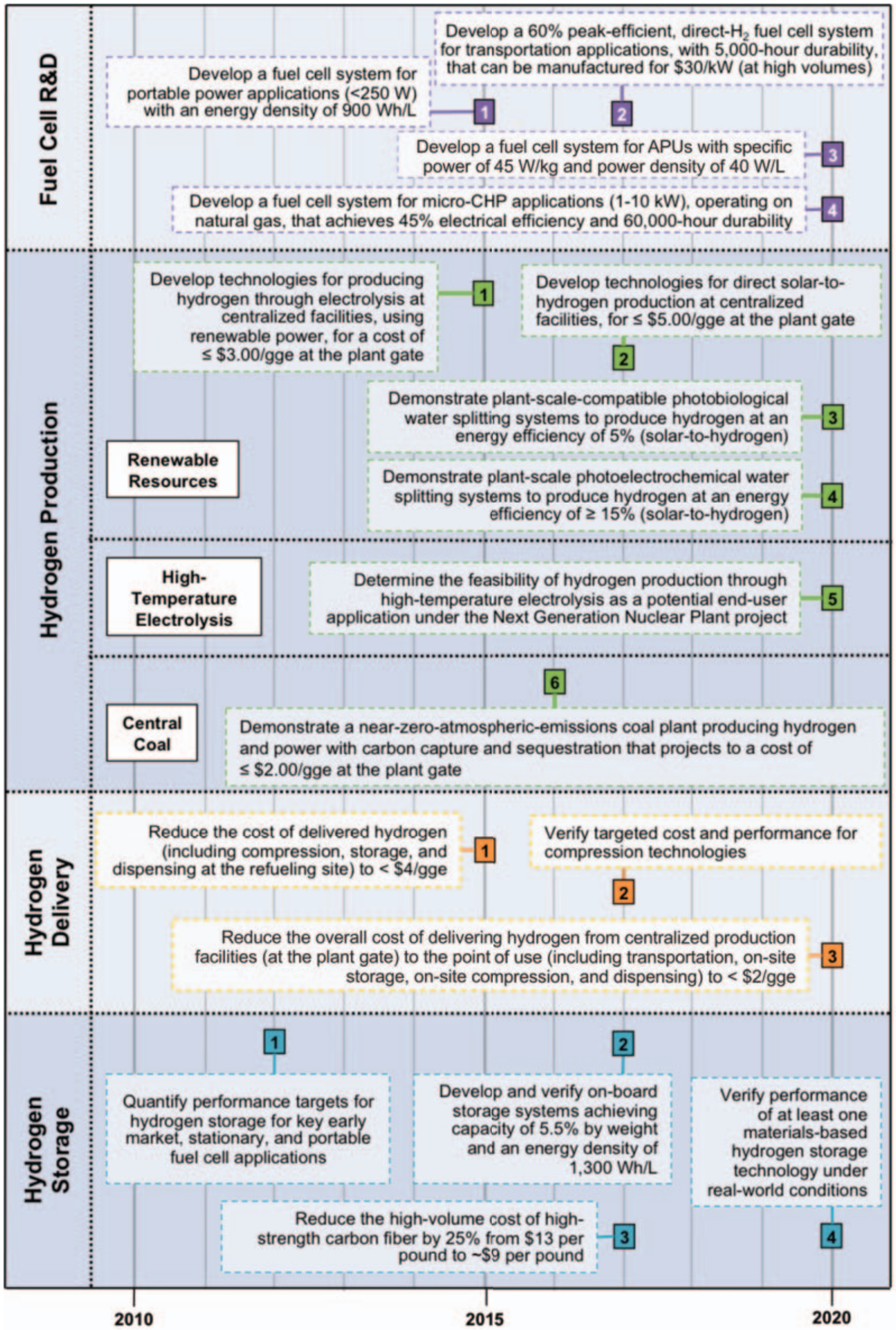


Figure 2.9a. Technology Development Timeline—Key Milestones. More-specific milestones are in the hydrogen and fuel cell–related plans of the participating DOE offices, including EERE's *Fuel Cell Technologies Program Multi-Year RD&D Plan*, www.hydrogenandfuelcells.energy.gov/mypp; and the Office of Fossil Energy's *Hydrogen from Coal RD&D Plan*, http://fossil.energy.gov/programs/fuels/hydrogen/2010_Draft_H2fromCoal_RDD_final.pdf.

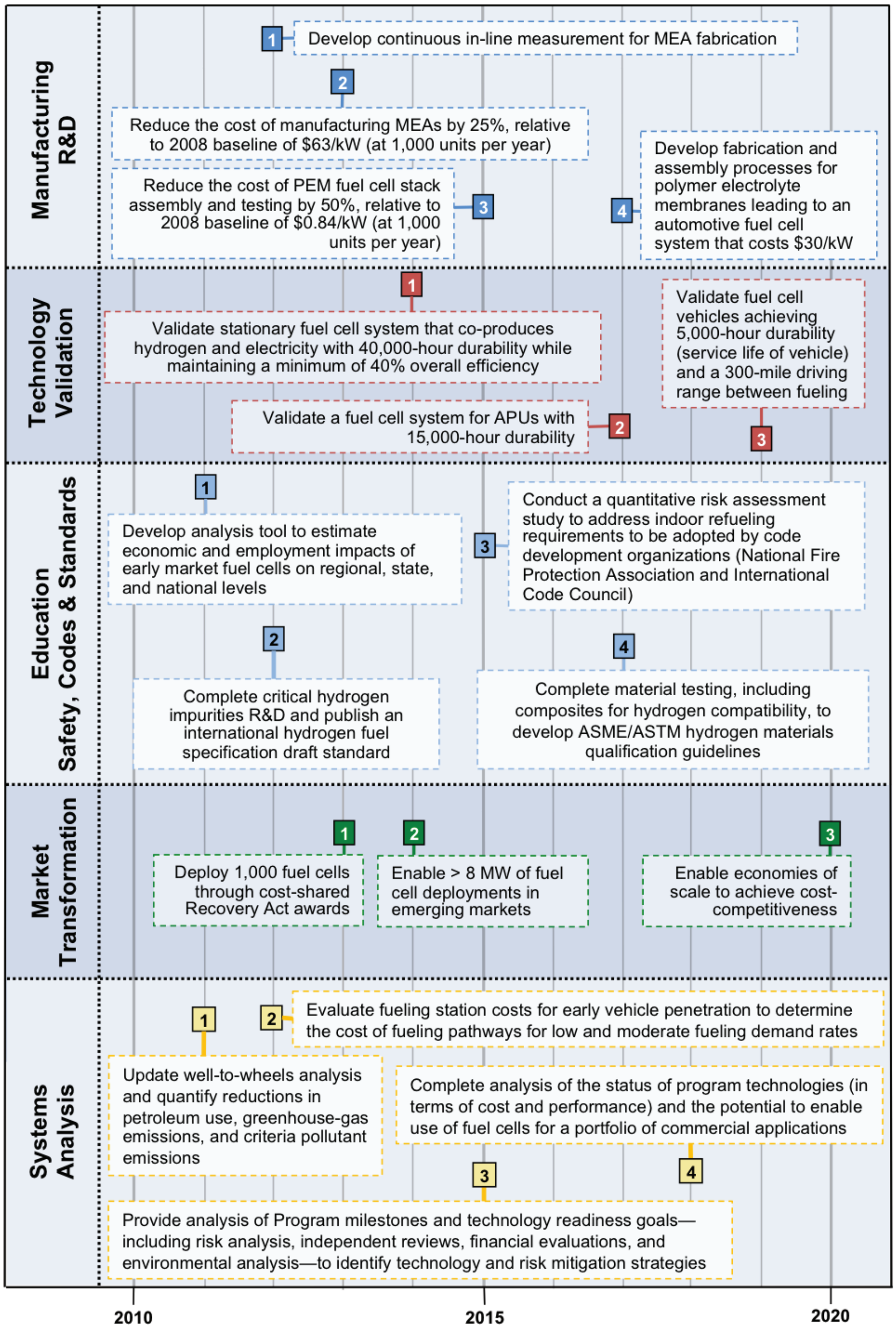


Figure 2.9b. Technology Development Timeline—Key Milestones.

3. Program Direction, Processes, and Stakeholder Input

The DOE Hydrogen and Fuel Cells Program utilizes effective tools and management processes, including stakeholder input, to ensure the effectiveness and maximize the value of its efforts.

