ENERGY INNOVATION IN THE UNITED STATES

AUTOMOTIVE FUEL CELL APPLICATIONS

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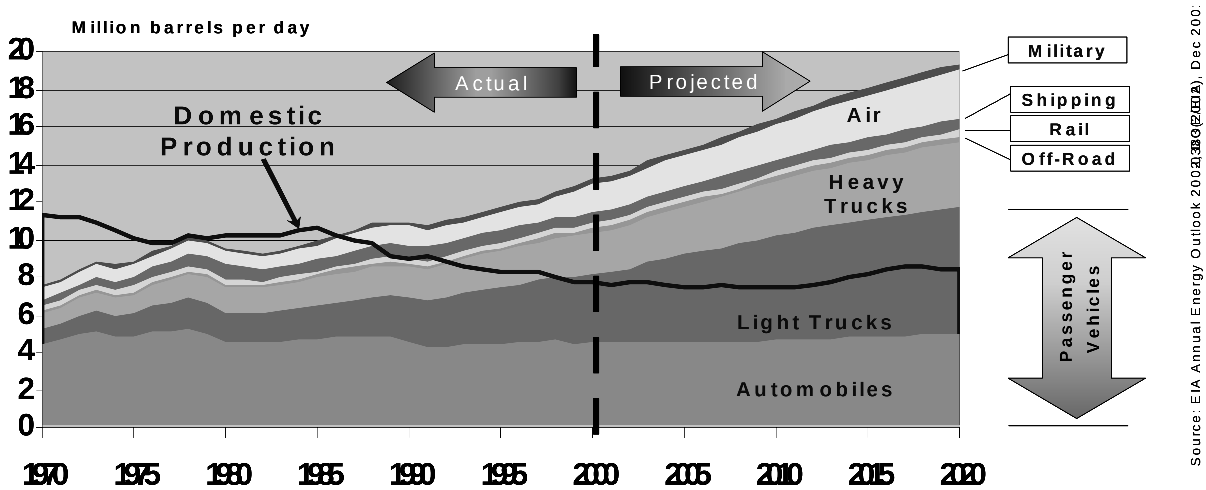
Preface

In the United States, a vast number of companies, universities, organizations, and other research entities are actively involved in developing polymer electrolyte membrane (PEM) fuel cell technology for automotive applications. An analysis of the *entire* national innovation system for automotive fuel cell technologies is not feasible because of its immense scope and diversity. This report focuses, instead, on a large component of the system: the PEM fuel cell research, development, and deployment programs supported by the U.S. Department of Energy (DOE). As discussed in this report, these DOE programs rely on a wide range of collaborative partnerships among industrial firms, laboratories, universities, and other stakeholders throughout the country. Private-sector contributions are noted as appropriate in recognition of their significant role in spurring fuel cell technologies.

1.0 Introduction

The U.S. transportation sector remains heavily dependent on petroleum for more than 96 percent of its fuel, consuming 13.6 million barrels per day (MBPD) in 2001. Highway vehicles account for three-quarters of all transportation energy use, with automobiles and light trucks alone using nearly 60 percent of all transportation energy (see Figure 1.1). With the growing popularity of vans, pickup trucks, and sport utility vehicles, the average fleet fuel economy for light-duty vehicles has now declined to a level below that of the mid to late 1980s. This declining fuel economy, coupled with increases in the number of drivers and vehicles in use, and per-capita miles driven, is propelling U.S. petroleum consumption steadily upward. By the year 2025, petroleum consumption in the sector (including on-and off-highway, air, rail, and marine) is projected to increase by 62 percent to 22.1 MBPD. Currently, over half (55 percent) of the petroleum used in the United States is imported, and the imported share is expected to grow to 68 percent by 2025. In 2000, oil imports cost the United States approximately $109 billion.

Figure 1.1



Trends in Demand: U.S. Transportation Petroleum Use

According to the U.S. Environmental Protection Agency (EPA), more than 100 million people live in areas of the country that do not meet National Ambient Air Quality Standards for ground-level air quality in populated areas. The transportation sector contributes heavily to non-attainment in many of these areas. On an overall basis, the EPA estimates that transportation produces 79 percent of carbon monoxide (CO), 53 percent of nitrogen oxides (NOx), 44 percent of volatile organics, and 33 percent of man-made carbon dioxide (CO_2) emissions—a key component of greenhouse gases. Emissions of greenhouse gases are a growing concern, as are the concentration of these gases in the atmosphere and their potential impacts on the climate.
In response to these challenges, the U.S. government has launched a number of energy policies and initiatives to encourage research, development, and demonstration (RD&D) of fuel cells and

hydrogen infrastructure technologies. The Energy Policy Act of 1992 calls for the Secretary of Energy to establish a program that promotes the development of domestic replacement fuels, including hydrogen, for use in light-duty motor vehicles to reduce greenhouse gas emissions.

The National Energy Policy of 2001 assigned national priority to the development of technology that improves energy efficiency and environmental performance. The policy calls for the development of hydrogen-based technology for a variety of applications, including hydrogen-fueled and fuel cell vehicles (FCVs) as well as the integration of existing programs in hydrogen, fuel cells, and distributed energy.

In the 2003 State of the Union Address, President Bush proposed "$1.2 billion in research funding for developing clean, hydrogen-powered automobiles." Together, the President's hydrogen fuel and FreedomCAR initiatives commit $1.7 billion to the RD&D of hydrogen and fuel cell technologies over the next five years: $1.2 billion for hydrogen and fuel cells plus $0.5 billion for hybrid and advanced vehicle technologies. These initiatives will accelerate the RD&D of hydrogen and fuel cell technologies, enabling industry to reach a commercialization decision by 2015. The goal is to have fuel cell vehicles in showrooms and hydrogen at refueling stations by 2020.

The U.S. Department of Energy (DOE) recognized the potential of fuel cells in transport applications in the early 1980's. At that time, the Department initiated a small program at Los Alamos National Laboratory (LANL) to examine the feasibility of using PEM fuel cell technology for vehicles. In 1987, DOE began development on a bus powered by a phosphoric acid fuel cell (PAFC). The transit bus platform was chosen because it offered the greatest flexibility for packaging the fuel cell with the auxiliary component technology available at that time. By 1990, the progress achieved in PEM fuel cell performance prompted General Motors to join the DOE in launching a light-duty fuel cell vehicle program. Methanol was selected as the fuel because of its availability, simplicity of storage, high energy density, rapid refueling characteristics, and ability to be easily reformed. In 1994, the DOE initiated programs with two industry teams led by Ford and Pentastar (a Chrysler subsidiary) to develop direct hydrogen-fueled PEM fuel cell propulsion systems. In 1995 Arthur D. Little, Inc. was contracted to develop a flexible fuel processor for the on-board reforming of gasoline and other common transportation fuels into hydrogen. At the same time, the growth of the U.S. fuel cell industry had begun attracting substantial investments in R&D.

More recently, heightened environmental and energy security concerns have prompted the Federal government to increase R&D activities on PEM fuel cell. DOE's current Office of Hydrogen, Fuel Cells, and Infrastructure Technologies under the DOE Office of Energy Efficiency and Renewable Energy (EERE) funds critical fuel cell R&D, creating and diffusing the knowledge necessary to advance the technology. Over time, the Office has established an extensive network of innovators in PEM fuel cells. This report describes the U.S. national fuel cell innovation system, focusing mainly on DOE's innovation system for the automotive PEM fuel cell. While the report does not represent the entire national innovation system, it captures a significant part of it.

Chapter 2 examines various factors in the United States driving the development of PEM fuel cells for transportation applications, including public policy, R&D funding, and other economic, technical, and regulatory factors. Chapter 3 describes the complex organizational network of players who interact with DOE, and to the extent possible, how their interactions generate, diffuse, and spur use of new knowledge to produce innovations. Chapter 4 identifies policy measures that affect the innovation process, and Chapter 5 evaluates the performance of DOE's fuel cell innovation process by various statistical measures. Chapter 6 assesses the benefits of the U.S. fuel cell innovation system using the framework of the U.S. National Academies of Sciences. Chapter 7 summarizes the report and presents some conclusions.

2.0 Driving Fuel Cell Innovation

A combination of factors drives U.S. innovation in polymer electrolyte membrane (PEM) fuel cell technology. The primary drivers are energy security and environmental concerns. Other stimulating factors include technical innovation, international competition, and state interests.

2.1 Public Policy Foundation

U.S. policy regarding fuel cells has been shaped by the need to ensure an adequate and secure supply of energy at reasonable cost, and by a desire to enhance environmental quality.

Energy Security

Currently, the United States uses close to 20 million barrels of oil per day, and over half of those barrels are used to power highway vehicles. Small changes in the price of crude oil or disruptions to oil supplies could have dramatic impacts on the U.S. economy, affecting the trade deficit, industrial investment, and employment. Because hydrogen can be derived from a variety of fossil fuels, renewable resources, and nuclear power, it would allow the United States to diversify its energy supply and reduce its dependence on foreign energy sources. By 2040, with a projected 150 million hydrogen-powered light-duty cars and trucks on the road, hydrogen and fuel cells could reduce oil use by as much as 11 million barrels per day.

Fuel cells are significantly more energy efficient than combustion-based power generation technologies. Internal-combustion engines in today's automobiles convert less than 30 percent of the energy in gasoline into engine power for moving the vehicle. Vehicles using electric motors powered by hydrogen fuel cells utilize 40 to 60 percent of the fuel's energy. Successful commercialization of fuel cells both in transportation and stationary applications could potentially lower U.S. energy demand.

Environmental Quality

Government policy to improve environmental quality has also stimulated innovation in fuel cell technologies. Hydrogen generation and carbon-management technologies can significantly reduce pollutants and greenhouse gases from conventional fuels. Using renewable or nuclear-based hydrogen in high-efficiency fuel cells to fuel vehicles and to generate power could virtually eliminate greenhouse gas emissions. Fuel cells powered by pure hydrogen emit no harmful pollutants.

Approximately 60 percent of Americans live in areas where levels of one or more air pollutants are high enough to affect public health and/or the environment. Automobiles and electric power plants are significant contributors to the air quality problems in the U.S. Most states are now developing strategies for reaching national ambient air quality goals and for bringing their major metropolitan areas into attainment with the requirements of the Clean Air Act. The State of

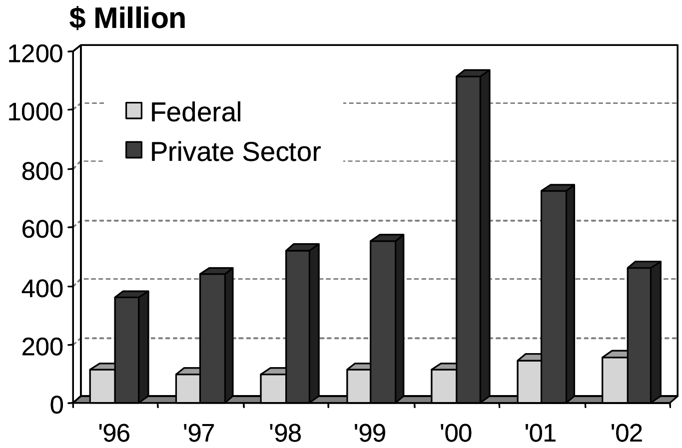
California, where 90% of the population breathes unhealthy levels of one or more air pollutants during some part of the year, has been one of the most aggressive in their strategies and has launched a number of pilot programs targeted at improving urban air quality. The introduction of hydrogen-fueled commercial bus fleets is one of the approaches that states are taking to improve air quality.

The combustion of fossil fuels accounts for the majority of anthropogenic greenhouse gas emissions (chiefly carbon dioxide, CO_2) released into the atmosphere. The largest sources of CO_2 emissions are the electric utility and transportation sectors. Hydrogen can play an important role in a low-carbon global economy. Should strong constraints on carbon emissions be required, hydrogen production from coal, natural gas, and oil (with the capture and sequestration of carbon), can provide a way for domestic fossil fuels to remain viable energy resources. Fuel cells operating on hydrogen produced and distributed from renewable resources or nuclear energy result in near-zero carbon emissions.

2.2 R&D Funding

A key driver of innovation in fuel cell technology has been the substantial R&D investments by the government and the private sector. Total U.S. R&D spending on fuel cells over the period 1996-2002 was $5,013 million (Figure 2.1). As shown in the figure, private sector investment has been substantially larger than that of the federal government, although overall federal support for fuel cells is likely to be significantly higher because for many federal government agencies including Department of Transportation, Department of Defense, Department of Commerce, and the National Aeronautic and Space Administration (NASA) spending on fuel cells is often included as part of spending on other programs to make it difficult to be separated out. Private sector investment peaked in 2000 at over $1 billion and since declined to about half that level in 2002.

Figure 2.1
Fuel Cell Funding



Source: *Fuel Cells at the Crossro*ads, Breakthrough Technologies, Inc.

DOE's R&D funding has supported industry, universities, national laboratories and other research institutions to carry out exploratory research on critical fuel cell components and materials (Table 2.1). Between 1992 and 2004, DOE's budget for PEM fuel cell technology innovation was close to $400 million.

Table 2.1
DOE PEM Transportation Fuel Cell Funding

FY	$Million		FY	$Million
1992	9.5		1999	33.7
1993	12.0		2000	37.0
1994	19.5		2001	41.5
1995	22.2		2002	41.2
1996	21.5		2003	48.0
1997	21.1		2004	65.2
1998	23.5		2005 Request	77.5

In addition, some states have also provided funding to encourage fuel cell technology research, development, and demonstration.

