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ADVANCED TECHNOLOGY PROGRAM

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National Institute of Standards and Technology ? Technology Administration? U.S. Department of Commerce

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ADVANCED TECHNOLOGY PROGRAM
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Abstract

This report originated in the authors' participation in a multi-country study of national innovation systems and their impact on new technology development, sponsored by the Organization for Economic Cooperation and Development (OECD). Our task was to look at the U.S. national innovation system's impact on the commercial development of Proton Exchange Membrane (PEM) fuel cells for residential power applications.

Early drivers of PEM fuel cell innovation were the aerospace and defense programs, in particular the National Aeronautics and Space Administration (NASA), which used fuel cells on its spacecraft. In the early 1990s, deregulation hit the electric utility industry, which made utilities and entrepreneurs see the potential in generating electricity from distributed power.

Throughout the 1990s, the Department of Energy funded a significant portion of civilian fuel cell research, while the Department of Defense and NASA funded more esoteric military and space applications. In 1998, the Department of Commerce's Advanced Technology Program (ATP) awarded the first of 25 fuel cell projects, as prospects for adoption and commercialization of fuel cell technologies improved.

Based on findings from this study and discussions with an OECD-sponsored working group studying innovation in energy technologies, we find that private industry conducts significant amounts of basic research in fuel cells. This is partially driven by the significance of the automotive, energy, and electronics industries in the participating countries. Energy security is another prime driver. Industry receives a majority of the new fuel cell patents issued. However, national laboratories and universities continue to publish the majority of papers devoted to fuel cells. These findings support the value of public-private partnerships such as ATP, especially projects that link universities or national labs with private industry either through a formal joint venture or as a subcontractor. In addition, the working group acknowledged government's important role both in terms of developing fuel cell standards through collaborations between standards development organizations and national labs, and in dealing with a wide variety of public safety issues. These findings support National Institute of Standards and Technology initiatives in facilitating standards development for fuel cells.

Despite the excitement generated by discussion of the "hydrogen economy," most fuel cell applications are still at the pre-commercialization stage. Commercial products for small portable uses may be available in the marketplace within the next year or two.

Acknowledgments

This report originated in the authors' participation in a multi-country study of national innovation systems and their impact on new technology development, sponsored by the Organization for Economic Cooperation and Development (OECD). We would like to thank Inja Paik from the Department of Energy and Jerry Sheehan from OECD for asking us to participate in this study. We learned a great deal of new information about fuel cell development through this exercise. We would like to thank the following people in the Advanced Technology Program's (ATP's) Economic Assessment Office: Connie Chang, Jeanne Powell, and Stephanie Shipp. We would also like to thank Purabi Mazumdar, Dilip Banerjee, Elissa Sobolewski, and Don Bansleben from ATP; Laura Schultz from the Building and Fire Research Laboratory of the National Institute of Standards and Technology; and Brian Belanger, former Deputy Director of ATP; for their helpful comments.

We thank Nita Congress, with the editing firm Grammarians, for her outstanding editing and desktop design. We are grateful to the following people at Plug Power for the generous use of their time during our interviews and for sharing many of their insights during the past decade of fuel cell development: Glenn Eisman, John Elter, Bill Ernst, and Wayne Huang.

Executive Summary

The authors of this report were asked to participate in a Conference on Innovation in Energy Technologies sponsored jointly by the Organization for Economic Cooperation and Development (OECD), International Energy Agency, U.S. National Academies, and the U.S. Department of Energy (DOE). The objective of the conference was to examine the national innovation systems in various OECD countries, with a particular emphasis on understanding the organization of energy innovation systems so that appropriate links can be established between the public and private sectors, and effective public policy developed and implemented. While the conference theme was not limited to fuel cells, this technology was a prime focus, since it is a key initiative in many national energy innovation programs. The studies prepared for the conference focused on the following issues:

- The respective roles of market forces and government policies in establishing objectives for energy innovation and directions for research.
- The relative contributions and degree of collaboration among industry, universities, and government in financing and performing research and development (R&D).
- Obstacles impeding the commercialization of new energy technologies.

The focus of this project was to study the role and impact of the U.S. national innovation system in the technological and commercial development of the stationary fuel cell (for example, to provide energy for a residence) as opposed to an automotive fuel cell, which would be used to power a car. The authors chose to limit the study's scope to the development of the Proton Exchange Membrane (PEM) fuel cell for residential use.

The study methodology entailed a review of both the fuel cell industry as a whole, including its history, drivers of knowledge innovation, and patterns of knowledge creation; and an examination of a single company, Plug Power, that has played a central role in the development of stationary fuel cell systems for powering residences and businesses independent of the power grid. The researchers drew upon personal experience in the fuel cell area as scientists or project managers with the Advanced Technology Program (ATP). Additionally, extensive interviews were conducted with executives from Plug Power; the research also encompassed a literature review.