- **Expert and Stakeholder Input.** Stakeholders and outside experts have been involved closely in all phases of the Program, from development of strategy, to identifying specific R&D targets, to reviewing individual projects and evaluating progress.
- **Ensuring Effectiveness.** The Program maintains the effectiveness of its efforts through competitive selection processes, rigorous internal controls, systematic tracking of progress with respect to targets, extensive partnerships with stakeholders, and regular external evaluations and reviews.
- **Maximizing Value.** Collaboration and coordination on the federal, state, and international levels help to maximize the value of the efforts of the Program and its partners.
- **Transparency.** The Program upholds transparency in its activities through a variety of mechanisms, including the publication of merit review proceedings, reviewer feedback and project scores, annual progress reports, and the results of independent analyses and assessments.

3.1 Organization & Partnerships

3.1.1 Organization

Hydrogen and Fuel Cell Coordination Group

The Program established the Hydrogen and Fuel Cells Coordination Group to coordinate activities among the DOE offices of Energy Efficiency and Renewable Energy, Fossil Energy, Nuclear Energy, and Science, in addition to coordinating with the Department of Transportation (DOT). This group meets monthly to:

- Evaluate the progress of hydrogen and fuel cell activities with regard to milestones and performance goals
- Strengthen information exchange on programmatic and technical developments
- Provide suggestions for improving management practices and technical performance
- Collaborate on systems analysis activities to gain understanding of the impacts of alternative technology pathways, from environmental, energy, and economic standpoints

3.1.2 Partnerships

Stakeholder input is vital to Program planning as well as to sustaining and improving the Program's effectiveness and the value of its efforts. The input that is received through collaborative partnerships helps ensure that the Program will achieve maximum societal, economic, and environmental benefits. These partnerships also help to ensure that the RD&D efforts of government, academia, and industry are well coordinated, their diverse capabilities are well integrated, and their resources are effectively utilized.

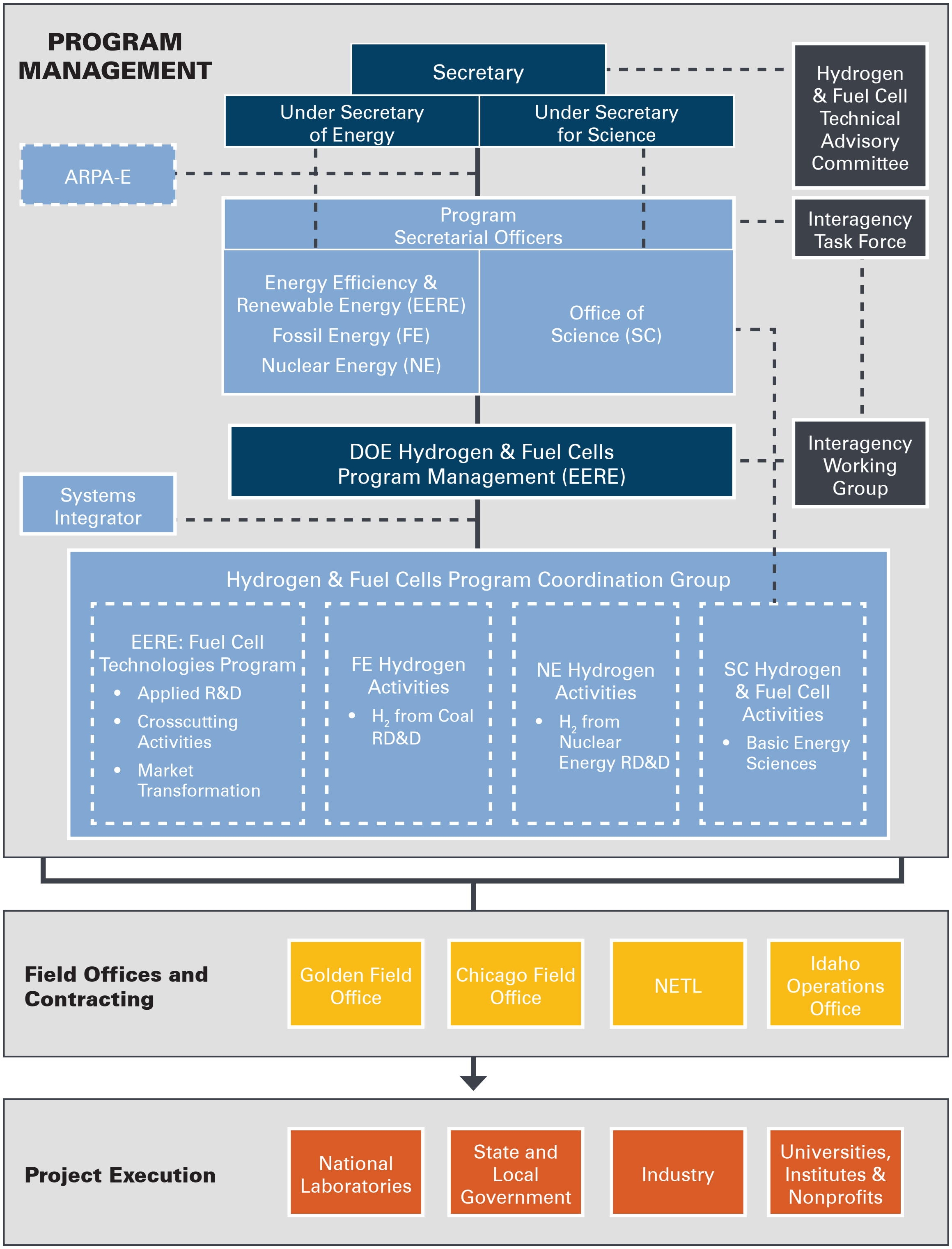


Figure 3.0. The Hydrogen and Fuel Cells Program's Organizational Structure.

Basic Research	Applied Research & Technology Development	Learning Demonstrations	Market Transformation

• Universities
• Federal laboratories
• Research institutes
	• Equipment manufacturers and industry suppliers
	• Federal laboratories
	• Universities
	• Research institutes
	• Codes and standards development organizations
		• Automobile and energy companies
		• Industrial gas suppliers
		• Equipment manufacturers
		• Utility companies
		• State and local governments and code officials
			• Federal agencies, e.g.,
			  ◦ Department of Transportation
			  ◦ Department of Defense
			  ◦ U.S. Postal Service
			  ◦ Department of Commerce
			• Industry, e.g.,
			  ◦ End-users, early adopters
			  ◦ Automobile and energy companies
			  ◦ Industrial gas suppliers
			  ◦ Utility companies
			  ◦ Energy service companies
			  ◦ Venture capital firms
			• State and local governments
			• Industry trade groups

Figure 3.1. The Types of Entities Involved in the Program, and Their Roles.

For several years, the Program has maintained a strategic partnership with industry stakeholders that has been instrumental in establishing high-level strategic priorities and goals and in guiding the Program's R&D efforts. DOE established the partnership, currently known as U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability), to focus on pre-competitive, high-risk research needed to reduce the dependence of the nation's personal transportation system on imported oil and to minimize harmful vehicle emissions. A major goal of the partnership is to identify and develop the technologies required for the high-volume production of affordable light-duty vehicles, including electric, hybrid-electric, advanced combustion, and hydrogen vehicles—along with the national infrastructure necessary to support them. Partners currently include DOE, 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 utilities (DTE Energy and Southern California Edison). Additional partners are added as the scope and needs of the partnership evolve. Regular meetings of the technical teams, which are co-chaired by DOE and industry, are a key asset of the partnership, providing a valuable channel for industry input on technical targets and R&D priorities.

The Program also benefits from continual interaction with stakeholders through its involvement with a number of other organizations, including the following:

- The Fuel Cell and Hydrogen Energy Association (FCHEA), which is dedicated to the commercialization of fuel cells and hydrogen energy technologies and was created by a merger of the United States Fuel Cell Council and the National Hydrogen Association (FCHEA's membership represents a broad range of stakeholders, including: manufacturers of fuel cell components, systems, and materials; hydrogen producers and fuel distributors; universities; government laboratories; and others.)
- The California Fuel Cell Partnership, a collaboration of about 30 organizations that seeks to advance the use of fuel cell electric vehicles in California

- The Hydrogen Utilities Group, a partnership of utilities and industry associations seeking to integrate promising hydrogen-energy-related business applications into the electric utilities sector
- The California Stationary Fuel Cell Collaborative, a public-private partnership working to advance the commercialization of stationary fuel cells for distributed generation throughout the state of California

The Program also utilizes a number of working groups, such as the High Temperature Membrane Working Group, the Storage Systems Analysis Working Group, the Pipeline Delivery Working Group, and several others, to coordinate activities in addressing specific technology areas. In addition, the Program works extensively with international organizations; these activities are discussed in detail in section 3.3.3.

3.2 Program Implementation

Several mechanisms, both internal and external, help to ensure the vitality and effectiveness of the Program. Program strategies and approaches are refined and updated at all levels through extensive analysis, meetings with stakeholders, discussions with key strategic partners, and feedback from external review panels.