2.3 Technical Drivers

Often, technical innovation itself is a principal driver of innovation for fuel cell systems. Each major technical innovation that has occurred over the last half century has spurred greater interest and increased public/private investment.

During the Apollo program, when NASA sought a compact, lightweight, reliable and efficient power system for manned space flight, the technology "took off." What emerged from the program was the General Electric solid polymer electrolyte (SPE™) fuel cell, which became the PEM fuel cell.

In the late 1980s, PEM fuel cell performance was essentially stagnant, which stifled strong interest in PEM technology. A new membrane was developed with much stronger performance, resulting in a surge of interest. The new interest in PEM fuel cells caused higher levels of R&D and, consequently, more significant and rapid innovation.

While not an issue for NASA, the cost of the platinum stifled any commercial applications at that time. In the late 1980s and early 1990s, however, Los Alamos National Laboratory (LANL) developed low-platinum PEM electrodes, which dramatically lowered the required precious-metal catalyst loadings by a factor of more than 20 while simultaneously improving performance. This achievement significantly advanced the status of PEM fuel cells for commercial applications.

Another integral innovation in the mid 1990s was the development of "autothermal" reforming techniques at several organizations. Here, successful gasoline reforming was accomplished by partial oxidation of the gasoline to provide heat including steam reforming of the remaining hydrocarbons and conversion of the residual carbon monoxide to carbon dioxide and hydrogen via reaction with water (the so-called water-gas shift).

The 1990s also saw the development of the carbon monoxide (CO) clean-up system by LANL, which enables low-temperature PEM fuel cells to operate not only with pure hydrogen, but also with hydrogen-rich gas streams derived from hydrocarbon fuels (such as gasoline, methanol, propane, or natural gas).

Additionally, in 1997, a team from Engineering Sciences and Applications' Energy and Process Engineering Group integrated the Los Alamos CO cleanup system with a gasoline reformer developed by Arthur D. Little, and a PEM fuel cell stack developed by Plug Power. To great acclaim, the "integrated" system generated the world's first electrical power from a low-temperature fuel cell operating on gasoline reformate. Industrial interest in fuel cell systems (particularly transportation) exploded following successful demonstration of the gasoline-to-electricity PEM/fuel cell reformer system. Since then, funding for fuel cell systems at automotive OEMs, fuel cell developers, and suppliers have risen into the hundreds of millions of dollars annually. However, although technology development over the last two decades has been dramatic, PEM fuel cells are still too expensive and do not have the power density, durability, or reliability to be economically and functionally competitive with conventional power conversion devices.

2.4 Regulatory Regimes

Regulatory measures to curb pollutants, such as those implemented by some states, have also pushed fuel cell technology development. A prime example of such a measure is California's Zero-Emission Vehicle (ZEV) Program.

California ZEV

In 1990, the California Air Resources Board (CARB) adopted the Zero-Emission Vehicle Program. The ZEV program is an integral part of California's Low Emission Vehicle program and is intended to improve air quality for California over the long term. The CARB ZEV program mandates the percentage of zero-emitting cars that manufacturers must supply to comply with the State's clean air rules. Financial incentives/credits are provided to purchasers of ZEVs.

Codes and Standards

Fuel cell installations and vehicles will have to meet existing building and transportation codes and standards. Technological innovation will be required so funding is being provided for R&D to enable code compliance and to develop codes and standards friendly to fuel cells. This could also have positive impacts on fuel cell vehicle innovation.

2.5 Markets

Market Pull

Conventional vehicles with internal combustion engines (ICEs) powered by gasoline meet the current requirements of the consumer and the relevant regulatory bodies. ICEs also set the standard for alternative propulsion systems and fuels. While fuel cell vehicles (FCVs) will ultimately offer higher efficiency and lower emissions than today's ICEs, at present they cost more and offer lower driving range and durability. Even if the technical, economic, and institutional barriers are successfully overcome, the consumer may still be satisfied with current options and resist change to an unproven alternative. Consumers may only accept the change if the advantages of the new technology are substantive. In short, no significant grassroots demand currently exists for transportation fuel cell vehicles.

Low gasoline prices constitute another market barrier. Efficiency alone may be inadequate to drive the adoption of FCVs as long as gasoline prices remain low, especially if the initial purchase cost of the FCV is high. The impact of low gas prices on consumer choice of vehicles is evident in the proliferation of large passenger vehicles on the roadways.

Fortunately, this lack of "market pull" to drive innovation has triggered another powerful driver. Noting the absence of an adequate market mechanism to bring FCVs to the marketplace, the Federal government has decided that the societal benefits (energy security, environmental quality, international competitiveness) warrant a dramatic increase in funding to overcome the remaining technical and economic hurdles.

Corporate Mission

On a corporate level, innovation is driven by the profit motives of the companies that develop and manufacture fuel cells, buy and use fuel cells (automotive OEMs), or supply products to these companies. According to a recent survey conducted by the United States Fuel Cell Council (USFCC), hundreds of companies, employing 4,500-5,500 workers, are engaged in various aspects of fuel cell technology development. Their common mission is to successfully commercialize fuel cell vehicles, and success in that mission will require innovation.

Fuel cell developers**:** Among the major players in this segment of the industry is UTC Fuel Cells, a company with over forty years of experience with the technology. PEM fuel cell systems for transportation are a logical extension of the company's existing fuel cell business.

Automotive OEMs**:** Knowledge of customer requirements drives such automaker giants as General Motors, Ford, and DaimlerChrysler to commission R&D efforts (internal or external) to solve specific problems (at all levels) impeding the market entry of fuel cells.

Suppliers**:** Suppliers play a critical role in providing raw materials as well as subsystems to the fuel cell developers and automotive OEMs. Obviously, the finished products must meet customer specifications. PEM systems for FCVs have many requirements for durability, operating cycle and range, and performance, which cannot be met by existing products. If the suppliers wish to keep their customers, they must innovate to meet these stringent requirements.

Military Applications

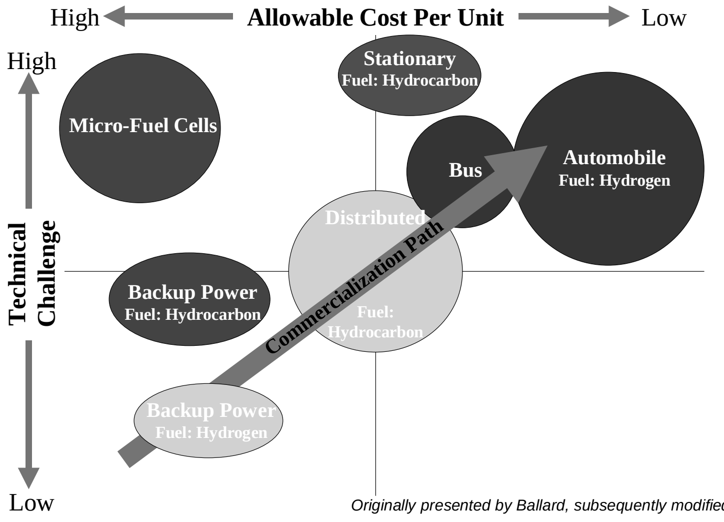
PEM fuel cells, because of their low operating temperatures, offer low thermal signatures for military (combat) vehicles. Their higher efficiency is also attractive for logistics and range reasons. For these reasons, the Department of Defense has provided substantial R&D funding for fuel cell research, including certain aspects of propulsion PEM fuel cell technology.

Synergies among Fuel Cell Applications

Industry and government initially embraced PEM fuel cell technology as a possible replacement for the internal combustion engine in light-duty vehicles. The technology has now expanded its appeal to other markets, including power systems for portable electronic devices, power for homes, reliable off-grid and back-up power systems for commercial buildings, and distributed power generation systems. Figure 2.2 shows current and potential market applications of fuel cells. In the near term, fuel cells are most likely to succeed in premium markets that can more easily absorb a higher cost per kilowatt, such as portable power supply (somewhere on the order of $5,000 per kilowatt), stand-by or emergency power, remote power, or stationary power (where the current estimated cost of $1,000 to $1,500 per kilowatt may be offset by relatively long service life). In the long term, however, the volume associated with the transportation sector will help to establish a strong component supplier base and drive down costs. Supplier R&D is leading to improvements in materials performance and in high-volume manufacturing processes, which is reducing current technology costs in areas such as membranes and electrodes. As a result, synergy exists between transportation, stationary, and portable power applications. While transportation applications (being driven by volume) provide a major incentive for development activities, early success in stationary and portable power applications is crucial.

Many developers are producing stack and fuel cell technologies that are applicable to both distributed generation and transportation applications. This approach allows them to take advantage of niches in both market segments while lowering the costs of fuel cells through

Figure 2.2
Fuel Cell Applications



Originally presented by Ballard, subsequently modified by DOE.

manufacturing technology improvements and volume. As technological advances in fuel cell materials and fuel processing are realized in one area of fuel cell technologies, assimilation into the other applications will soon follow.

2.6 International Economic Competitiveness

The aspiration of the United States to remain competitive in emerging global fuel cell markets is another key driver of innovation in fuel cell technology. Heavy dependence on imported oil threatens America's energy and economic security. Hydrogen's diversity in production and flexibility in use offers opportunities for new players in energy markets, broader energy choices, and enhanced competitiveness in global energy markets. In particular, a leadership role in hydrogen fuel cell technologies for automobiles will help the United States to maintain future economic competitiveness in the global automotive market.

Interest in hydrogen and fuel cell technology has been growing around the globe, as reflected in the dramatic increase in public and private R&D spending in the area since the mid-1990s. In 2003, the Japanese government nearly doubled its fuel cell R&D budget to $268 million, and, in April 2003, launched a joint government/industry demonstration of hydrogen FCVs, including the deployment of at least seven new hydrogen refueling stations. Governments and companies in Canada, Europe, and Asia are also investing heavily in hydrogen research, development, and demonstration. For example, 10 new hydrogen refueling stations will be built in Europe over the next few years to fuel hydrogen-powered buses.

The economic stakes are high—a recent report by PricewaterhouseCoopers projects global demand for all fuel cell products (in portable, stationary, and transportation power applications) to reach $46 billion annually by 2011 and to grow to more than $2.5 trillion per year in 2021.

2.7 State Interests

Many individual states have entered the fuel cell R&D arena, often as a result of economic development and/or environmental concerns. Regardless of the motivation, these states are actively driving fuel cell innovation. States offer incentives in the form of environmental and insurance regulations, tax credits, rebates, subsidies, grants, and R&D and demonstration funding. Thirty-six out of the fifty states currently offer some type of incentive program that may apply to FCVs.

Connecticut

Connecticut is heavily involved in state funding of fuel cell developers, manufacturers, and universities located in the state. Some of these developers and manufacturers have operated in Connecticut for 30 to 40 years. Connecticut involvement is aimed at economic development and job creation in the state.

The Connecticut Clean Energy Fund (CCEF), which is administered by Connecticut Innovations, invests in enterprises and other initiatives that promote and develop sustainable markets for energy from renewables and fuel cells that will benefit the ratepayers of Connecticut. The CCEF is financed by a surcharge levied against the electrical ratepayers in the state.

The Connecticut Clean Energy Fund was created under 16-245n of the Connecticut General Statutes to promote investment in and growth of renewable energy sources. Expenditures of the fund may include grants, direct or equity investments, contracts, or other actions that support renewable energy technologies such as wind, solar, fuel cells, wave power, and biomass. As part of its comprehensive plan, CCEF is supporting a Fuel Cell Initiative that includes educational and research functions as well as provides funding for the installation and demonstration of fuel cells in applications for commercial, industrial, and institutional buildings in Connecticut. In 2001, the state provided $5 million for commercial, demonstration and R&D projects. Funding levels for 2002 were set at up to $8 million for projects to be executed in 2003.

Michigan

Fuel cell involvement by the State of Michigan is primarily embodied in the automobile OEMs, which see the fuel cells as the next generation of transportation propulsion. Announced in April 2002, Michigan NextEnergy is a comprehensive set of actions and incentives designed to position Michigan as the world's leading center for alternative energy technology, research and development, education, and manufacturing. These actions will support technologies for both mobile and stationary applications using renewable and distributed energy solutions.

The intent of NextEnergy is to create —

- Exemptions from state business taxes and personal property tax for companies whose primary focus is alternative energy R&D or manufacturing.
- Steps to include an exemption from the sales and use tax of any purchases of stationary and vehicular devices using alternative energy technologies.
- A 40,000 square-foot facility affiliated with Wayne State University's Technology Park in Detroit. The facility's power grid will include the use of fuel cells, advanced combustion engines, clean-burning Sterling Engines, photovoltaics, and advanced solar systems. The building will also house a laboratory, conference room, product demonstration area, office space, and exhibition area.

California

California drives innovation through environmental regulations and funding of transportation fuel cell R&D and demonstrations.

California Fuel Cell Partnership: The California Fuel Cell Partnership was initiated by the state's air quality regulatory officials as a voluntary effort in which government and industry participate cooperatively. The Partnership is primarily a demonstration program, because FCVs are still a number of years from commercialization. Partners contribute approximately $100,000 annually to a common budget, which goes to efforts such as facility start-up costs, demonstration projects, joint studies, public outreach and education, and program administration. Partnership members plan to operate more than 50 FCVs (cars and buses) on the road in California by 2003.