3.2.1 Stakeholder Input

An essential element of the Program's strategy has been to solicit and include stakeholder feedback in the planning of its activities. This approach helps to ensure that the Program is aligned with the priorities of key players, including industry, end-users, academia, and other government agencies. Among the primary channels for this input are requests for information (RFIs) and workshops conducted by DOE to help establish high-level program direction and to develop and update technology-specific RD&D plans.

DOE has convened major strategic planning workshops over the past several years, which have been instrumental in laying the groundwork for the Program's efforts. Senior executives and other representatives from the energy and transportation industries, universities, environmental organizations, federal and state government agencies, and national laboratories have met to establish a common vision for the role of hydrogen in the nation's energy future and to identify the key milestones that would have to be met to realize that vision. These strategic workshops have resulted in several publications that have laid the foundation for the Program's planning documents (for more information, see http://hydrogen.energy.gov/guiding_documents.html).

The Program also regularly conducts workshops for specific technology areas, to identify and update RD&D priorities, develop plans, and identify technical targets and milestones. Like the Program's strategic planning workshops, these workshops involve a wide range of stakeholders and provide an open forum for discussion of the status of the technologies and the challenges facing their development. Through these workshops, the Program develops a strategic path forward for each technology area and identifies the role of the federal government on that path. Some examples of the workshops the

Program has held are shown in figure 3.2. As new opportunities evolve, the Program will continue to issue RFIs and hold workshops with relevant stakeholders to provide input into the development of plans and priorities. For example, to identify and develop plans in the area of fuel cells for aircraft applications, the Program has convened workshops which include relevant industry partners such as Boeing and Airbus as well as relevant fuel cell developers. Workshops are publicly announced to ensure transparency and inclusiveness and to enable widespread involvement of relevant stakeholders.

3.2.2 Internal Measures—Program Management

An important aspect of the Program's strategy is ensuring the most effective use of funds, which is accomplished through the development of appropriate targets and milestones, a rigorous competitive-selection process, cost-sharing with private-sector partners, and an extensive peer-review process.

Setting Targets & Milestones

Specific targets and milestones for all R&D pathways are developed in close consultation with experts in industry and the research community. The target-setting process is driven by requirements to be competitive with emerging and incumbent technologies in terms of cost and performance. The Program's multi-year RD&D plans document more than 200 specific targets and hundreds of specific milestones that are required to demonstrate and gauge progress toward those targets. As progress is made and as more information becomes available through technology demonstrations and stakeholder feedback, DOE regularly updates its milestones to reflect changing conditions in the market and industry.

Developing Project Portfolios to Address Targets

DOE selects program activities on the basis of technical feasibility, high-impact potential, innovation, and likelihood of making progress toward DOE's milestones and targets. Because the Program places a high value on engaging the best possible partners to help carry out its work, a high priority is placed on the use of competitive solicitations. This process allows the Program to select the best proposals

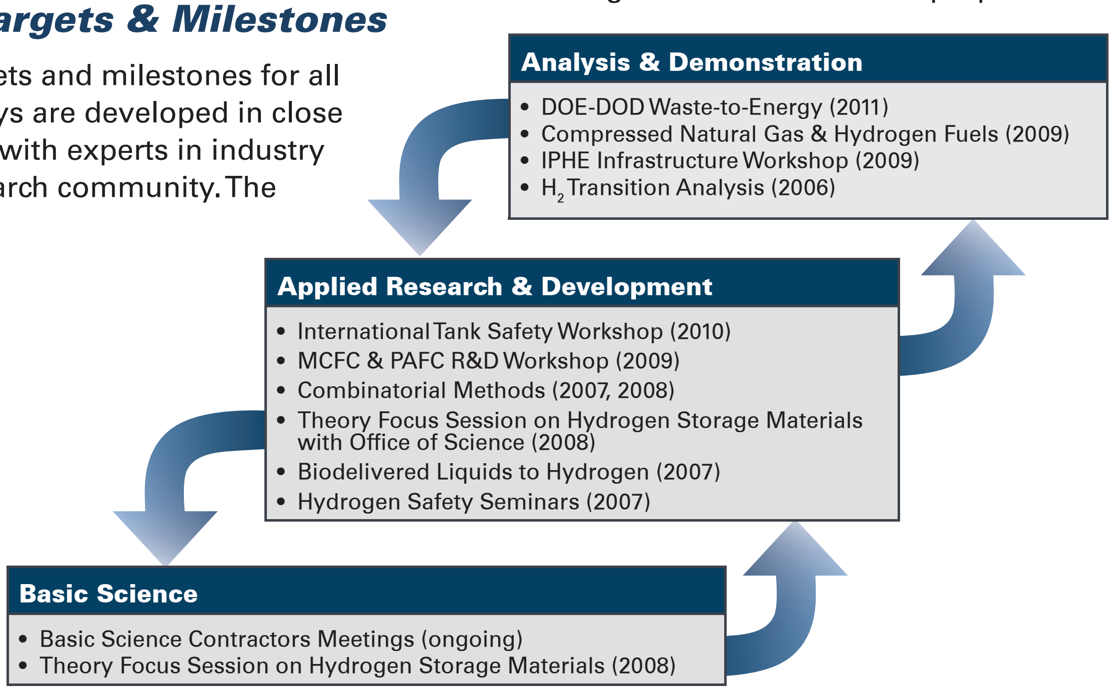


Figure 3.2. Examples of the Program's Technology Workshops.

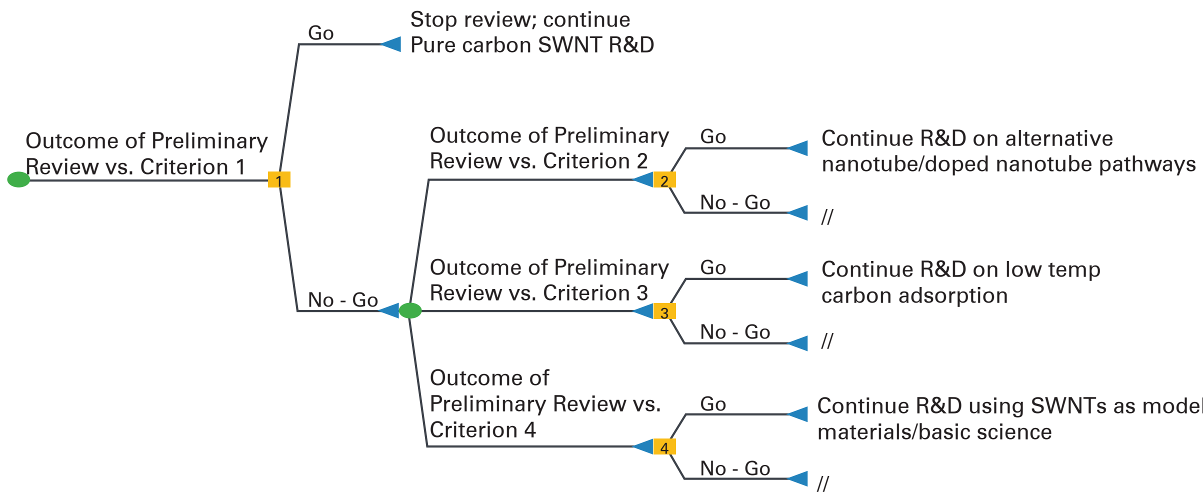


Figure 3.3. The decision tree used by the Program in the process of down-selecting single-walled carbon nanotubes (SWNTs) for hydrogen storage.[71] DOE's criteria were: (1) the technical progress on capacity for hydrogen storage in pure, undoped carbon SWNTs and whether SWNTs have met the criterion of 6 weight percent hydrogen storage (on a materials basis) at room temperature; (2) whether a technically viable pathway exists to meet the original criterion of 6 weight percent at room temperature using either pure, undoped SWNTs or a "hybrid" approach (e.g., metal doped nanotubes); (3) whether hydrogen adsorption on carbon nanotubes at low temperature (77K) should be considered at the early stages of the Program's efforts in hydrogen storage; and (4) whether SWNTs may be used as model materials for fundamental research, theoretical simulation and an improved understanding of nanoscale hydrogen storage mechanisms and the interplay between factors such as hydrogen charge/discharge efficiency, thermodynamics/kinetics considerations, and volumetric/gravimetric capacities.

from the most qualified teams, based on the input of independent expert reviewers. Most solicitations involve an initial RFI, which gathers a wide range of input to help the Program determine the topics for projects that will be most useful. This is often followed by a pre-solicitation workshop, which also engages diverse stakeholders, providing the opportunity to further explore and refine topics before the final solicitation is announced. Once the proposals are received, they are reviewed by experts with the appropriate technical background and ability to provide independent, unbiased input before DOE makes selections.

Program Execution

The Program also employs a comprehensive approach to managing projects that involves both top-down and bottom-up priority setting. This allows crucial feedback through all levels of the Program, from the project level, to the task-areas, to the sub-programs, and to Program management. The Program's approach to directing research efforts includes a systematic process for discontinuing certain research pathways ("down-selecting") to focus on the most promising areas. This involves "go/no-go" decision points defined by performance-based technical milestones and quantitative metrics at the sub-program, task area, and project level. When a "no-go" decision is reached, this does not necessarily mean that a line of R&D is completely abandoned; there may be cases where further breakthroughs in basic research are needed, in which case these needs can be communicated to the Program's basic science efforts. In some cases, an entire technology pathway may be eliminated, such as the on-board fuel processing of gasoline.

An example of a down-selection decision process is shown in figure 3.3, which illustrates the methodology used in deciding to discontinue research of pure single-walled

[71] "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.

carbon nanotubes. In this case, funds were diverted to more promising approaches such as other sorbents that could potentially store hydrogen with higher capacities and at higher temperatures. Another example of down-selection is in thermochemical production of hydrogen. This down-selection was the outcome of an objective scoring process developed and implemented to select the best, most cost-effective cycles for thermochemical production of hydrogen (using high-temperature nuclear or solar energy). This process employed analysis of data from laboratory studies and used common assumptions and parameters suitable to address the economic and technical feasibility of a pilot demonstration facility. Over 350 unique cycles were analyzed for this effort. Three thermochemical cycles and high-temperature electrolysis were selected for continuing R&D.

To ensure that the Program is managed in an integrated manner and that it is guided by sound, critical analysis, the Program conducts systems analysis and systems integration activities. These efforts provide valuable information for high-level decision-making and ensure that all Program activities effectively contribute to achieving its goals. (The Program's Systems Analysis and Systems Integration activities are discussed in detail in sections 2.1.1 and 2.1.2, respectively.)

External Review and Evaluation

The Program employs a number of mechanisms for obtaining external input in the form of reviews and evaluation. As directed by EPACT, the National Academies review the Program every four years. The National Academies also conduct biennial reviews of DOE's RD&D progress under the partnership with USCAR, energy companies, and utilities (the most recent reviews were published in August 2005 and March 2008). The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) provides technical and programmatic advice to the secretary of energy on hydrogen RD&D efforts. HTAC includes up to 25 members representing domestic industry, academia, professional societies, government agencies, financial organizations, and environmental groups, as well as experts in the area of hydrogen safety. The Government Accountability Office (GAO) has also conducted a review of the Department's hydrogen activities and released its report in February 2008 (GAO-08-305).

In addition to these reviews, the Program receives feedback through its Annual Merit Review and Peer Evaluation Meeting, which involves the participation of more than 200 technical experts reviewing individual RD&D projects. These experts provide independent assessment of the performance and overall value of the Program's projects, and their findings are used to help guide Program funding. For example, in 2010 approximately 1,700 stakeholders and project participants took part in the Annual Merit Review, which was conducted jointly with EERE's Vehicle Technologies Program. A case study conducted by the EERE Office of Planning, Budget and Analysis in 2008 found that the Program's Annual Merit Reviews conducted from 2003 to 2007 saved nearly $30 million by avoiding continued investment in projects determined to be unproductive or misaligned with the Program's goals. In addition, the study found that the peer reviews led to improvements in project performance, with more than 80% of the low-rated projects achieving higher ratings in subsequent reviews.[72]

The Program, though its Systems Integration function, convenes independent technical reviews to gauge progress toward meeting specific technical targets and to provide technical information necessary for key decisions. These independent reviews provide

[72] "DOE Hydrogen Program Saved Nearly $30 Million by investing in Annual In-Progress Peer Reviews," U.S. Department of Energy, October 2008, www1.eere.energy.gov/ba/pba/pdfs/EERE_Financial%20 SavingsExecutiveBrief.pdf.

an unbiased understanding of the status of technical targets based on the input of independent experts. This understanding is critical to Program decision-making, budget planning, and prioritization of RD&D activities. These reviews are also of interest to the Office of Management and Budget, which assesses the Program's needs and budgets based on progress toward targets. And these assessments help ensure the quality, objectivity, utility, and integrity of information disseminated to the public. Independent reviews conducted to date include the following:[73]

- Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis (see text box on page 46)
- Fuel Cell System Cost for Transportation—2008 Cost Estimate (see text box on page 43)
- Go/No-Go Recommendation for Sodium Borohydride for On-Board Vehicular Hydrogen Storage
- Measurement of Hydrogen Production Rate Based on Dew Point Temperatures
- Cryo-Compressed Hydrogen Storage for Vehicular Applications
- Distributed Hydrogen Production from Natural Gas (see text box on page 46)
- Fuel Cell System for Transportation—2005 Cost Estimate
- On-Board Fuel Processing Go/No-Go Decision

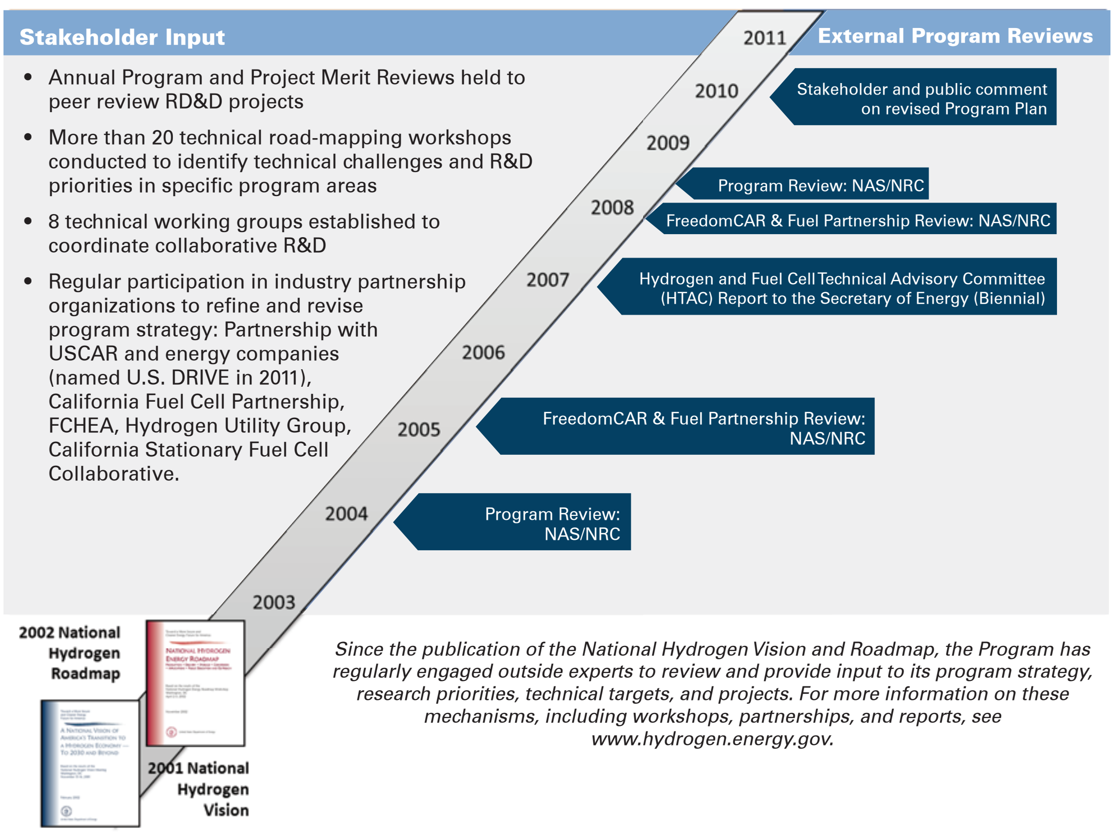


Figure 3.4. External Review and Feedback to the Program. The Program incorporates extensive stakeholder input and feedback from external reviews. These mechanisms ensure that its strategy is robust and its efforts are directed in the most effective way.

[73] "Independent Peer Reviews," DOE Hydrogen and Fuel Cells Program website, accessed October 7, 2010, http://hydrogen.energy.gov/peer_reviews.html.