California's Clean Fuel Infrastructure Program: The California Energy Commission (CEC) offers grants to support the establishment of public-access, alternative fuel dispensing stations. Funding for this program in FY '01 was $6 million, compared to a total of $1.5 million over the previous three years. Eligible projects include all non-petroleum fuels such as natural gas, alcohol, and hydrogen (for fuel cell applications) – alternative fuel (CNG, LNG, and LPG) projects have been the dominant use of funds in previous years. Both public and private entities are eligible.

Non-Monetary Incentives: Alternative fuel vehicles are allowed to use High Occupancy Vehicles ("HOV") lanes with less than the required number of vehicle occupants.

Local California Programs: Several local air pollution control and air quality management districts in California fund alternative fuel projects with revenues generated from a surcharge on motor vehicle registrations. These programs annually fund approximately $20 million worth of alternative and electric vehicle projects, including about $14 million in alternative-fuel vehicle purchases, $1 million in alternative fuel infrastructure, $3 million in electric vehicle purchases, and $2 million in electric fuel infrastructure. As one example of a local project, the San Joaquin Valley Air Pollution Control District provides monetary purchase incentives for light- and medium-duty alternative fuel vehicles.

Ohio

Ohio, like Connecticut, has several fuel cell developers and manufacturers and a strong university fuel cell program. The state unveiled a $100 million, three-year initiative in May 2002 to invest in research, project demonstration, and job creation. Ohio's fuel cell initiative provides (1) $75 million in financing to make strategic capital investments that will create and retain jobs, (2) $25 million for fuel cell research, development and demonstration, and (3) $3 million for worker training. Economic development and job creation are the goals.

Research, Development & Demonstration: $25 million is designated for Research, Development & Demonstration (RD&D) grants. In 2003, the Ohio Department of Development (ODOD) received 26 proposals for fuel cell-related projects. Ultimately, seven projects were awarded a total of $6.4 million. R&D proposals must be submitted to ODOD by an Ohio entity that is part of a larger project team that can include out-of-state partners. The $25 million RD&D budget is comprised of $13 million from oil overcharge monies, $2 million from the Ohio Coal Development Office to further develop coal gasification and hot gas cleanup technologies for hydrogen supply for fuel cells, and a $10 million Third Frontier Action Fund for competitive technology development and commercialization projects.

Training: $1 million per year is set aside for three years for fuel cell-related companies from the Ohio Investment Training Program. Through this program, Ohio companies are eligible to receive grants valued at up to 50 percent of the cost for training to upgrade the skills of their employees, or to train or re-train employees in areas related to fuel cells.

Public Education: ODOD conducts educational workshops and business seminars in conjunction with the Ohio Fuel Cell Coalition and maintains informational materials on the State's Third Frontier Project web site (www.ohio3rdfrontier.org) and the Ohio Fuel Cell Coalition (www.fuelcellsohio.org) web site. Ohio's fuel cell initiative is an integral part of the state's Third Frontier Project, a 10-year, $1.6 billion plan to create high-tech, high-paying jobs through the expansion of the state's high-tech research sector and promotion of start-up companies.

3.0 Knowledge Creation, Diffusion, and Use - U.S. Department of Energy's Fuel Cell Innovation System

In the United States, fuel cell innovation is carried out by a wide range of individual companies, organizations, and research entities. Since the early 1980's, the U.S. Department of Energy (DOE) has played a critical role in creating, diffusing, and using knowledge to spur the development of fuel cell technologies. Through its visioning and roadmapping processes, the DOE has included industry every step of the way, from research and development planning through commercialization, to ensure that the processes result in marketable, successful innovations.

Federal government-provided financial support plays a significant role in the research, development, and demonstration of all types of fuel cells over a wide variety of applications, and has done so for over 25 years. Currently, the DOE is working closely with a variety of stakeholders to develop next-generation technology, including hydrogen, while focusing research and development efforts on integrating current progress regarding hydrogen, fuel cells, and distributed energy.

The DOE's fuel cell innovation system is underpinned by strategic and tactical goals. Strategic goals incorporate envisioning the industry's future and planning a technology pathway or "roadmap" for reaching that vision. Tactical goals focus on technical target development, R&D funding support, partnerships and implementation, review processes, demonstration, and validation.

3.1 Visioning, Roadmapping, and Planning

Fuel cells deliver increased economic and environmental benefits and run most efficiently on nearly pure hydrogen (as opposed to reformate). However, the United States must first develop a broad hydrogen production, storage, and distribution system to support hydrogen use. In concert with industry, the DOE initiated a National Hydrogen Vision and Roadmapping Process in response to the recommendations of the National Energy Policy of 2001. *A National Vision of America's Transition to a Hydrogen Economy–to 2030 and Beyond (February 2002)*, identifies a common vision for transitioning the nation to a hydrogen-based economy, the timeframe in which such a transition could be expected to occur, and the key milestones for achieving it.

Two major conclusions emanate from the hydrogen vision:

- Federal and state governments will need to implement and sustain consistent energy policies that elevate hydrogen and related technologies as a priority.

- Strong public-private partnerships will need to focus on finding ways to collaborate on the development and use of hydrogen energy and related technologies.

The joint government-industry *National Hydrogen Energy Roadmap (November 2002)* identifies the strategic goals, barriers, and key activities required to evaluate the costs and benefits of a hydrogen economy and to begin establishing the necessary public-private partnerships for implementation. The roadmap is intended to inspire organizations that invest in hydrogen and fuel cell energy systems (public and private, state and Federal, business and interest groups) to coordinate their efforts in order to effectively reduce risk; improve performance; decrease cost; and implement a secure, clean, and reliable future.

The roadmapping process illustrates that the industrial segments of a hydrogen energy system-production, delivery, storage, conversion, and end-use applications-are closely interrelated and interdependent. Design and implementation of a hydrogen economy must be done as a "whole system." Cross-cutting challenges include insuring safety, building government/industry partnerships for technology demonstration and commercialization, coordinating activities by diverse stakeholders, maintaining a strong research and development program in both fundamental science and technology development, and implementing effective public policies. Two additional cross-cutting areas could become powerful drivers to assist in addressing these challenges: customer education and the development of codes and standards.

The Fuel Cell Report to Congress (February 2003) on ". . . the technical and economic barriers to the commercial use of fuel cells in transportation, portable power, and stationary and distributed power applications by 2012" calls for an assessment of the need for public and private cooperative programs to demonstrate the use of fuel cells in commercial-scale applications.

The report concludes:

- Public and private cooperative programs are needed to overcome major technical, institutional, and economic barriers and realize potential fuel cell benefits of reducing dependence on imported oil, improving air quality, and reducing greenhouse gas emissions.
- Cost and durability are the primary technical barriers to commercializing fuel cells. Considerably more government and industry cooperative research is required to overcome these barriers, and government must develop codes and standards for safe and reliable use of hydrogen and fuel cells.
- A new hydrogen production, delivery, and refueling infrastructure is necessary for transportation fuel cell technology to achieve its potential energy and environmental benefits.

Based on these findings, the report recommends that:

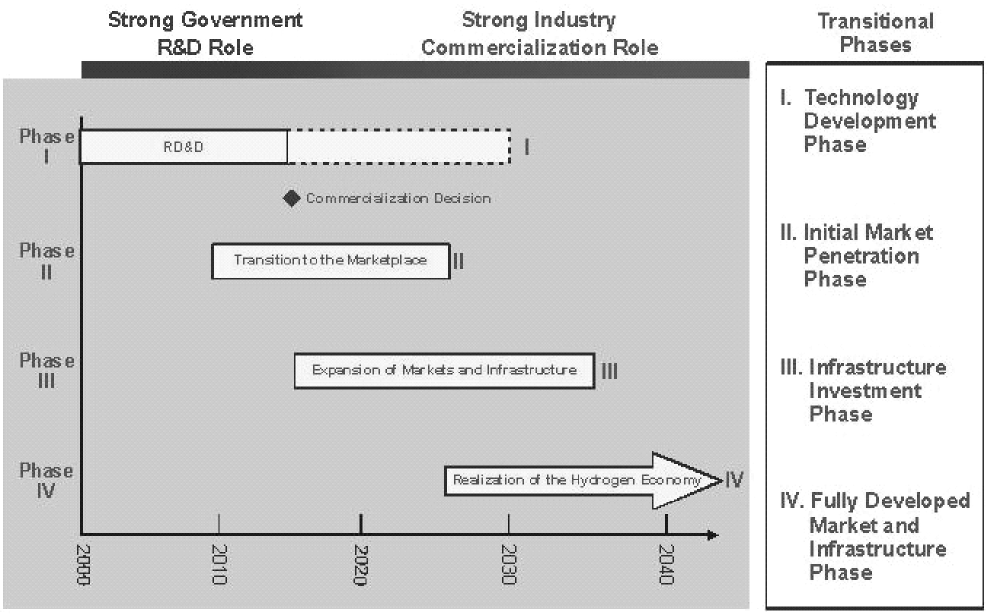
- Core technology development should focus more on advanced materials, manufacturing techniques, and other advancements to lower cost, increase durability, and improve reliability of fuel cell systems.
- More emphasis must be placed on hydrogen production and delivery infrastructure, storage, codes and standards development, and education.

In response to the need for public and private cooperative partnerships, the following cost-shared partnerships are recommended:

- Stationary and Distributed Generation Partnership to continue robust research activities to lower costs and improve durability, and to establish necessary field evaluations leading to commercialization.
- Transportation and Infrastructure Partnership to test FCVs and evaluate critical cost, performance, and reliability information; and to address safety, cost, and standardization issues associated with a hydrogen infrastructure for FCVs.

Lastly, the *Hydrogen Posture Plan* outlines the activities, milestones, and deliverables that the DOE plans to pursue to support America's shift to a hydrogen-based energy system. The Posture Plan integrates the DOE's planning and budgeting for program activities and lays the foundation for a coordinated approach for accelerated research on hydrogen, fuel cell, and infrastructure technologies. The Plan envisions a four-phase process to fully realize a hydrogen economy by 2030-2040 (Figure 3.1).

Figure 3.1
Four-Phase Approach to Hydrogen and Fuel Cell Technology Introduction

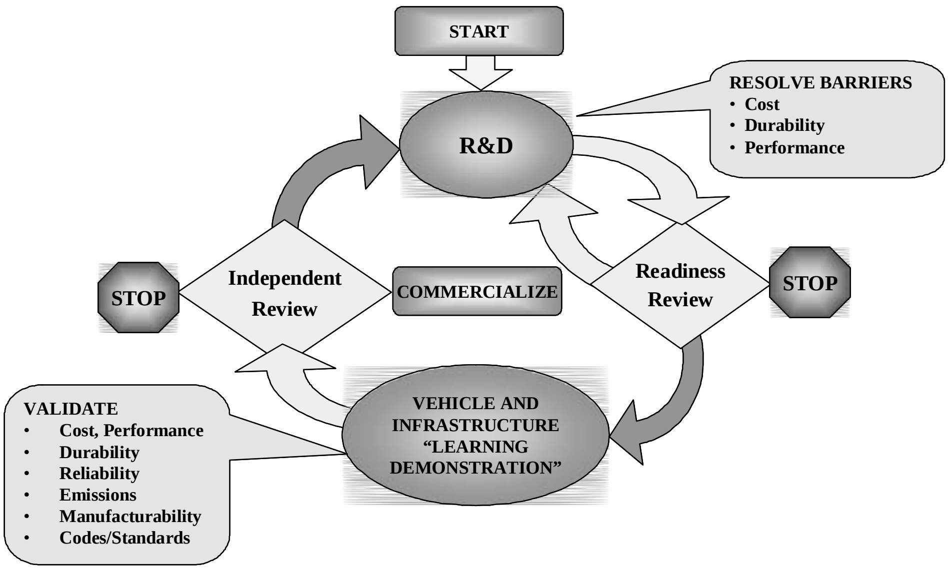


Infrastructure and Technology Validation

Transitioning the current petroleum fuel supply infrastructure to a hydrogen infrastructure will require extensive public-private cooperation due to the magnitude of technology challenges, costs, associated regulatory codes and standards, and anti-trust issues. Testing and demonstration is essential for both fuel cell vehicle and hydrogen infrastructure technologies to validate laboratory progress and "readiness" for commercialization. Public-private demonstrations are needed to address remaining technical and institutional barriers, and to defray the substantial investment cost necessary to bring fuel cell vehicle and hydrogen infrastructure technologies to market. The preferred approach is one that combines public-private demonstrations with concurrent R&D efforts focusing on reducing technology and business risk.

Technology validation will evaluate complex, integrated hydrogen and fuel cell systems representative of commercial units operating under real-world conditions. Performance data from the operation of these systems will be used to validate component technical targets. Complete validation will require collecting sufficient data to develop statistical confidence that the systems meet customer expectations for reliability and durability while satisfying regulatory requirements (e.g., emissions and safety). The data flowing from the demonstrations will allow government and industry to gauge progress, establish research requirements leading into the next research cycle, and determine the investment necessary to carry out the next demonstration phase. In turn, the results from each demonstration phase will be used to define the requirements for further technology development and to make appropriate adjustments in the R&D "success" criteria. The relationship between the phased R&D and demonstration is shown generically in Figure 3.2. This figure illustrates the use of independent reviews between each R&D demonstration stage, with the provision to terminate the program at various stages.