3.3 Federal, State, and International Collaboration and Coordination

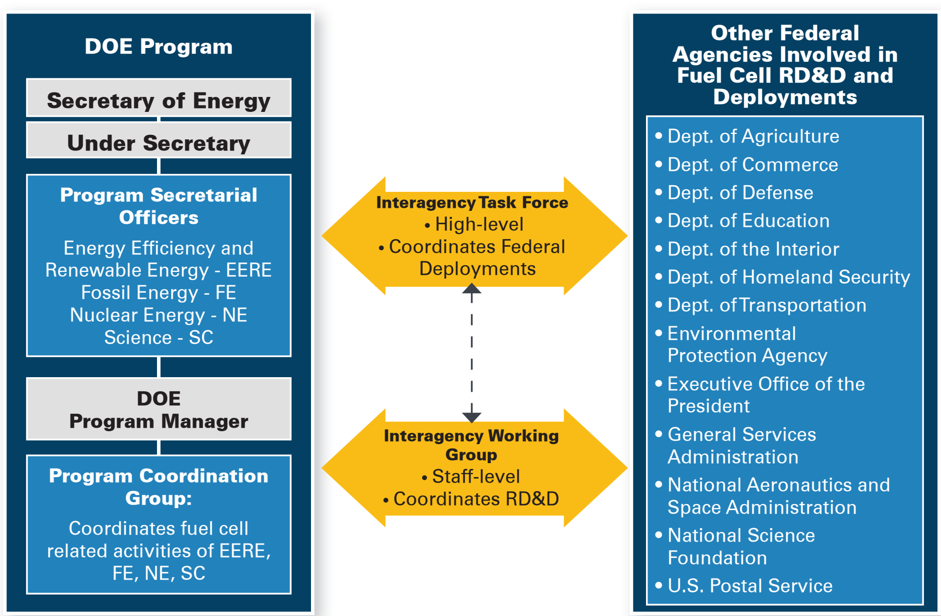
The Program collaborates and coordinates extensively with other efforts at the national, state, and international levels to make the most of the diverse capabilities of these ongoing efforts and to ensure that activities are harmonized and integrated to the highest degree possible. The Program's efforts are also closely coordinated with other programs within DOE that are contributing to achieving the Program's goals, including efforts in: hybrid electric vehicles; biomass and biorefinery systems; wind, solar, and geothermal energy; carbon sequestration and carbon management; and high-temperature stationary fuel cells, for use with fossil fuels (for more information on these activities, see the sidebar on the Office of Fossil Energy's SECA Program, in section 2.2.1).

3.3.1 Federal Interagency Coordination

The Program actively pursues opportunities for coordination and collaboration with other federal agencies. By exchanging information on research, development, and demonstration projects, and collaborating on demonstration and deployment activities, participating organizations can leverage each other's resources to achieve the maximum benefit from their efforts. For example, the Program collaborates extensively with the Department of Defense (DOD) on early market deployment activities, and a recent memorandum of understanding between DOE and DOD has provided a valuable mechanism for an array of future collaborations, including opportunities for the use of fuel cells in waste-to-energy applications, shipboard APUs, and aircraft APUs. DOD and DOE have already held workshops to identify opportunities, challenges, and other areas of interest for all three of these topics.

To facilitate broad interagency coordination, a staff-level Hydrogen and Fuel Cell Interagency Working Group (IWG) has held monthly meetings since 2003. With representatives

Figure 3.5. Interagency Coordination. Through its leadership of the Interagency Task Force and Interagency Working Group on Hydrogen and Fuel Cells, the Program plays a key role in coordinating federal efforts to advance and promote the commercialization of hydrogen and fuel cells.



of more than 10 federal agencies, the IWG provides a forum for sharing research results, technical expertise, and lessons learned about hydrogen and fuel cell program implementation and technology deployment, as well as coordinating related projects to ensure efficient use of taxpayer dollars. Currently, agencies participating in the IWG include the Department of Agriculture, Department of Commerce, DOD, DOE, Department of Homeland Security, Department of State, DOT, Environmental Protection Agency (EPA), National Aeronautics and Space Administration, National Science Foundation, Office of Science and Technology Policy, and the U.S. Postal Service. DOE, DOT, the EPA, and the National Institute of Standards and Technology (Department of Commerce) also coordinate their activities involving safety, codes and standards, and regulations.

DOE also serves as chair of the Hydrogen and Fuel Cell Interagency Task Force (ITF), as directed by section 806 of EPACT. The ITF includes senior-level representatives from agencies participating in the IWG. Members are at the functional level of assistant secretary, providing the ITF with the ability to make departmental decisions that can influence the development and implementation of hydrogen and fuel cell programs. Work resulting from decisions by the ITF is complemented and supported by the staff-level IWG. To date, the ITF has focused its efforts on facilitating hydrogen and fuel cell demonstrations and deployments to help federal agencies meet the requirements of EPACT Sections 782 and 783 and Executive Order 13423, "Strengthening Federal Environmental, Energy, and Transportation Management."

For a detailed description of hydrogen and fuel cell activities at other federal agencies, see www.hydrogen.gov, a portal maintained by DOE that provides access to federal efforts related to hydrogen and fuel cells.

3.3.2 Coordination with States

The Program's activities with state governments and organizations are key to implementing its overall strategy for real-world demonstrations, public outreach and education, and early market deployments. By coordinating closely with states, the Program is able to ensure that these activities—at the federal, state, and local levels—are integrated into a well-planned timeline that maximizes their benefits and enables a broader transformation of the marketplace. Examples of current and planned Program activities involving coordination with states include:

- Utilizing the Program's unique analytical capabilities to gather and analyze data from state and local demonstration projects and publish fact-sheets that are useful for future demonstrations and deployments
- Leveraging the Program's broad base of outreach and education resources—such as lessons-learned from demonstration projects across the nation—to improve the impact of diverse state and local projects
- Conducting demonstration projects for hydrogen infrastructure in carefully planned locations that are most likely to provide the greatest benefit for state and local fuel cell deployments

Several states—including California, Connecticut, Hawaii, Ohio, New York, and South Carolina—have major hydrogen and fuel cell programs underway, and the Program is actively involved with all of them. Through such coordinated efforts, federal resources can efficiently leverage state and local resources and encourage additional investment. This coordination also enables the Program to evaluate a regional-based strategy, which focuses efforts on certain areas with the highest likelihood of success. By pursuing longer-term, sustained efforts, with resources concentrated on key regions, the Program aims to push markets closer to the critical tipping point where they can become self-sustaining.

One channel for coordination with states and local governments is through state projects funded by the Education sub-program. The state projects participate in monthly regional and state outreach calls organized by the Program. These calls provide an informational forum for communication among state agency officials, state energy fund officials, individuals involved in state and regional hydrogen and fuel cell initiatives, and others with an interest in advancing and advocating hydrogen and fuel cell use at the state and local government levels.[74] These calls cover a range of relevant topics, such as deployment success stories and lessons-learned.

In addition, the Education sub-program funds several state and local government outreach projects—in areas with an active hydrogen and fuel cell presence, in addition to two nationwide state-level projects—to develop case studies, best practices, and technical assistance resources to help decision-makers identify and assess opportunities for future deployment. These organizations have been utilizing these resources to work directly with state agencies to implement policies and programs that can support the growth of hydrogen and fuel cell markets in local economies.

3.3.3 International Coordination and Collaboration

As mentioned in Chapter 1, countries all over the world have recognized the importance and potential benefits of hydrogen and fuel cell technologies, and they are investing significant and growing amounts of funding. The United States is working with many of these countries through the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), which includes eighteen member countries and the European Commission, and the International Energy Agency (IEA) Implementing Agreements, which include more than 25 countries.

Formed in 2003, the IPHE is focused on four strategic priorities: accelerating the market penetration and early adoption of hydrogen and fuel cell technologies and their supporting infrastructure; advancing policy and regulatory actions to support widespread deployment; raising the profile of these technologies with policy-makers and the public; and monitoring technology developments in hydrogen, fuel cells, and complementary technologies. The United States is a founding member of IPHE and served as the IPHE secretariat for its first four years until 2007. The IPHE has co-sponsored more than 13 conferences, organized a series of workshops on issues ranging from hydrogen storage to infrastructure development, and leveraged the resources of its members by facilitating and endorsing 30 international collaborative projects. Through this partnership, the Program has collaborated on joint R&D projects with partners in Europe, Asia, Australia, and South America.

The Program collaborates with other countries on R&D of hydrogen and fuel cell technologies through participation in the IEA, where it is a member of both the Advanced Fuel Cells Implementing Agreement (AFCIA)[75] and the Hydrogen Implementing Agreement (HIA).[76] The Program participates in five AFCIA annexes and ten HIA task areas.

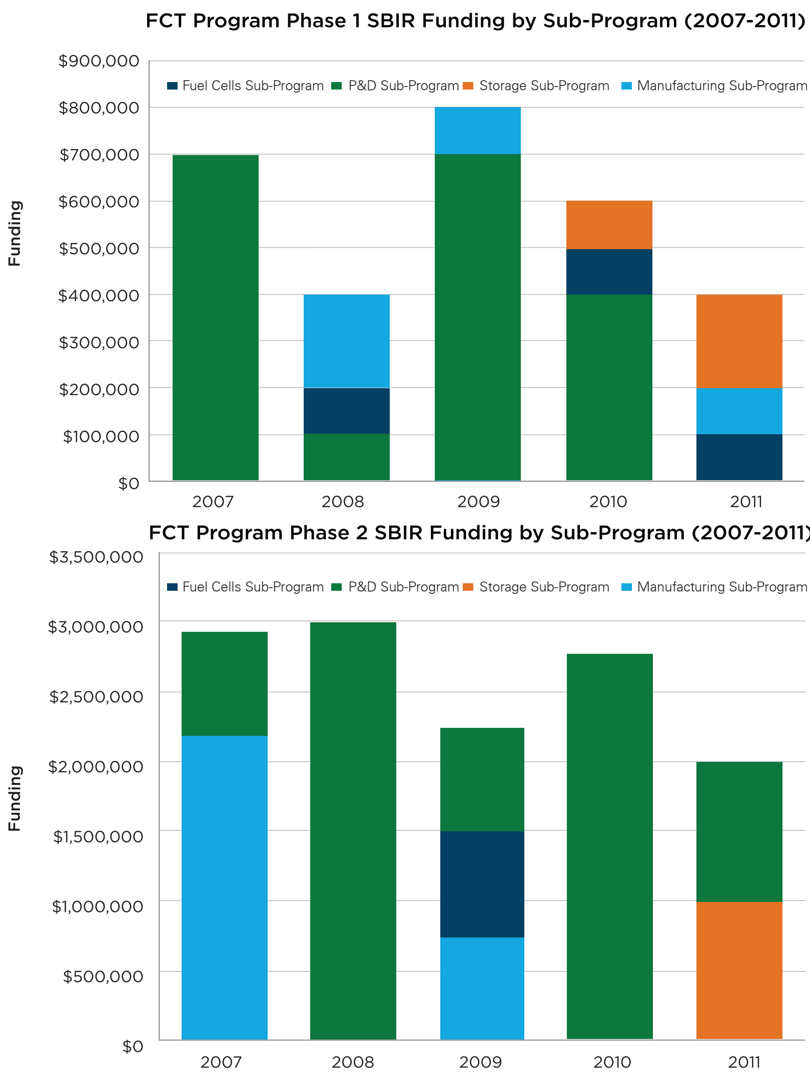
[74] "For State and Local Governments," DOE Fuel Cell Technologies Program website, www1.eere.energy.gov/hydrogenandfuelcells/education/state_local.html.

[75] International Energy Agency Advanced Fuel Cells Implementing Agreement website: www.ieafuelcell.com.

[76] International Energy Agency Hydrogen Implementing Agreement website: http://ieahia.org.

3.3.4 Small Business Participation

In addition to the core Program, opportunities for participation by small businesses are available through DOE's activities in the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. Solicitation topic areas are selected to complement core Program areas and to encourage innovation and entrepreneurship by funding small businesses. Figure 3.6 shows examples of projects and funding over the last few years. Successful Phase-1 projects are awarded Phase-2 funding. The Program plans to continue fostering small business participation through DOE's SBIR/STTR activities.



Production & Delivery: 23 Projects
- Hydrogen Production, Hydrogen Production Process Intensification, Hydrogen Compression & Liquefaction, Hydrogen Home Fueling Analysis, and Hydrogen Dispensing

Storage: 4 Projects
- Advanced Materials for Hydrogen Storage

Fuel Cells: 8 Projects
- Fuel Cell Coolants & Membranes, Bio-Fueled Solid Oxide, Innovative Fuel Cell Concepts & Balance of Plant, Stationary & Transportation Applications

Manufacturing: 10 Projects
- Hydrogen Production Equipment, Hydrogen Storage Containers, Polymer Electrolyte Membrane (PEM) Fuel Cells & Bipolar Plates, Fuel Cell Range Extenders

Production & Delivery: 11 Projects
- Hydrogen Compression Technology, Hydrogen Production, Hydrogen from Waste, Energy Storage for Intermittent Renewable Resources

Storage: 1 Project
- Advanced Energy Storage for Early Market Applications

Fuel Cells: 3 Projects
- Fuel Cell Coolants & Membranes, Dimensionally Stable High Performance Membrane, Bio-Fuel Solid Oxide Fuel Cell

Manufacturing: 4 Projects
- Manufacturing of Hydrogen Storage Containers, Manufacturing of Polymer Electrolyte Membrane (PEM) Fuel Cells, Manufacturing of Bipolar Plates

Figure 3.6. DOE's Small Business Innovation Research Funding (SBIR) for Hydrogen and Fuel Cells. Through the SBIR program, since 2004, DOE has provided $4.5 million for 45 Phase-1 projects and more than $15 million for 19 Phase-2 projects in hydrogen and fuel cell technologies (note that the bar graphs in this figure do not include SBIR funding prior to 2007). An additional $6.6 million has been awarded to four Phase-3 projects, in advanced materials for fuel cells and bio-fueled solid-oxide fuel cells.

Appendix A: *About This Document*

The Department of Energy Hydrogen and Fuel Cells Program Plan (the *Plan*) outlines the strategy, activities, and plans of DOE's Hydrogen and Fuel Cells Program, part of DOE's diverse efforts for addressing the critical energy challenges facing the nation. The *Plan* describes the Program's activities—which are conducted to overcome the technical, institutional, and economic barriers to the widespread commercialization of hydrogen and fuel cell technologies for transportation, stationary, and portable applications. The *Plan* also identifies the specific obstacles each Program activity addresses, the strategies employed, key milestones, and future plans for each activity and the Program as a whole.

The *Plan* updates and expands upon previous editions of the *Hydrogen Posture Plan*, issued in 2006 and 2004, and it continues to serve the purposes for which those documents were developed. The *2006 Posture Plan* fulfilled the requirement in EPACT (sec. 804) that the secretary of energy transmit to Congress a coordinated plan for DOE's hydrogen and fuel cell activities. The original *Posture Plan*, issued in 2004, outlined a coordinated plan for DOE and the Department of Transportation to meet the goals of the Hydrogen Fuel Initiative (HFI) and implement the *2002 National Hydrogen Energy Technology Roadmap*. The HFI was launched in 2004 to accelerate existing efforts in R&D of hydrogen and fuel cell technologies for use in transportation, electricity generation, and portable power applications. The *Roadmap* provides a blueprint for the public and private efforts required for development of the hydrogen energy systems needed to fulfill a long-term national vision for hydrogen energy (as outlined in A *National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond*). Both the *Roadmap* and the *Vision* were developed out of meetings involving DOE, industry, academia, non-profit organizations, and other stakeholders. The *Roadmap*, the *Vision*, the *Posture Plans,* and several workshops continue to form the underlying basis for this current edition of the *Program Plan*.

The *Plan* addresses the Government Accountability Office's January 2008 report on the Hydrogen Fuel Initiative (HFI), which included the following key recommendation:

> *"To accurately reflect the progress made by the Hydrogen Fuel Initiative and the challenges it faces, we recommend that the Secretary of Energy update the Hydrogen Posture Plan's overall assessment of what DOE reasonably expects to achieve by its technology readiness date in 2015, including how this may differ from previous posture plans and a projection of anticipated funding needs."*

In describing the Program's current and planned activities, the *Plan* reflects a number of changes in the Department's overall strategy for hydrogen and fuel cells, including:

- Diversifying its RD&D portfolio to include a wider range of applications for hydrogen and fuel cells, including stationary power and auxiliary power applications—whereas previous efforts were heavily weighted toward light-duty vehicles
- Adopting a technology-neutral approach toward fuel cell RD&D, with efforts focused on the most appropriate fuel cell technology for a given application—whereas previous efforts were exclusively focused on polymer electrolyte membrane fuel cells
- Reducing emphasis on a single "technology-readiness" milestone for light-duty vehicles and pursuing a vision of technology advancement that involves continuous improvement in many technology areas and for many applications, with new applications reaching technology readiness at different times
- Adopting a more comprehensive approach to market transformation—including expanded efforts to leverage the work of other DOE activities, state programs, and other federal agencies—to ensure that the early market successes of certain applications can have the most beneficial impact on the advancement of all hydrogen and fuel cell technologies and the industry as a whole

While the Program has broadened its focus beyond the 2015 technology readiness milestone for fuel cell electric vehicles (FCEVs), it continues to pursue technology advancements needed for their commercialization. The milestone for automotive fuel cells has shifted from 2015 to 2017, and a key milestone for hydrogen production has already been met—enabling hydrogen to be produced (at high volumes and widespread deployment of stations) from natural gas at fueling stations for approximately $3 per gallon gasoline equivalent (however, the cost of producing hydrogen at low volumes continues to be a challenge, which the Program is addressing through hydrogen fuel RD&D activities). The Program continues to pursue a number of other pathways for hydrogen production, including several renewable pathways, with different milestones for expected technology readiness—ranging from 2015 to 2020 (specific milestones are detailed in section 2.5). To enable widespread commercialization of FCEVs in the 2015–2020 timeframe, continued funding for DOE's RD&D efforts will be required. While precise funding requirements are difficult to predict due to the sometimes irregular pace of technological progress, the National Academies have estimated that an average of about $310 million in funding per year will be required to enable widespread commercialization (this estimate is from the 2008 report *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*, which projected a total funding requirement of $5 billion from 2008 through 2023, at which time the report predicts that FCEVs will break even competitively and become self-sustaining in the marketplace).[77]

This edition of the *Plan* also addresses the recommendations of the Hydrogen and Fuel Cell Technical Advisory Committee's October 2007 letter to the secretary of energy and the National Academies' 2008 *Review of the Research Program of the FreedomCAR and Fuel Partnership: Second Report*, as well as the hydrogen- and fuel cell-related requirements in the Energy Independence and Security Act of 2007 and the Energy Policy Act of 2005 (EPACT). The Program will continue to periodically revise the *Plan*, along with all program office RD&D plans, to reflect technological progress, programmatic changes, policy decisions, and updates based on external reviews.