Figure 3.2
"Learning" Demonstration Activity with Clearly Defined Objectives, Milestones, and Go/No-Go Decisions

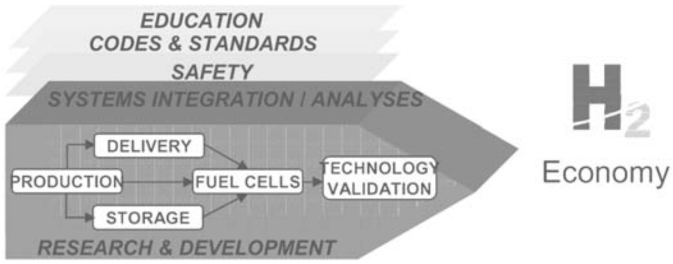


3.2 Goals and Technical Targets

The DOE has developed a set of program strategic performance goals to achieve the hydrogen vision and fulfill its mission. This mission is to research, develop, and validate fuel cells and hydrogen production, delivery, and storage technologies for transportation, stationary, and portable power applications. Detailed planning is undertaken to formulate supporting programmatic objectives, activities, and milestones to achieve the program strategic performance goals. Extensive consultation with industry, national labs, and academia via meetings, workshops, and program reviews, as well as the use of analytical tools, are used to provide information for better decision making, including the development of the R&D portfolio. The Hydrogen, Fuel Cells, and Infrastructure Technologies Multiyear Research, Development and Demonstration Plan summarizes the technical objectives, activities, and milestones that have been developed for each of the key areas (as shown in Figure 3.3) to achieve a hydrogen economy.

Figure 3.3

Hydrogen Fuel Cells and Infrastructure Technologies Program



More than 100 specific individual technical targets have been established for fuel cells for transportation, stationary, portable power, and auxiliary power units. Tables 3.1 and 3.2 present technical targets which have been established for 50 kWe integrated fuel cell power systems operating on Tier 2 gasoline and direct hydrogen for automotive applications. These targets have been established through extensive consultation and analysis with industry, academia, and other government entities.

Table 3.1

Technical Targets: 50 kWe (net) Integrated Fuel Cell Power Systems Operating on Tier 2 Gasoline Containing 30 ppm Sulfer, Average

(Including fuel processor, stack, auxiliaries; excluding gasoline tank and vehicle traction electronics)

Characteristics	Units	2001	2005	2010
Energy efficiency[a] @25% of rated power	%	34	40	45
Energy efficiency @ rated power	%	31	33	35
Power density	W/L	140	250	325
Specific Power	w/kg	140	250	325
Cost[b]	$/kW	300	125	45
Transient response (time from 10 to 90% power	Sec	15	5	1
Cold start-up time to rated power @ -20°C ambient temperature @ +20°C ambient temperature	 min min	 TBD <10	 2 1	 1 <0.5
Survivability[c]	°C	TBD	-30	-40
Emissions[d]		<Tier 2 Bin 5[e]	<Tier 2 Bin 5[e]	<Tier2 Bin 5[e]
Durability[f]	Hours	1000[g]	2000[h]	5000[i]
Greenhouse Gases	One-third reduction with conventional Si-IC engines in similar type vehicles			

Notes to Table 3.1

[a] Ratio of dc output energy to the lower heating value of the input fuel (gasoline)
[b] Includes projected cost advantage of high-volume production (500,000 units per year) and includes cost for assembling/integrating the fuel cell system and fuel processor
[c] Achieve performance targets at 8-hour cold-soak at temperature
[d] Emissions levels will comply with emissions regulations projected to be in place when the technology is available for market introduction
[e] 0.07 NO_xg/mile and 0.01 PM g/mile
[f] Performance targets must be achieved at the end of the durability time period
[g] Continuous operation
[h] Includes thermal cycling
[I] Includes thermal and realistic drive cycles
All targets must be achieved simultaneously and are consistent with those of FreedomCar

Table 3.2

Technical Targets: 50 kWe (net) Integrated Fuel Cell Power Systems Operating on Direct Hydrogen[a]

Characteristics	Units	2001	2005	2010
Energy efficiency[b] @25% of rated power	%	59	60	60
Energy efficiency @ rated power	%	50	50	50
Power density				
Excluding H_2 storage	W/L	400	500	650
Including H_2 storage	W/L	TBD	150	220
Specific power				
Excluding H_2 storage	W/kg	400	500	650
Including H_2 storage	W/kg	TBD	250	325
Cost[c] (including H_2 storage)	$/kW	200	125	45
Transient response (time from 10 to 90% rated power)	Sec	3	2	1
Cold start-up time to rated power				
@ -20°C ambient temperature	sec	120	60	30
@ +20°C ambient temperature	sec	60	30	15
Emissions		Zero	Zero	Zero
Durability[d]	Hours	1000	2000[e]	5000[f]
Survivability[g]	°C	-20	-30	-40

[a] Targets are based on hydrogen storage targets in an aerodynamic 2500-lb vehicle
[b] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen)
[c] Includes projected cost advantage of high-volume production (500,000 units per year)
[d] Performance targets must be achieved at the end of the durability time period
[e] Includes thermal cycling
[f] Includes thermal and realistic drive cycles
[g] Achieve performance targets at 8-hour cold-soak at temperature
All targets must be achieved simultaneously and are consistent with those of FreedomCar

3.3 Organizational Network: Partnerships among Stakeholders

The vast U.S. national fuel cell innovation system contains a complex network of government agencies, national laboratories, industry, universities, state and local governments, and international organizations. All of these entities are engaged in creating, diffusing, and/or using knowledge to advance PEM fuel cell technologies. Because the system is complex and dynamic, it would be impossible to describe precisely what kind of knowledge is created, how and when it is created, by whom, and how it is used.

Figure 3.4
DOE Organizational Network for Fuel Cell Innovation

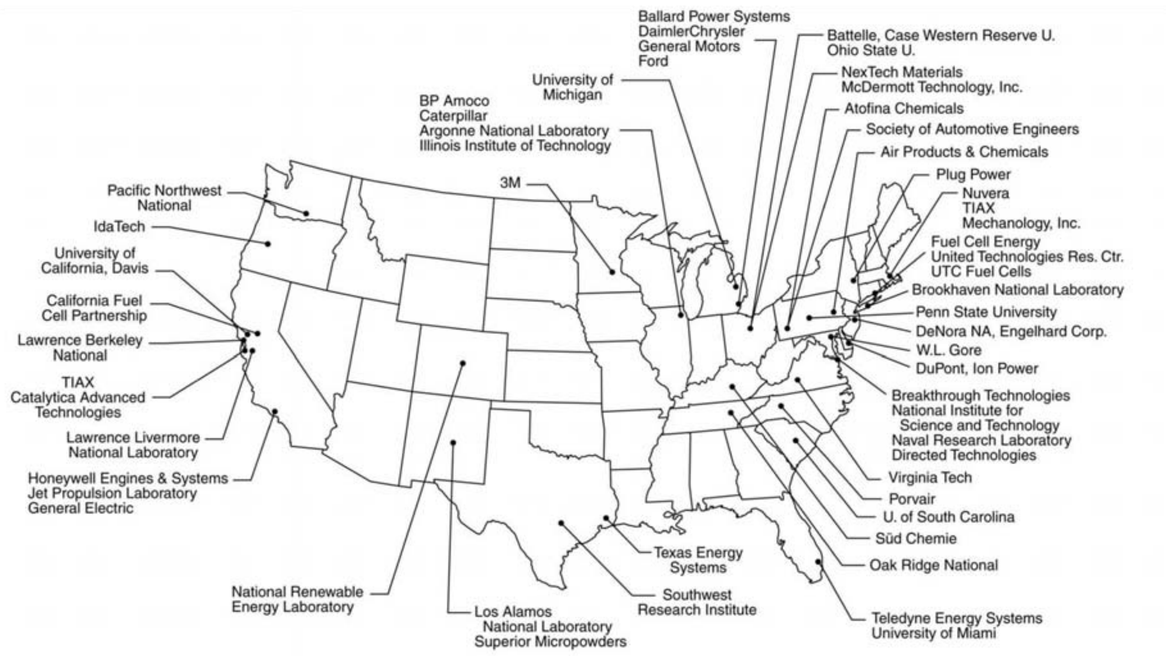


Figure 3.4 shows the DOE's principal players engaged in PEM fuel cell technology R&D and their geographical distribution. Many of the players have their own organizational network for creating, diffusing, and using knowledge. A large company such as General Motors (Appendix A), for example, might have its own organizational network that could be much larger than that of the DOE. Also missing from the figure are the complex interrelationships among the players that enhance knowledge flow.

The bulk of DOE's R&D work is currently carried out by the national laboratories. Table 3.3 illustrates the principal U.S. national laboratories and their specific expertise in PEM fuel cell research and development. They have and will continue to carry out many critical research activities on key areas of PEM fuel cell technology innovation, creating, diffusing and using knowledge. In particular, the Los Alamos Laboratory played a seminal role in early fuel cell R&D, funded by DOE, in cooperation with General Motors Company. Again, each laboratory has its own organizational network for fuel cell innovation.

The DOE has made extensive use of public-private partnerships as a vehicle for advancing fuel cell technologies and their commercialization. These partnerships among the stakeholders – government agencies, industry, state and local governments, and foreign entities, have helped DOE identify the need for basic and applied research, and barriers for commercialization of PEM fuel cells. While their roles vary, broadly these stakeholder groups fill the following roles:

- ***Federal agencies**:* Research and development, safety, codes and standards, and environmental and regulatory issues.
- ***State and local agencies**:* Partnerships in codes and standards, field evaluation, and education.
- ***Industry**:* Partnerships in developing, validating, and deploying advanced fuel cell and hydrogen energy technologies.
- ***International**:* Partnerships in research and development, validating codes and standards, and safety.

Table 3.3
National Laboratory PEMFC Priorities and Expertise

Laboratory	Priority
Argonne	Systems Analysis Fuel Proc Catalysts Fast-Start Fuel Proc
Brookhaven	Low-Pt Electrodes
Oak Ridge	Hydrogen Production Stack Materials Stack Components
Lawrence Berkeley	Electrocatalysts
Lawrence Livermore	Sensors Hydrogen Storage
Los Alamos	Sensors Improved Cathodes High-Temp Membrane Durability Studies Fuels Effects
Energy Technology	Fuel Processing
Renewable Energy	Vehicle Analysis Hydrogen Production Hydrogen Storage
Pacific Northwest	Microchannel Fuel Processing
Sandia	Hydrogen Purification Hydrogen Storage

Table 3.4 describes DOE-supported R&D activities by universities and private companies. Activities are grouped into six broad categories: membranes and electrodes, fuel processing, bipolar plates and components, system integration, air and water management, and analysis. These activities are considered critical to advancing PEM fuel cells for automotive applications.

How the DOE Fuel Cell Innovation System Works

A variety of funding mechanisms help to drive collaborative research, development, and demonstration activities. Government-supported R&D with national laboratories, industry, and universities can be funded directly or through cooperative agreements or grants. DOE national laboratories are directly funded through existing management and operating contracts that are re-competed regularly. Cooperative Research and Development Agreements (CRADAs), a form of financial assistance (50-50 cost share), is established between national laboratories and private partners. CRADAs employ mechanisms to protect the intellectual property and ownership rights of industry and national laboratories while tapping into the national laboratories' world-class scientific expertise to address critical technical barriers. National laboratories also conduct "Work for Others" on a strictly "pay as you go" basis. Intra laboratory projects, frequently funded by government, are conducted to use the laboratories' unique expertise to overcome the multi-disciplinary nature of technical barriers facing fuel cell systems.

Table 3.4
Government-Supported Industry/University Fuel Cell R&D Partnerships

Membranes and Electrodes	**Fuel Processing**
3M – MEAs and production techniques 3M – Improved cathodes and high-temp MEA Atofina Chemicals – Membrane durability DeNora/DuPont – Advanced MEAs Fuel Cell Energy – High-temp membrane Plug Power – High-temp membrane UTC Fuel Cells – Improved cathodes and high-temp membrane Superior Micropowders – Low Pt cathode SWRI/Gore – Pilot production methods	Catalytica – Plate reformer Nuvera – STAR fuel processor Nuvera – Hi-Q fuel processor U. of Michigan – Microchannel UTRC – Hydrogen enhancement Ohio State U. – H_2 enhancement McDermott – Autothermal reforming Exaco Energy Systems - reforming
Bipolar Plates/Components	**Systems Integration**
• Porvair – Low-cost, mass-produced plates • Honeywell – Sensors • UTC Fuel Cells – Sensors • Engelhard – Platinum recycling • Ion Power – Platinum recycling	• UTC Fuel Cells • Caterpillar – Ethanol • GE Honeywell • IdaTech – Stationary • Plug Power – Stationary
Analysis	**Air/Water Management**
• TIAX – Costing, Pt cost and availability, fuel effects • Breakthrough Technologies Inc. – Foreign transportation FC programs • Directed Technologies – Transpotation FC costs • Battelle – Economic analysis	• Honeywell – Turbocompressor, water management • Mechanology – Torroidal Intersecting Valve Machine • UTC Fuel Cell – Blowers • TIAX – Hybrid

For university and industry work efforts, two types of financial assistance mechanisms are used: grants and cooperative agreements. Grants, where there is little DOE involvement or management of the work, are used only for exploratory research. Cooperative agreements, on the other hand, account for the vast majority of funded work and incorporate substantial management and guidance from the DOE. This work includes non-competitive, Congressionally directed projects. Competitive solicitations for work conducted by industry and universities can be established for up to five years.

Interagency Agreements are used to conduct DOE-sponsored applied research at various Department of Defense laboratories (e.g., Naval Research Laboratory), vehicle testing at the Environmental Protection Agency, and, potentially, safety testing with the Department of Transportation.

The DOE often uses standing working groups and workshops to address particularly stubborn technical issues impeding the development of fuel cell systems. Notable examples include the high-temperature membrane working group, which meets twice each year to examine critical barriers to the development of polymer membranes operating at 120-150^{o}C and exhibiting adequate stability and conductivity. The group is examining polymers that require water for conduction and those that do not. The DOE has also hosted and will continue to host non-platinum electrocatalyst workshops focusing on the identification of novel, very low-, and non-platinum electrocatalysts. Platinum is a major cost barrier for PEM fuel cell systems and the development of viable, highly active, and stable low- or non-platinum electrocatalysts would significantly reduce cost barriers to the commercialization of PEM fuel cells. In the past, the DOE has hosted workshops to identify technical targets and to make hard trade-offs in the development of air management systems meeting the unique requirements of fuel cell systems.

FreedomCAR

The FreedomCAR public-private partnership between the DOE and USCAR (U.S. Cooperative Automotive Research, a pre-competitive research organization consisting of General Motors, Ford, and Daimler Chrysler) is the vehicle through which PEM fuel cells are being developed for use in transportation. The FreedomCAR partnership involves a broad range of automotive technologies such as hybrid electric propulsion, power electronics, advanced diesel engines, emissions control, lightweight materials, and fuel cells. The FreedomCAR Partnership now includes a Hydrogen Storage and Refueling Interface Technical Team, a Fuel Cell Technical Team, and a new team being formed to address hydrogen production and infrastructure issues. These teams are the cornerstone of the public-private R&D partnership and consist of automotive and energy industry professionals, along with DOE and national laboratory personnel.

Similar partnerships to test fuel cell vehicles under real operating conditions yield valuable cost, performance, and reliability information that will help focus future research. Recognizing the direct linkage between the need for a robust, cost-effective hydrogen infrastructure and the effective utilization of fuel cell technologies, the DOE is working with energy providers to determine the form and function of a potential partnership for a hydrogen-based fuel infrastructure. Public-private cooperation is needed because of the magnitude of the technology challenges and the associated regulatory and anti-trust issues. Anti-trust concerns of the energy industry must be addressed as it develops and demonstrates the new infrastructure in a collaborative manner, especially as these concerns pertain to the initial placement of refueling stations.

The DOE also fosters innovation by funding small businesses and providing financial support to graduate students through the following programs:

- **Cooperative Automotive Research for Advance Technology (CARAT)**
  The CARAT program focuses exclusively on automotive technologies and was designed to: 1) offer small businesses and universities the opportunity to contribute to fuel cell vehicle R&D; 2) accelerate progress on energy-efficient technologies for advanced vehicles; and 3) enhance working relationships between small businesses and universities and the automotive manufacturers/suppliers.

- **Graduate Automotive Technology Education (GATE)**
  Initiated by the DOE in 1998, the two-phase GATE program blends graduate-level education with technology development and transfer by training automotive engineering students in critical multidisciplinary technologies, fostering cooperative research in those technologies, and transferring the technologies directly to industry. The program focuses on five key technology areas: hybrid-electric vehicles, fuel cells, direct-injection engines, energy storage, and lightweight materials.

Technical and Programmatic Review

A critical part of the research, development, and demonstration activities for fuel cell systems is the technical review process to track, analyze, and adjust RD&D activities as necessary. All industry projects are reviewed quarterly by the Hydrogen, Fuel Cells, and Infrastructure Technologies Program and annually by the FreedomCAR Tech Team. National laboratory and university projects are assessed mid year by the FreedomCAR Tech Team. Note that the FreedomCAR Tech Teams play an integral role in review and critique of all projects to ensure that government-sponsored R&D is accountable and consistent with industry direction and research needs. Annually, a Merit Peer Review and Evaluation is conducted, followed by an annual program report released in the late autumn. Once every two years, the National Academy of Sciences conducts a thorough review of the entire Hydrogen, Fuel Cells, and Infrastructure Technology Program, including direction, thrusts, partnerships, management, and technical progress and needs.

4.0 Current Public Policy Trends

U.S. fuel cell policy will continue to be shaped by concerns over energy security, the environment, and sustained economic growth. The Federal government plays a key role in stimulating fuel cell innovations, specifically targeting precompetitive issues of broad benefit to the entire industry. The federal government's role falls loosely into four categories: 1) identification of strategic issues and solution pathways; 2) advancing technical and scientific knowledge; 3) fostering partnerships and cooperation; and 4) market conditioning.

Identification of Strategic Issues and Solution Pathways

In cooperation with industry, the U.S. government identifies strategic national and industry-wide technical and policy issues facing hydrogen and fuel cell technologies and appropriate solution pathways. This is largely accomplished through the visioning, roadmapping, and planning processes mentioned earlier in this report. With industry involved in every step, from R&D through commercialization, these processes enable the DOE and industry to develop marketable, successful innovations.

Advancing Scientific and Technical Knowledge

The DOE will continue to fund high-risk, long-term R&D by identifying technical targets and barriers. The DOE provides funding support for basic R&D that is deemed essential but is unlikely to be conducted by industry alone due to its high-risk and high capital investment. Figure 4.1 shows the DOE's funding history for PEM fuel cell systems. It indicates a steady increase in funding over the past decade with the total spending reaching over $473 million by the end of 2005. The breakdown of requested DOE budget for 2005 (Table 4.1) indicates an emphasis on the stack component (36%), followed by fuel processing (25%) and technology validation (19%).

Further, in 2003, more than half of the DOE's PEM fuel cell funding went to the private sector, small and large businesses combined. National laboratories received more than one third of the funds and universities received the remaining 8 percent (Figure 4.2).

Fostering Partnerships and Cooperation

The DOE fosters and supports partnerships among industry, national laboratories, academia, small businesses, states, other government agencies, and international organizations. To promote the adoption and acceptance of new hydrogen and fuel cell technologies, it is important that activities are well-coordinated across a number of DOE offices and programs, and throughout the federal government. Other federal agencies, such as the Department of Commerce (DOC), Department of Defense (DOD), Department of Transportation (DOT), Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF), all play critical roles in developing and deploying hydrogen and fuel cell technology for stationary and transportation applications. The DOE coordinates with these agencies through various mechanisms such as the Inter-agency Advanced Power Group and the Hydrogen Interagency Task Force.

Figure 4.1

DOE's PEM Transportation Fuel Cell Funding History in $Million

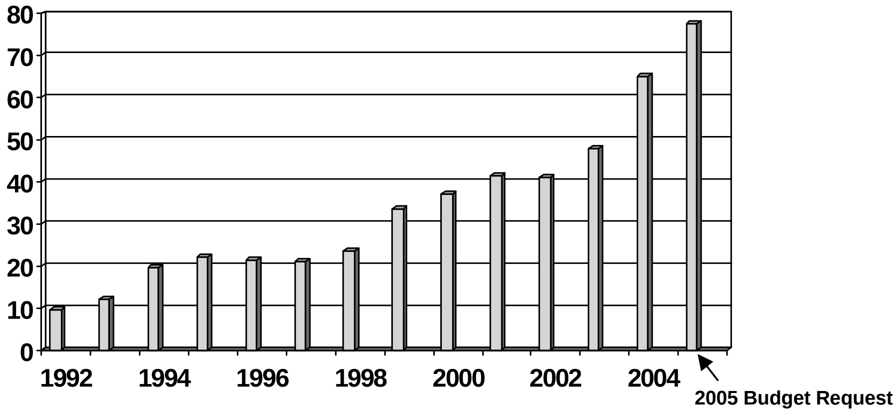


Table 4.1

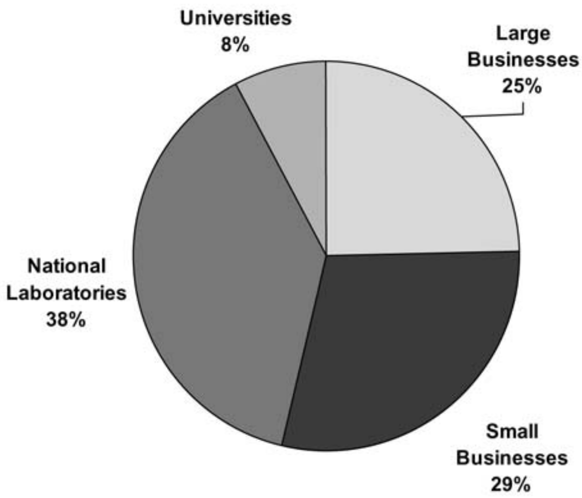
PEM Transportation Fuel Cell Funding History in $Million

Table 4.1 - PEM Fuel Cell Budget Breakdown, in $ Million, 2005

Transportation System	Distributed Generation	Stack Component	Fuel Processor R&D	Technology Validation	Technical Support	Total
7.6	7.5	28.0	19.0	15.0	.4	77.5

Figure 4.2

PEM Fuel Cell FY 2003 Budget Distribution

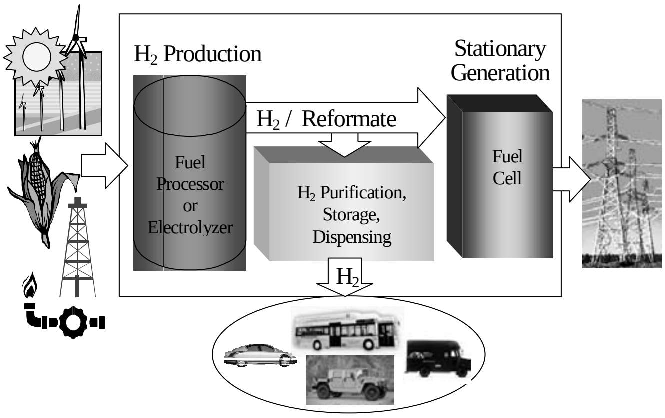


In addition to federal activities, the development of hydrogen and fuel cell technologies crosscuts the activities pursued by state governments. The combination of Federal and state funding is a valuable means of demonstrating the societal benefits of hydrogen energy technologies. The DOE is working with a number of states to implement hydrogen, fuel cells, and infrastructure technologies across the country. In Hawaii, Pennsylvania, and Nevada, plans to operate centrally fueled hydrogen fleets and "Power Parks" are underway (Figure 4.3). Because education is a critically important aspect in the implementation and safe use of new technologies, the DOE is providing funding to a number of projects with state agencies through the DOE's "State Energy Project" grants.

Another area of critical importance to the implementation and safe use of new technologies is the development of codes, standards, and safety procedures. Responsibility for the adoption and enforcement of codes and standards resides with states and local jurisdictions within the states. The DOE supports state and local governments with a series of meetings designed to provide information to key localities.

Figure 4.3

Power Park Concept: Integrated Stationary Power Generation and Hydrogen Refueling Station



In addition, the DOE is hosting regional hydrogen infrastructure forums, in which participants:

- Discuss hydrogen infrastructure deployment options and opportunities emphasizing the near term;
- Share information and improve networks for collaboration and follow-through; and
- Provide a focus for coordinating hydrogen infrastructure planning and deployment in their regions.

Regional hydrogen infrastructure forums are intended to facilitate the development of infrastructure from existing hydrogen facilities, especially merchant, by-product, and captive producers. These local and regional initiatives have expectations that regional hydrogen nodes will become the nation's infrastructure over time. Synchronization of supplier and user investments is critical where a key governmental role is to facilitate the first steps.

International Partnerships: The DOE is working with many international groups, such as the International Code Council and the International Standards Organization to develop and commercialize hydrogen and fuel cell technologies. The agency is also coordinating activities involving the European Union and the International Energy Agency (Japan, Europe, and Canada) to help smooth the progress of these technologies. The DOE is actively participating in the International Partnership for a Hydrogen Economy (IPHE), which is striving to efficiently organize, evaluate, and coordinate multinational research, development, and deployment programs that advance the transition to a global hydrogen economy.

Market Conditioning

Throughout the world, nations have established laws or regulations that require products and systems to meet certain codes and standards for safety. Meeting these standards is a means of demonstrating that the products do not impose unnecessary risks to the users and others. Hydrogen is well known as a chemical, but its use as an energy carrier on a large-scale commercial basis is largely untested. Codes and standards have repeatedly been identified as a major institutional barrier to deploying hydrogen and fuel cell technologies, and developing a hydrogen economy.

The U.S. government is in a unique position as a neutral third party to catalyze and coordinate the work of professional societies, trade associations, and international organizations in hydrogen codes and standards development. The aim is to facilitate the creation and adoption of model building codes and equipment standards for hydrogen and fuel cell systems in commercial, residential, and transportation applications. Efforts are underway to identify and facilitate the development of equipment standards for design, safety, and performance testing, which can be referenced by building codes to help expedite approval of hydrogen technologies by regulatory authorities, and thus facilitate their commercialization. Because the development of hydrogen energy and fuel cell technologies are of national interest, the DOE will serve as a facilitator to accelerate the identification of gaps in the standards development process and provide funding to address these gaps. By working with states and local code officials, the program will assist in the development of training programs. The program is also assuming a communication and education role, so that accurate and relevant information is prepared and disseminated to stakeholders in a timely manner. Finally, continued efforts will focus on research, testing, and certification for hydrogen and fuel cell components and equipment. Early efforts to develop common codes and standards will moderate business risks substantially and are instrumental to the successful commercialization of hydrogen fuel cell technologies.