77 *Transitions to Alternative Transportation Technologies—A Focus on Hydrogen*, National Research Council of the National Academies, 2008, p. 93. www.nap.edu/catalog.php?record_id=12222.

Appendix B: *Examples of Domestic Hydrogen Production Options and Resource Needs*

The Department's long-term strategy for hydrogen is to enable hydrogen production from a diverse array of low-carbon domestic energy resources, including renewable resources (such as biomass, wind, and solar energy), nuclear power, and coal (with carbon sequestration). Table B.0 provides perspective on the availability of these domestic resources to meet the potential demand for hydrogen. The example assumes a future scenario with approximately 100 million fuel cell electric vehicles (FCEVs), which would require an annual hydrogen production of 20 million metric tons. This scenario provides examples of how domestic resources could be utilized to provide a large amount of hydrogen. For illustration purposes, each resource is examined as if it were relied upon to provide 20% of this future hydrogen demand (4 million metric tons, enough for 20 million FCEVs). It is important to note, however, that what is shown here does not represent all the potential production pathways—there are a number of other promising pathways under development, including direct conversion of solar energy through photoelectochemical, biological, and high-temperature thermochemical systems.

Table B.0 provides the following information for biomass, coal, natural gas, wind, solar, and nuclear resources: the availability and current consumption of the resource, a "business as usual" projection of consumption in 2040 (which doesn't include any resource use for hydrogen production), the amount of that resource needed to produce 4 million metric tons of hydrogen, and the percentage increase in projected consumption that would be required to produce 4 million metric tons of hydrogen. For example, the total availability of biomass energy resources is estimated to be between 0.4 and 1.2 billion (dry) metric tons per year, current consumption is 214 million metric tons per year, and projected consumption is 566 million metric tons per year. Approximately 50 million metric tons per year would be required to produce 4 million metric tons of hydrogen, which would increase total biomass resource consumption by approximately 9%.

As Table B.0 shows, the availability of various domestic, low-carbon energy resources for hydrogen production appears to be more than adequate for a high level of hydrogen demand. It must be noted, however, that a total hydrogen demand of 20 million metric tons for FCEVs is speculative. Several factors could reduce hydrogen demand, including (1) other options for replacing oil in the transportation sector, such as biofuels and plug-in hybrid electric vehicles, and (2) advances in hydrogen production technologies that make production processes more efficient.

Finally, hydrogen production from natural gas is included in the table even though it is not considered a viable long-term strategy due to concerns of limited supply, price volatility, and the demands of other sectors. For this analysis, a 50-50 mix of distributed and centralized production of hydrogen from natural gas was assumed. Market conditions will determine whether or for how long this and other pathway options are implemented during the initial market penetration of FCEVs and over the long term.

Table B.0. Examples of Domestic Hydrogen Production Options and Resource Needs

Resource	Resource Availability	Resource Consumption *(without hydrogen production for FCEVs)*		Resources Needed to Produce Hydrogen for 20 million FCEVs[b,c]	Increase in Projected Consumption Required for 20 million FCEVs
		Current (2008)	Projected (2040)		
Gasification and Reforming [d]					
Biomass	384 million[e] – 1.2 billion[f,g] (dry) metric tons/year	214 million (dry) metric tons/year[a]	566 million (dry) metric tons/year[a]	50 million (dry) metric tons/year	9%
Coal (with carbon sequestration)	239 billion metric tons (estimated recoverable reserves)[h]	1,070 million metric tons/year (all grades)[a]	1,153 million metric tons/year (all grades)[a]	54 million metric tons/year	5%
Natural Gas	273 trillion cubic feet (proven reserves)[i]	22 trillion cubic feet[a]	26 trillion cubic feet[a]	634 billion cubic feet	2%
Water Electrolysis [j]					
Wind	3,500 GWe (nameplate capacity, not power output)[k]	22.6 GWe (installed nameplate capacity, not power output)[l]	50 GWe (installed nameplate capacity, not power output)[m]	48 GWe	96%
Solar Energy (photovoltaic and concentrated solar thermal)	5,400 GWe (capacity, entire U.S.)[n]	1,293 MWe (net summer capacity)[o]	100 – 250 GWe (net summer capacity)[p]	92 GWe	40 – 90%
Nuclear Energy (high-temperature electrolysis)	67 million metric tons of uranium at $66/kg; 385 million metric tons of uranium at $110/kg[q]	100.6 GWe[a] (power output, using ~22,000 metric tons of uranium/ year)	111.1 GWe[a] (power output using ~24,000 metric tons of uranium/ year)	15 GWe (power output, using ~3,200 metric tons of uranium/ year)	14%
Thermo-Chemical					
Nuclear Energy	67 million metric tons of uranium at $66/kg; 385 million metric tons of uranium at $110/kg[q]	314 GWth[r] (thermal output, using ~22,000 metric tons of uranium/ year)	347 GWth[r] (thermal output, using ~24,000 metric tons of uranium/ year)	27 GWth (thermal output, using ~1,900 metric tons of uranium/ year)	8%

Notes:

a Current and projected consumption based upon the 2010 Annual Energy Outlook Reference Case, with projections to 2035 (U.S. Department of Energy, *Annual Energy Outlook 2010*, (April 2010) DOE/EIA-0383(2010), www.eia.doe.gov/oiaf/aeo/pdf/0383(2010).pdf. Linear trend-lines were used to estimate additional growth in consumption from 2035 to 2040.

b In this scenario, total hydrogen demand for 100 million light-duty FCEVs is projected to be 20 million metric tons/yr, 20% of which would be 4 million metric tons/yr (enough for 20 million FCEVs). This level of demand assumes 100 million light-duty FCEVs traveling an average of 13,000 miles per year with an average fuel economy of 67 mpgge. For the annual number of miles and fuel economy, see: U.S. Department of Energy Hydrogen and Fuel Cells Program records, "Record No. 11002, Number of Cars Equivalent to 100 Metric Tons of Avoided Greenhouse Gases per Year" and "Record No. 10001, Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles," www.hydrogen.energy.gov/program_records.html.

c The National Renewable Energy Laboratory H2A Production Model, version 2.0, was used to determine the amount of hydrogen needed for each advanced technology (available online: www.hydrogen.energy.gov/h2a_analysis.html) using assumptions consistent with those used elsewhere in this report. For solar and wind resources, a conversion efficiency of 47.9 kWh per kg hydrogen was assumed (70% LHV).

d Calculations were made for the exclusive production of the amount of hydrogen requested. However, some small-scale systems can be configured to recover useful heat, providing both heat and electricity in combined heat and power (CHP) systems.

e Milbrandt, A., *Geographic Perspective on the Current Biomass Resource Availability in the United States*, NREL Report No. TP-560-39181, 2005, www.nrel.gov/docs/fy06osti/39181.pdf.

f Includes only biomass not currently used for food, feed, or fiber products.

g Perlack, R. D. et al., *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, April 2005, Oak Ridge National Laboratory for the U.S. Department of Agriculture and U.S. Department of Energy, ORNL/TM-2005/66, DOE/GO-02995-2135, http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf.

h U.S. Department of Energy, Energy Information Administration, *Annual Coal Report – 2007*, Table 15: "Recoverable Coal Reserves at Producing Mines, Estimated Recoverable Reserves, and Demonstrated Reserve Base by Mining Method, 2006," www.eia.doe.gov/cneaf/coal/page/acr/table15.html.