Development of FCVs for transportation applications requires controlled fleet testing and evaluation (of personal and commercial vehicles, buses, and off-road vehicles) to validate performance and cost, servicing, maintenance requirements, and to develop a better understanding of issues related to the vehicle and hydrogen refueling infrastructure. Under the umbrella of the California Fuel Cell Partnership (CaFCP), auto manufacturers, energy companies, fuel cell technology companies, and government agencies have joined to demonstrate approximately 50 FCVs under day-to-day driving conditions and to examine fuel infrastructure issues. Smaller demonstrations are also underway at the SunLine Transit Agency in Southern California and in Las Vegas. R&D will be carried out concurrently to improve fuel cell durability and to lower fuel cell and hydrogen production costs. Infrastructure-related activities include analyzing the feasibility of various fuels for providing hydrogen to FCVs, developing codes and standards for direct hydrogen refueling, and identifying major barriers to each fuel infrastructure option. Commercial-scale demonstrations of targeted vehicles and their supporting refueling infrastructure would allow industry to produce enough vehicles and refueling stations to fully illuminate life cycle costs and performance issues, as well as refine manufacturing techniques and gauge public acceptance of these new technologies.

5.0 Fuel Cell Innovation System Performance and Assessment

Over the past decade, substantial technical progress has been achieved in PEM fuel cells, largely as a result of strategic and financial support from the U.S. Department of Energy (DOE). Table 5.1 illustrates selected technical accomplishments achieved in recent years through DOE support. These accomplishments demonstrate that the DOE's fuel cell innovation system has worked effectively, in particular, over the recent years.

Table 5.1 — PEM Fuel Cell
Selected Technical Accomplishments

Fuel Cell System Achievement	Year
Preferential oxidation (PROx) CO cleanup system (LANL)	1997
Fuel flexible fuel processor (A.D. Little)	1997
World's first gasoline-to-electricity fuel cell system demonstration (LANL, Plug Power, A.D. Little, Engineering Sciences and Applications)	1997
30 kW brassboard methanol- powered PEM fuel cell system (GM)	1998
CO tolerant anode catalyst (LANL)	1998
Molded composite bipolar plates achieve performance comparable to machined graphite plates (IGT)	1999
50 kW near ambient fuel flexible fuel cell system operating on gasoline (IFC)	2000
50 kW fuel flexible fuel processor (NUVERA)	2000
World's first 50 kW gasoline PEMFC (Plug Power)	2000
Air stable, non-precious metal water gas shift catalyst (LANL)	2000
High volume fabrication of MEAs (3M Corporation)	2000
Bipolar plates meets cost/projection goals for automotive PEM fuel cell systems (ORNL)	2001
12 kW microchannel steam reformer (PNNL)	2001
Carbon foam for radiators (ORNL)	2001
Development/demonstration of pilot production plant for low-Pt electrodes (SwRI and W.L. Gore)	2002
Anode catalyst achieves similar activity to SOA commercial catalysts with 10X less platinum (BNL)	2002

Analysis of Fuel Cell Patents

CHI Research maintains an extensive data base on automotive fuel cell patents, and has performed in depth analyses of the patent activity of automotive fuel cells for the United States, EU, and Japan. This section includes some of its analysis to indicate the success of the U.S. automotive fuel cell innovation system. CHI used the concept of patent families to avoid double counting of U.S. and European equivalent patents. Table 5.2 shows the number of automotive fuel cell patent families issued by the United States, the European Union, and Japan, and their first publication year. Total number of automotive fuel cell patent families issued during 1983 and 2001 was 681, of which 329 are held by the United States, 184 by the European Union, and 168 by Japan. Patenting activities clearly accelerated since 1997 for all three regions. As a result, more than 70 percent of total patents were issued for the five-year period 1997-2001. Although not shown, these three areas are also very similar in terms of patent quality (citation index). Also analyzed in this section is the impact on automotive fuel cell technology of the scientific research funded by DOE and other government agencies. Impact is measured by compiling numbers of patent-to-paper links. For example, a paper that is cited by many patents has more impact than one cited by only one patent. This analysis is based on innovations patented in the U.S. Patent and Trademark Office and the European Patent Office between the years 1983–2001.

Table 5.2

Automotive Fuel Cell Patent Families by Region and First Publication Year

Year	U.S.	E.U.	Japan	Total
1983	1			1
1984	4	1		5
1985	2		2	4
1986	3			3
1987	9	2	3	14
1988	11	2	2	15
1989	10	4		14
1990	4	2	1	7
1991	2	2	4	8
1992	4		1	5
1993	17	5	7	29
1994	12	4	6	22
1995	11	6	6	23
1996	16	8	12	36
1997	27	19	6	52
1998	16	17	26	59
1999	45	30	23	98
2000	62	35	31	128
2001	73	47	38	158
Total of Family	329	184	168	681
5 years 1997-2001	223	148	127	495

Table 5.3 shows the top cited automotive fuel cell patents for U.S. organizations. The top two patents by the U.S. Department of Energy have the highest citation rating for all automotive fuel cell patents.

Table 5.3

Topic Cited Representative Automotive Fuel Cell Patents

Patent	Family No.	Pub. Date	Cite Rec	Assignee Name	Title
4876115	10035	10/24/1989	76	USA Energy Dept.	Electrode assembly for use in a solid polymer electrolyte fuel cell
5248566	10064	9/28/1993	56	USA Energy Dept.	Fuel cell system for transportation applications
4769297	10028	9/6/1988	55	International Fuel Cells Corp.	Solid polymer electrolyte fuel cell stack water management system
5234777	9	8/10/1993	48	Univ. California Regents	Membrane catalyst layer for fuel cells
5211984	10055	5/18/1993	44	Univ. California Regents	Membrane catalyst layer for fuel cells
5084144	10045	1/28/1992	38	Physical Sciences Inc.	High utilization supported catalytic metal-containing gas-diffusion electrode, process for making it, and cells utilizing it
5316871	10081	5/31/1994	36	General Motors Corp.	Method of making membrane-electrode assemblies for electrochemical cells and assemblies made thereby
E0399833	288	11/28/1990	36	Standard Oil Co.	Novel solid multi-component membranes, electrochemical reactor and use of membranes and reactor for oxidation reactions.
4910099	10038	3/20/1990	33	USA Energy Dept.	Preventing CO poisoning in fuel cells
5599638	10137	2/4/1997	32	Univ. Southern California	Aqueous liquid feed organic fuel cell using solid polymer electrolyte membrane
5620807	10143	4/15/1997	31	Dow Chemical Co.	Flow field assembly for electrochemical fuel cells
5264299	10071	11/23/1993	30	International Fuel Cells Corp.	Proton exchange membrane fuel cell support plate and an assembly including the same
5242764	10063	9/7/1993	29	BCS Technology, Inc.	Near ambient, unhumidified solid polymer fuel cell
5262249	10069	11/16/1993	27	International Fuel Cells Corp.	Internally cooled proton exchange membrane fuel cell device
5271916	10073	12/21/1993	27	General Motors Corp.	Device for staged carbon monoxide oxidation
5635039	10148	6/3/1997	26	LynnTech Inc.	Membrane with internal passages to permit fluid flow and an electrochemical cell containing the same
5460905	10110	10/24/1995	25	Moltech Corp.	High capacity cathodes for secondary cells
4824741	63	4/25/1989	24	International Fuel Cells Corp	Solid polymer electrolyte fuel cell system with porous plate evaporative cooling
4746329	10024	5/24/1988	23	Energy Research Corp.	Methanol fuel reformer
5525436	37	6/11/1996	22	Case Western Reserve Univ.	Proton conducting polymers used as membranes
4865925	10034	9/12/1989	20	Hughes Aircraft Co.	Gas permeable electrode for electrochemical system
4877693	10036	10/31/1989	20	Energy Research Corp.	Fuel cell apparatus for internal reforming
5187025	10052	2/16/1993	20	Analytic Power Corp.	Unitized fuel cell structure
4532192	49	7/30/1985	19	Energy Research Corp.	Fuel cell system
4751151	10025	6/14/1988	19	International Fuel Cells Corp	Recovery of carbon dioxide from fuel cell exhaust
5523177	10125	6/4/1996	19	Giner, Inc.	Membrane-electrode assembly for a direct methanol fuel cell
4473622	10006	9/25/1984	18	United Technologies Corp.	Rapid starting methanol reactor system
4737161	58	4/12/1988	18	International Fuel Cells Corp	Compact hydrogen generator
5340664	10086	8/23/1994	18	Ceramatec, Inc.	Thermally integrated heat exchange system for solid oxide electrolyte systems
5395705	10095	3/7/1995	18	Dow Chemical Co.	Electrochemical cell having an electrode containing a carbon-fiber paper coated with catalytic metal particles
4818637	10032	4/4/1989	17	United Technologies Corp.	Hydrogen/halogen fuel cell with improved water management system

Patent	Family No.	Pub. Date	Cite Rec	Assignee Name	Title
5240790	10061	8/31/1993	17	Alliant Techsystems Inc.	Lithium-based polymer electrolyte electrochemical cell
5573866	10133	11/12/1996	17	International Fuel Cells Corp	Direct methanol oxidation polymer electrolyte membrane power system
5637415	89	6/10/1997	17	General Motors Corp.	Controlled CO preferential oxidation
5641586	10151	6/24/1997	17	Univ. Calif., Off. of Tech. Transfer	Fuel cell with interdigitated porous flow-field
4657829	10017	4/14/1987	16	United Technologies Corp.	Fuel cell power supply with oxidant and fuel gas switching
4788110	10030	11/29/1988	15	Energy Research Corp.	Fuel cell with partially shielded internal reformer
5366819	15	11/22/1994	15	Ceramatec, Inc.	Thermally integrated reformer for solid oxide fuel cells
5403675	10098	4/4/1995	15	Maxdem Inc.	Sulfonated polymers for solid polymer electrolytes
5733347	10173	3/31/1998	15	International Fuel Cells Corp	Compact fuel gas reformer assemblage

Figure 5.1 shows U.S. organizations with five or more fuel cell patents for the period 1983 – 2001. It should be noted that many of the fuel cell patents assigned to these (and other) U.S. companies have their genesis in DOE-supported funding.

Figure 5.1 - PEM Fuel Cell

U.S. Organizations with Five or More Automotive Fuel Cell Patents Families 1983-2001

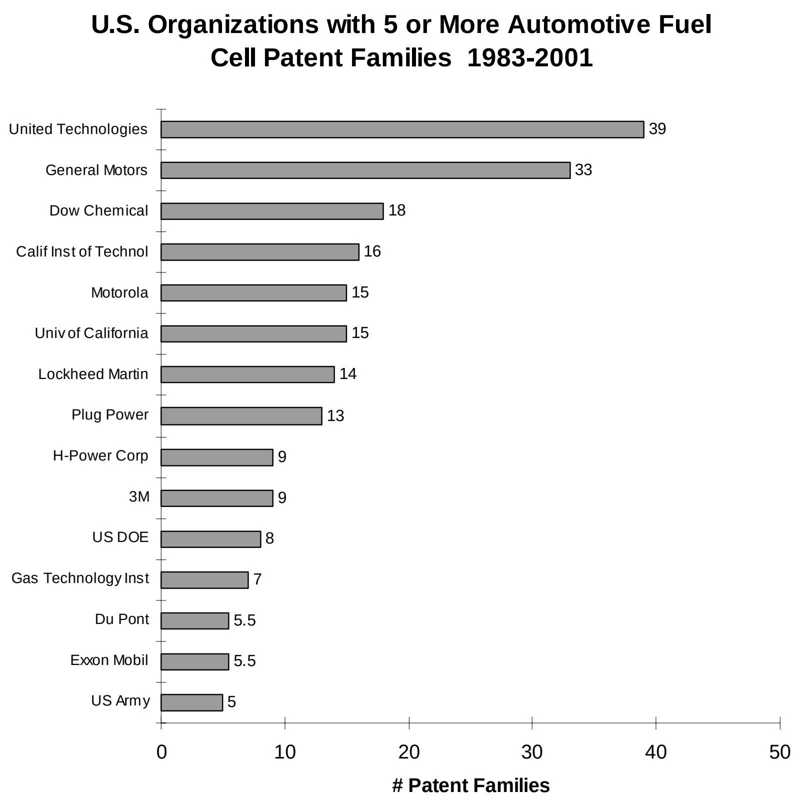


Figure 5.2 shows the percent distribution of patent-to-paper links for FreedomCAR technology patents. U.S. Government funding accounts for 52 percent of these links (DOE 11.5 percent). Table 5.4 shows patent-to-funded paper links broken out by funding organization. DOE funding has 150 patents to funded papers, i.e., more impact on FreedomCar technology (especially automotive fuel cells) than funding from any other single organization except the National Institutes of Health (NIH). NIH's impact is overwhelmingly focused on emissions control and air emissions. Figure 5.3 shows U.S. government funding accounting for roughly half the funded paper impact. In automotive fuel cell systems, the U.S. Government share is approximately 45 percent with DOE contributing 19 percent.

Figure 5.2

Percent of U.S. Patents on FreedomCar Technologies to U.S.-Authored Paper Links

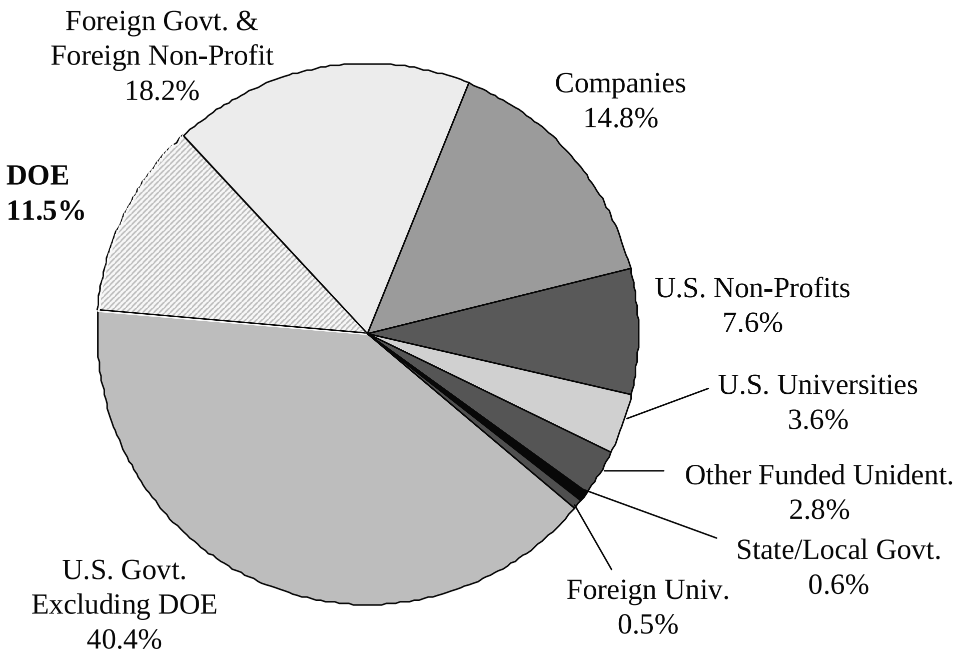


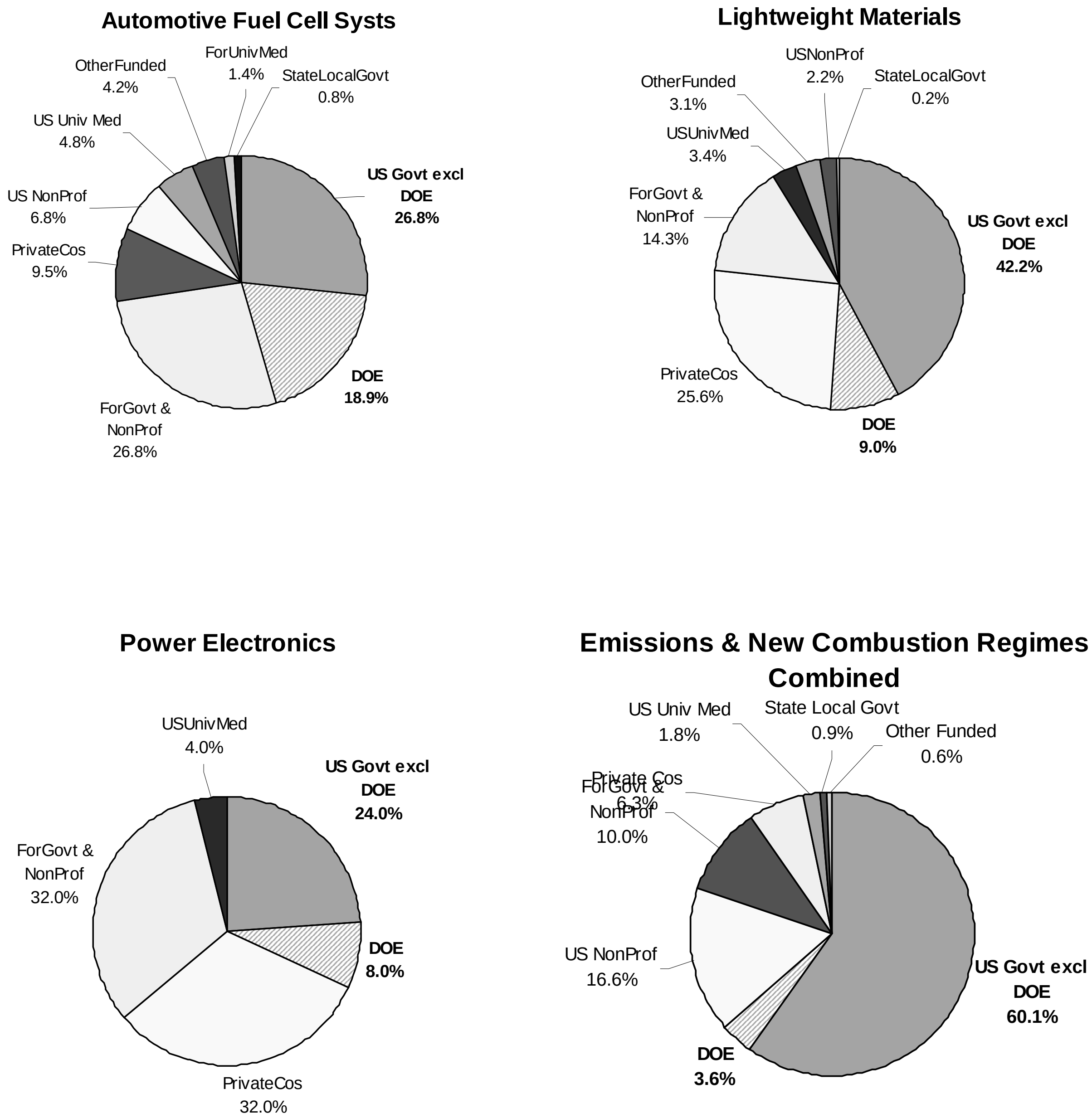
Table 5.4
Patent to Paper Links

(Number of U.S. FreedomCar Technology Patents to Funded U.S.-Authored Papers

		Category				
Funding Organizations	**No. of Patent to Funded Paper Links**	**Fuel Cell Systs**	**Lightwt Matls**	**Power Electrncs**	**Emiss Control/ Combust**	**Other**
All Foreign Gov'ts. & Non-Profits Combined	229	126	63	8	32	
All Companies Combined	192	46	114	8	21	3
NIH (all institutes combined)	190	5	13	1	170	1
Dept. of Energy	**150**	**94**	**40**	**2**	**12**	**2**
Navy	72	34	33	3	2	
Nat'l Science Foundation	68	35	27	2	4	
Advanced Research Projects Agency	55	17	30		8	
Army	50	16	34			
Funded, but specifics not avail.	37	21	14		2	
Air Force	35	9	25		1	
All other US private non-profits combined	31	7	4		20	
Nat'l Aero & Space Admin	30	16	14			
All US Univ & Med. Schls (State) combined	30	11	11	1	6	1
Welch Fdtn. (Rob't. Welch)	19	14	4		1	
All US Univ. & Med. Schls (Priv.) combined	17	13	4			
Amer. Heart Assn. (St. & Loc.)	14				14	
Amer. Cancer Soc.	11	1			10	
All United Nations/Sup. Nat'l. Org. combined	9				9	
All Other USGovt / Other'l Gov't combined	9	7	1		1	
All State or Local Gov't. combined	8	4	1		3	
All Foreign Univ., Med., Tech. Schls. combined	7	7				
Petroleum Research Fdtn.	7		7			
Nat'l Acad of Science	7	7				
Arthritis Foundation	5		1		4	
Nat'l Ctr for Research Resources	5				5	
Dept of Defense	4		3		1	
Sloan Fdtn. (Alfred P. Sloan)	4	2	2			
Amer. Chemical Soc.	3	3				
Nat'l. Fdtn. March of Dimes	3				3	
Muscular Dystrophy Assn.	2				2	
Dept. of Interior	1		1			
Office of Education (old)	1	1				
Res. Corp. (James Cottrell Gr)	1	1				
	1306	497	446	25	331	7

NIH funding is focused on emissions control technology

Figure 5.3
U. S. Government Support of Research Underpinnings for the Freedom Car Category Level
Percent of U.S. Patent to U.S. – Authored Paper Links



6.0 U.S. National Academy of Sciences Assessment Framework

A recent study by the U.S. National Academy of Sciences (NAS) developed a framework for summarizing the performance of Government R&D in nine categories, as shown below. The framework provides a convenient way to categorize the benefits of publicly funded R&D and could serve as a consistent basis for R&D planning as well as guide S&T policy formulation. The NAS framework was used to organize the costs and benefits associated with the innovation of fuel cell technologies. As fuel cells are a new technology and far from being commercialized in the transportation sector, quantifying the benefits associated with fuel cells proved to be a difficult task. Even knowledge benefits, while extensive, do not lend themselves easily to the NAS categories. In the following discussion, various benefits are described qualitatively within the NAS framework with some quantitative assessments where possible. As indicated in Figure 4.1, the total U.S. Department of Energy funding for fuel cells for transportation since the early 1990's is approximately $400 million.

	Realized **Benefits and Costs**	**Options** **Benefits and Costs**	**Knowledge** **Benefits and Costs**
Economic Benefits and Costs **Environmental Benefits and Costs** **Security Benefits and Costs**			

Realized Economic Benefits of Fuel Cells

While automotive applications of fuel cells are unlikely to be commercialized in the near future, other economic benefits are already being realized. Foremost, largely as a result of DOE-supported research starting in the late 1980's, important technical progress has been achieved. This progress awakened industry interest and has led to dramatic increases in private sector fuel cell R&D, as shown in Figure 2.1. While private sector investments have declined since 2000, they remain the major source of funding for fuel cell R&D. This stands in stark contrast to a decade ago, when there was very little private sector investment.

Few components of fuel cells have actually been commercialized to date. However, selected bipolar plates originating in DOE-supported research have reached the state of commercialization. One example is a graphic filled vinyl ester resin thermoset developed and patented by Los Alamos National Laboratory. The graphite provides conductivity and the resin is a binder for rigidity and chemical resistance. This technology was licensed to Bulk Molding Compounds, Inc., which subsequently 1) optimized flow and conductivity and 2) developed preforms and reduced cure times for high throughput. The BMC 940 compounds are widely used by molders (such as Imperial Custom Molding and Dicten and Masch) and fuel cell companies. Plug Power has a 100-percent supply contract for this compound. Today, approximately 100,000 lbs of BMC 940 compound is sold annually and is being used to develop thousands of bipolar plates for fuel cells.

Economic and Environmental Options Benefits of Fuel Cells

Multiple economic and environmental benefits can potentially be realized when and if market conditions become more favorable. Figure 6.1 illustrates the results of a well-to-wheel analysis of primary energy efficiency for various fuel-propulsion system options of light duty vehicles. A conventional gasoline-powered, spark-ignited vehicle has primary energy efficiency over its entire cycle of 0.12, while a gasoline-powered fuel cell vehicle demonstrates *a 50-percent improvement* of 0.18 primary energy efficiency. A *direct hydrogen fuel cell vehicle* (in this case, using steam reforming of natural gas) can achieve primary energy efficiency over the entire well-to-wheels cycle of 0.22, or approximately *an 80-percent improvement*. Efficiency improvements of this magnitude can lead to a significant reduction in petroleum use for the transportation sector, thereby significantly enhancing energy security. By 2040, with 150 million hydrogen-powered light duty cars and trucks on the road, hydrogen and fuel cells could reduce oil use by an estimated 11 million barrels per day.

Figure 6.1
Well-to-Wheel Energy Efficiency of Vehicles

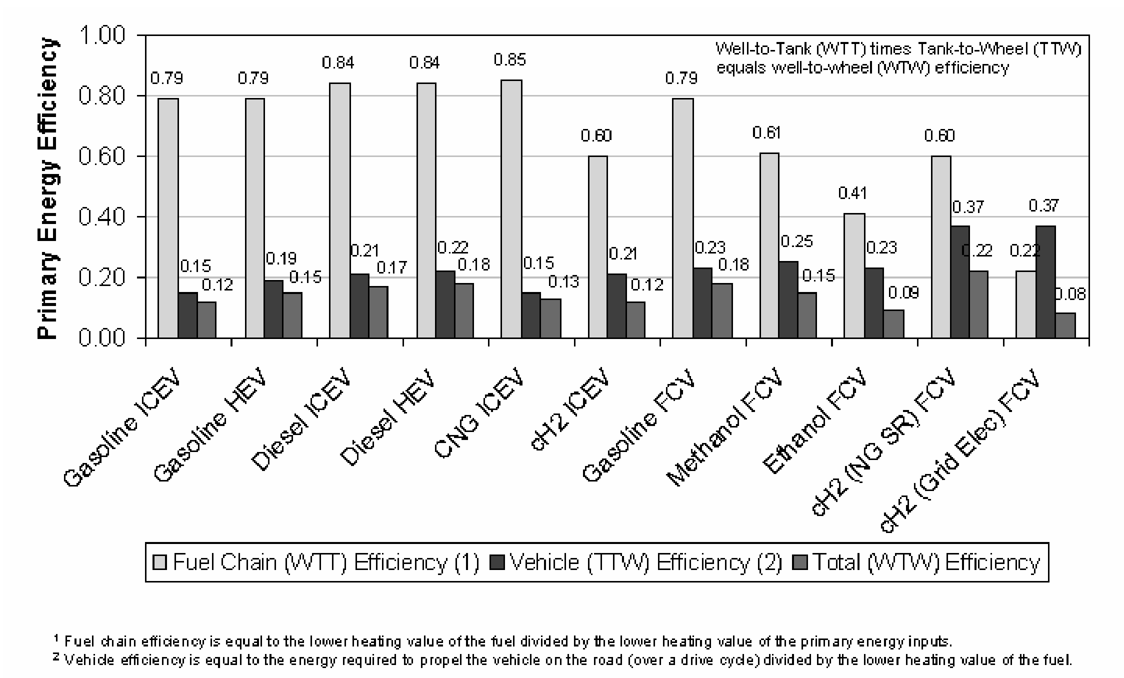
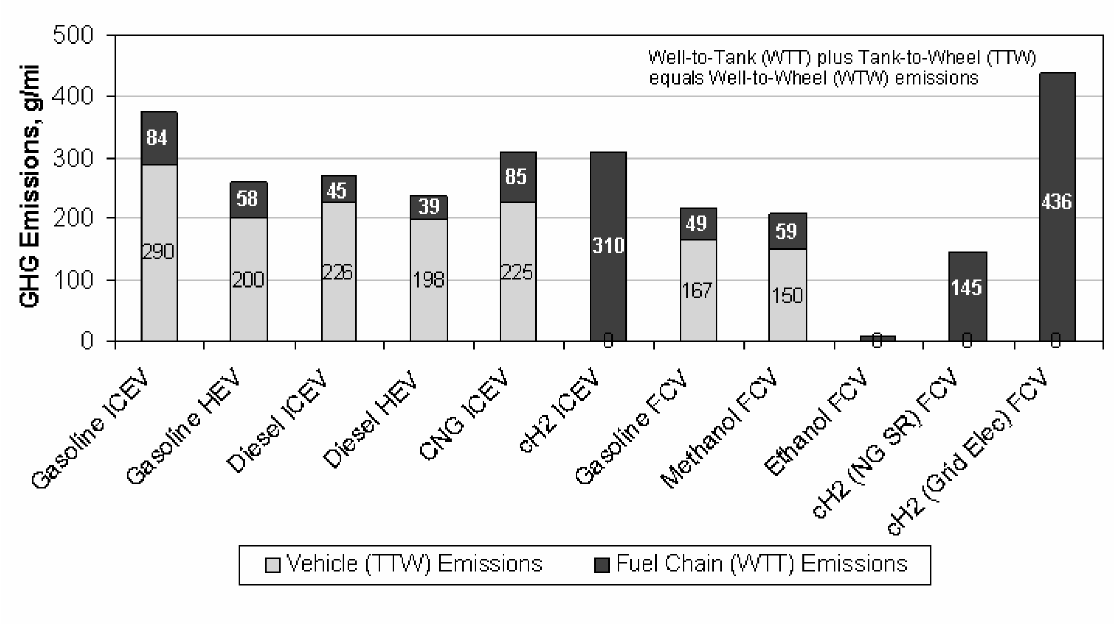