i Natural gas proven reserves estimate from U.S. Department of Energy, Energy Information Administration website, "Dry Natural Gas Proved Reserves," www.eia.gov/dnav/ng/ng_enr_dry_dcu_NUS_a.htm, accessed August 17, 2011.

j Other renewable power generation technologies can also serve as a resource for water electrolysis. For example, geothermal energy could provide 11 million tons of hydrogen per year, or up to 68 million tons of hydrogen if estimates of undiscovered accessible resources are considered (see Hydrogen Program Record #5009). Undeveloped hydropower resources and upgrades to existing hydroelectric plants could supply an additional 15 million tons of hydrogen per year (see Hydrogen Program Record #5024).

k "20% Wind Energy Penetration in the United States: A Technical Analysis of the Energy Resource," Black & Veatch, Walnut Creek, California, retrieved January 20, 2009, from link available at http://www.20percentwind.org/default.aspx. Table 6-3 indicates 3,484 GW of wind potential from onshore and shallow offshore wind resources, classes 4-7.

l U.S. Department of Energy and National Renewable Energy Laboratory, "Current Installed Wind Power Capacity," (as of September 30, 2008), retrieved January 20, 2009 from http://www.windpoweringamerica.gov/images/windmaps/installed_capacity_2008.jpg.

m Estimate of 330 GW by 2040 based upon growth of 10 GW per year continuing from the 300 GW installed by 2030, Figure 1-4, from "20% Wind Energy by 2030," National Renewable Energy Laboratory, Report number DOE/GO-102008-2567, July 2008, retrieved January 20, 2009, from http://www.20percentwind.org. Capacity needed is estimated with a 50% capacity factor and a hydrogen conversion efficiency of 47.9 kWh/kg (70% LHV). Note that the Reference Case from the Energy Information Administration's *2010 Annual Energy Outlook* (DOE/EIA-0383(2010), April 2010) predicts much lower installed wind capacity: 59 GW by 2035 (Figure 66).

n U.S. Department of Energy (Hydrogen and Fuel Cells Program), "Record 5006: Solar Resources in the U.S.," www.hydrogen.energy.gov/program_records.html.

o Cumulative installed capacity for both photovoltaic and concentrated solar in 2007. *Renewable Energy Data Book*, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, September 2008, p. 66, http://147.102.214.150/pm9/energy/eere_databook_091208.pdf.

p Estimates for future solar energy consumption are taken from the DOE Solar Energy Technologies Program's *Multi-Year Program Plan*, 2008-2012 (http://www1.eere.energy.gov/solar/pdfs/solar_program_mypp_2008-2012.pdf). A high estimate for future concentrated solar power (CSP) in 2040 is 50 GWe (summer peak capacity), and a low estimate is 40 GWe, both based upon the policy supported case shown in Figure 1-5. A high estimate for PV is 200 GWe by 2040, based upon an installation rate of 7 GWe per year continuing from the 24 GWe installed by 2015 in the policy supported case shown in Figure 1-3. A low estimate is 60 GWe, based upon an installation rate of 2.3 GWe per year continuing from the 16 GWe installed by 2020 in the program price parity goal case shown in Figure 2.3-1. Capacity needed is estimated with a 24% utilization factor for installed solar capacity and a hydrogen conversion efficiency of 47.9 kWh/kg (70% LHV). Note that the Reference Case from the *2010 Annual Energy Outlook* (DOE/EIA-0383(2010), April 2010) predicts much lower capacities: 3 GW of additional solar PV capacity by 2035 (Figure 49).

q U.S. Department of Energy, Energy Information Administration, U.S. Uranium Reserves Estimates by State, 2004, retrieved June 24, 2008 from http://www.eia.doe.gov/cneaf/nuclear/page/reserves/uresst.html.

r The nuclear thermo-chemical route to hydrogen production is based on the use of high-temperature reactor technology which is under development to generate the higher temperatures needed (800-1000°C). The 310 GWth is the amount of thermal energy equivalent currently generated by today's conventional nuclear energy that is in service for electricity production (100 GWe divided by 32% thermal efficiency).

Appendix C: *Glossary of Acronyms*

AFCIA – Advanced Fuel Cells Implementing Agreement

AFC – alkaline fuel cell

APU – auxiliary power unit

ARPA-E – Advanced Research Projects Agency-Energy

ASES – American Solar Energy Society

BER – The Biological and Environmental Research program (in the DOE Office of Science)

BES – The Basic Energy Sciences program (in the DOE Office of Science)

BEV – battery electric vehicle

BOP – balance-of-plant

CHP – combined heat and power

CHHP – combined heat, hydrogen, and power

DMFC – direct methanol fuel cell

DOD – U.S. Department of Defense

DOE – U.S. Department of Energy

DOT – U.S. Department of Transportation

DTI – Directed Technologies Incorporated (acquired by Strategic Analysis, Inc.)

EERE – DOE Office of Energy Efficiency and Renewable Energy

EPA – U.S. Environmental Protection Agency

EPACT – Energy Policy Act of 2005

FE – DOE Office of Fossil Energy

EFRCs – Energy Frontier Research Centers

FCHEA – Fuel Cell and Hydrogen Energy Association

FCEV – fuel cell electric vehicle

gge – gallon gasoline equivalent

GAO – Government Accountability Office

GREET – Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation

HEV – hybrid electric vehicle

HHV – higher heating value

HIA – Hydrogen Implementing Agreement

HTAC – Hydrogen and Fuel Cell Technical Advisory Committee

ICE – internal combustion engine

ICEV – internal combustion engine vehicle

IEA – International Energy Agency

IPHE – International Partnership for Hydrogen and Fuel Cells in the Economy

ITF – Hydrogen and Fuel Cell Interagency Task Force

IWG – Hydrogen and Fuel Cell Interagency Working Group

LCOE – levelized cost of energy

LHV – lower heating value

METI – Japanese Ministry of Economy, Trade and Industry

kW – kilowatt

MARKAL – Market Allocation model

MCFC – molten carbonate fuel cell

MEA – membrane electrode assembly

MOU – memorandum of understanding

NEMS – National Energy Modeling System

NFPA – National Fire Protection Association

NOx – nitrogen oxides

NREL – National Renewable Energy Laboratory

PAFC – phosphoric acid fuel cell

PEM – polymer electrolyte membrane

PEMFC – polymer electrolyte membrane fuel cell

PGM – platinum group metal

PHEV – plug-in hybrid-electric vehicle

PM – particulate matter

PSAT – Powertrain Systems Analysis Toolkit

RCS – regulations, codes and standards

R&D – research and development

RD&D – research, development and demonstration

RFI – Request for Information

SBIR – Small Business Innovation Research Program

SDO – standards development organization

SECA – Solid State Energy Conversion Alliance Program

SOFC – solid oxide fuel cell

STTR – Small Business Technology Transfer Program

SWNT – single-walled nanotubes

Appendix D: *Contacts & Links*

DOE Hydrogen and Fuel Cells Program Contacts

Sunita Satyapal, Hydrogen and Fuel Cells Program Manager

Fuel Cell Technologies Program
DOE Office of Energy Efficiency and Renewable Energy
Sunita.Satyapal@ee.doe.gov
202-586-2336

Richard Farmer, Deputy Program Manager

Fuel Cell Technologies Program
DOE Office of Energy Efficiency and Renewable Energy
Richard.Farmer@ee.doe.gov
202-586-1623

Fred Joseck, Lead Technology Analyst

Fuel Cell Technologies Program
DOE Office of Energy Efficiency and Renewable Energy
Fred.Joseck@ee.doe.gov
202-586-7932

Joseph Stanford, Policy, Analysis, and International Activities

Fuel Cell Technologies Program
DOE Office of Energy Efficiency and Renewable Energy
Joseph.Stanford@ee.doe.gov
202-586-6757

John Vetrano, Materials Sciences and Engineering Division

Office of Basic Energy Sciences
DOE Office of Science
John.Vetrano@science.doe.gov
301-903-5976

Guido B. Dehoratiis

Office of Advanced Energy Systems
DOE Office of Fossil Energy
Guido.b.Dehoratiis@hq.doe.gov
202-586-2795

Carl Sink

Office of Gas Cooled Reactor Technologies
DOE Office of Nuclear Energy
Carl.Sink@nuclear.energy.gov
301-903-5131

Links to Relevant Organizations

DOE Hydrogen and Fuel Cells Program: www.hydrogen.energy.gov

DOE Fuel Cell Technologies Program: www.hydrogenandfuelcells.energy.gov

DOE Office of Fossil Energy: www.fe.doe.gov

DOE Office of Nuclear Energy: www.nuclear.gov

DOE Office of Science: www.science.energy.gov

Hydrogen and Fuel Cells Interagency Working Group: www.hydrogen.gov

Solid State Energy Conversion Alliance: www.seca.doe.gov

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