Figure 6.2 illustrates a well-to-wheel analysis of greenhouse gas emissions for various fuel-propulsion system options for light duty vehicles. Gasoline-powered and direct hydrogen-powered FCVs demonstrate greater than 40- and 60-percent improvements in greenhouse gas emissions, respectively, compared to a conventional gasoline-powered vehicle. An ethanol-powered fuel cell vehicle emits essentially no greenhouse gas emissions over its life cycle. Additionally, FCVs emit essentially zero or near zero criteria pollutants, such as carbon monoxide and oxides of nitrogen, at the street level.

Figure 6.2

Well-to-Wheel Greenhouse Gas Emissions of Vehicles



[1] Well-to-wheel greenhouse gas emissions per mile driven, weighted by global warming potential relative to carbon dioxide. Note: ethanol fuel cell vehicle results are based on the net emissions from ethanol made from corn stover including byproduct credits.

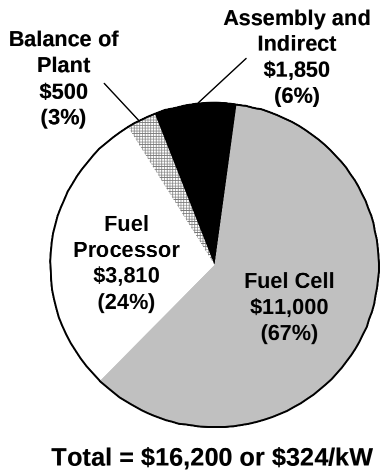
The projected costs of FCVs have been reduced dramatically within the last decade from about \$3000/kW to \$225/kW in year 2004. Figure 6.3 shows the estimated cost breakdown by A.D. Little for a 50 kW_{net} automotive PEM fuel cell system produced in year 2001 at high volumes (500,000 units per year). The overall cost for a fuel cell system produced in year 2001 is \$16,200 or \$324/kW. The cost of the fuel cell subsystem represents 67 percent of the overall system cost and the fuel processor subsystem about 24 percent, while the balance-of-plant and assembly account for the rest. The largest cost savings over the last decade have been achieved by the order of magnitude reduction in platinum loading, and increases in catalytic activity leading to much greater power density.

Options National Security Benefits of Fuel Cells

High dependence on oil imported from the politically unstable regions of the world is a national security concern of the United States. Hydrogen's diversity in production and flexibility in use via fuel cells offers opportunities for limiting oil import dependence, broadening energy choices, and stimulating economic growth. Thus, developing and leading the way in hydrogen fuel cell technologies for automobiles will help the U.S. to enhance its national security as well as energy security.

Figure 6.3

Estimated Costs for Year 2001 50kWe PEM Fuel Cell Power System



Knowledge Benefits of Fuel Cells

While successful application of fuel cells for automobiles still has a long way to go, a considerable amount of technical knowledge on fuel cells has been accumulated. The benefits of such knowledge are far-reaching and are pushing fuel cells closer to commercialization. As indicated in Table 5.1, DOE-supported research and development has led to numerous technical achievements and has advanced the innovation of fuel cell technology. The most important advancements in knowledge fall into several categories. A milestone for *systems integration and validation* was the successful 1997 demonstration of the world's first gasoline-to-electricity PEM fuel cell system. This was followed by the development of full-scale, 50kW gasoline-to-electricity systems in 2000 and 2001. These achievements demonstrated the viability of fuel cells for transportation powered by gasoline *fuel processing,* including the development of auto thermal reforming techniques. Significant *reduction in platinum loading, and increased catalytic activity,* have also been instrumental in increasing the commercial viability of fuel cells. Demonstration of pilot production lines and improved manufacturing of components are driving down costs leading to a faster transition to commercialization. Numerous advances in modeling have aided optimization and integration of the myriad fuel cell system components. Air, water, and thermal management technologies are being significantly improved to meet the unique system requirements of fuel cells. Finally, advances in other critical areas, such as high-temperature membranes, will lower system costs, improve durability, and facilitate system integration.

7.0 Conclusions

The United States consumes over 20 million barrels of petroleum daily. The transportation sector in particular remains heavily petroleum dependent—consuming about 14 million barrels per day. Currently, over half of the petroleum consumed in the United States is imported, and oil demand and imports are both expected to grow. The pollutants generated by fuel consumption in the transportation sector cause poor air quality in major urban areas. In addition, the transportation sector contributes one third of total U.S. CO_2 emissions—a major greenhouse gas.

Growing concerns about dependence on imported oil, global climate change, and deteriorating regional air quality have been major drivers of automotive PEM fuel cell technologies and the rapid growth of the fuel cell industry in the United States. Energy security and environmental concerns have also led to the promulgation of several important public policy measures, including the Energy Policy Act of 1992 and the National Energy Policy Act of 2001, which established hydrogen-fueled fuel cell vehicles as a national priority. Indeed, development of hydrogen-fueled fuel cell vehicles is now a Presidential initiative.

The U.S. national innovation system for fuel cells is too vast and complex to describe adequately. Instead, the study focuses on the Department of Energy's (DOE's) innovation system for automotive fuel cells. It comprises a large network of players, including national laboratories, private companies, universities, and other entities. These organizations interact in complex ways to generate, diffuse, and use knowledge to achieve innovations in fuel cell technology. Since the early 1980's, the DOE has played a critical role in fostering R&D by funding and facilitating partnerships among public and private partners. The early fuel cell research funded by DOE at the Los Alamos National Laboratory was critically important in advancing the technology. The DOE's fuel cell innovation system is underpinned by long-range visioning and roadmapping in conjunction with the fuel cell industry. It targets funding of high-risk, long-term research that industry alone would not pursue, and ensures that government activities are compatible with long-term industry needs. Heavy emphasis is placed on the development of government-industry-small business-university partnerships to overcome key technical and institutional barriers.

Key technical targets and barriers are identified through sponsorship and organization of various technical meetings, workshops, and industry partnerships. Formal review processes are an integral part of the DOE innovation system, and are conducted on a periodic basis to reassess and adjust, as necessary, programmatic and technical thrusts. As fuel cells progress along the research-development-demonstration-commercialization continuum, program emphasis is evolving as well. Recently, greater emphasis is being placed on demonstration activities to help increase awareness and obtain performance data consistent with real-world use of fuel cell vehicles and hydrogen refueling systems. This type of activity is essential to overcome substantial market barriers to the introduction of radically new vehicle technologies and infrastructure.

The private sector in the United States has played an important role in fostering fuel cell technology innovation by making substantial R&D investments. According to the U.S. Fuel Cell Council's estimate, between 1996 and 2002 the private sector invested over $4 billion in fuel cell R&D while the U.S. government spent close to $850 million.

Assessment of the DOE automotive fuel cell innovation system was conducted in a number of ways – both qualitative and quantitative. The total U.S. patent family on automotive fuel cells over the period 1983-2001 was 329, close to half of total patents for the EU countries and Japan combined, indicating high marks for performance by the U.S. fuel cell innovation system. Moreover DOE was the first (76) and second (56) on the top-cited automotive fuel cell patents for U.S. organizations. Finally, DOE has the highest count (150) of patent-paper links between U.S. fuel cell technologies patents and funded, U.S.-authored papers.

The National Academy of Sciences (NAS) framework for performance assessment showed that while automotive fuel cells are far from being commercialized, the research has generated important economic, environmental, and national security gains in terms of realized, options and knowledge benefits. First, due largely to DOE-supported research, the private sector is spending hundreds of millions of dollars annually on fuel cell R&D. Further, selected bipolar plates, also supported by DOE research, have reached the state of commercialization. Economic and environmental benefits include a 50-percent gain in well-to-wheel primary energy efficiency for various fuel-cell propulsion systems of light duty vehicles. Reductions in greenhouse gas emissions are 40 to 60 percent. The projected cost of fuel cell vehicles has been reduced dramatically within the last decade. Finally, DOE-sponsored research and development has led to numerous technical achievements, including systems integration and validation, fuel processing, reduction in platinum loading, and increased catalytic activity.

8.0 Appendix

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Contributors

- Pat Davis, U.S. Department of Energy
- JoAnn Milliken, U.S. Department of Energy
- Inja Paik, U.S. Department of Energy
- Phyllis Yoshida, U.S. Department of Energy
- Tom Benjamin, Argonne National Laboratory
- Fred Wagner, Energetics, Inc.
- CHI Research, Inc.

Appendix A

General Motors Fuel Cell Innovation System—In Brief

Among the companies that pioneered the innovation of fuel cells, General Motors ranks at the top. The following provides a synopsis of the genesis of the innovation system for fuel cells at General Motors (GM).[1]

General Motors' earliest fuel cell efforts started modestly through collaboration with Los Alamos National Laboratory (LANL). Los Alamos' core competencies were basic science understanding including what is happening in the stack, chemistry, physics, and fundamental fuel cell knowledge. GM's core competencies were mechanical, electrical, and electrochemical engineering skills that provided knowledge of how to build things and take measurements. A key innovation mechanism was a DOE contract that allowed the exchange of insights and information between GM and LANL. This effort consisted of GM scientists and engineers working at Los Alamos as a joint team. Funded by the Department of Energy and GM, this effort led to the establishment in 1991 of the LANL/GM Joint Development Center. The JDC team worked on all aspects of the power system, from optimizing the membrane electrode assembly to system integration, modeling, and testing.

In the 1990s, GM took two large steps to further develop additional fuel cell capabilities. 1) GM recruited experts in electrochemistry, electrical engineering, and material science to complement skills already at GM, and 2) GM began to mathematically model the fundamental phenomena of the fuel cell and invested in special instrumentation for measurement inside fuel cells. Approximately 35-50 people were involved in developing the new set of core competencies. The majority of the accelerated change occurred since 1997.

General Motors' fuel cell innovation process contains a number of key tenets including "learning by doing," minimizing reinvention, and extensive partnership development. Mr. McCormick believes "learning by doing" was the key element that allowed fuel cell technology to expand beyond the laboratory setting. Scaling up a technology leads to the revelation of subtle issues that may not be evident at the lab-bench scale. Some of these issues include: what must be controlled—and how carefully—in the construction and manufacturing processes and where and why failures arise. GM and LANL's joint "learning by doing" activities combined and expanded competencies at both organizations.

Fuel cell systems require expertise in a variety of technical disciplines—no single organization can master and control all key technologies. Recognizing this, GM makes a strong effort to keep a finger on the pulse of the fuel cell industry in general and to leverage advancements that are made elsewhere. One key mechanism is to identify and forge partnerships with other organizations, particularly in industry-wide, precompetitive areas. GM believes that collaboration between industry and the Federal government is integral to the deployment of FCVs. GM looks to government partnerships such as FreedomCAR to address industry-wide issues, not to solve specific competitive barriers industry should be handling themselves.

The following are some of GM's publicly announced fuel cell partnerships and alliances:

OEMs:	Toyota and Suzuki Motor Corporation
Energy:	ExxonMobil, BP Amoco, and Chevron Texaco
Fuel Cell Technology:	Quantum Technology, General Hydrogen, Hydrogenics, and Gines Electrochemical Systems

[1] Based on telephone interview with Byron McCormick, who heads the fuel cell program at GM.