The study's key findings in terms of the three OECD objectives are presented below.

Respective Roles of Market Forces and U.S. Government Policies in Establishing Objectives for Energy Innovation and Directions for Research

- Because the technology entails limited emissions and no moving parts, fuel cells are a relatively attractive energy source. This attractiveness notwithstanding, commercial development of fuel cell technology, which is a fairly old technology, has been progressing at a glacial pace. To date, market forces have been unable to pull fuel cell technology into the commercial marketplace.

- The Federal Government played a role in the early development of fuel cells through sponsorship of private research by large mission-oriented agencies involved in space and defense. These arrangements worked well, because cost was not an issue, only performance. Technical advances were thus enabled without researchers being held back by the economics of commercialization.

- As fuel cell technology has moved closer to commercialization, U.S. national innovation policy has shifted toward leveraging the assets of the public sector with those of the private to ensure the technology's marketplace competitiveness with regard to cost and reliability.

- The DOE Hydrogen Roadmap provides a means of establishing objectives and directions for future fuel cell research. The Roadmap calls for a 2015 commercialization decision by industry based on the success of government and private research. There are no arbitrary sales quotas or scheduled deployment targets. Only after consumer requirements can be met and a business case justified will market introduction begin. A report by the National Research Council (2004) reviews many of the technical goals laid out by the Hydrogen Roadmap and provides suggestions for improvement. One of the report's primary recommendations to DOE is to regularly update the report to reflect progress. It suggests that the best way to achieve this objective is for DOE to develop and deploy a systems analysis approach to understanding full costs, defining options, evaluating research results, and helping balance its hydrogen program for the short, medium, and long term.[1]

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[1]p. 4.

Relative Contributions and Degree of Collaboration among Industry, Universities, and Government in Financing and Performing R&D

- President Bush continues to push for higher hydrogen/fuel cell funding. His FY 2005 budget request exceeds the FY 2004 appropriation by 23 % and is almost double the FY 2003 level.[2]

- DOE has been the primary government-funding source for fuel cell research since 1978. While the actual contribution of the private sector is unknown, a reasonable estimate of the costs of 10 to 20 years of fuel cell research by the "Big 3" automakers would probably exceed the government figure by a substantial amount.[3] However, given the lack of commercial success by private companies in this arena, the government will probably need to play a vital role in facilitating the commercialization of this technology.

- Universities spent over $4 billion in research funds for all of 1999 in disciplines related to fuel cell research, although the exact figure devoted to fuel cells is unknown. It is most likely a small fraction of that figure.[4]

- The amount of patenting in the fuel cell area has increased substantially from the mid-1990s. Most recent patents are assigned to private corporations rather than to government or academic organizations. This is at least a partial result of revisions to the Federal Acquisition Regulations in 2003, which permitted advance patent waivers to be granted to small businesses for technology development programs that are cost shared by industry.[5]

- Collaborations between the government and private sector in civilian fuel cell research applications are generally of two types: those funded by DOE, the largest federal monetary contributor to fuel cell research, and those supported by ATP. DOE collaborations lead to work done by either

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[2]U.S. DOE (2004), p. 13.

[3]The U.S. automakers do not disclose R&D figures in their annual reports. Daimler-Chrysler, a German automaker, spent approximately $7 billion on R&D in 2003. Daimler-Chrysler has been working on automotive fuel cell technology for 10 years now. If it even spent 1 % of its R&D budget on fuel cell technology, the figure would be $70 million. Therefore, one could extrapolate a similar amount to the two remaining U.S. automakers since they are similar in size to Daimler-Chrysler.

[4]Stoup (2001).

[5]www.epa.gov/fedrgstr/EPA-IMPACT/2003/August/Day-21/i21172.htm.

private companies or universities, but research outcomes are dependent on the scope specified by the agency request. ATP, on the other hand, creates open competitions wherein the companies suggest projects involving high-risk R&D project ideas they believe will have high commercial possibilities and a large potential for broad-based economic benefits to the national economy.

- The Department of Defense (DOD) conducts significant fuel cell research for various mission-oriented applications. In FY 2004, DOD was authorized to spend approximately $70 million in fuel cell R&D.[6]

- Collaborations within the private sector reveal an interesting phenomenon. Despite a relatively paltry record of commercialization success, the fuel cell industry is already global in nature. For example, a small firm such as Plug Power has already partnered with a Japanese company, Honda, to create a reformer that allows hydrogen to be produced at a residence for automobiles, as well as electricity and heat. Plug also has partnerships with two German companies, Celanese and Vaillant. Celanese develops high-temperature membranes for Plug. Vaillant is helping Plug demonstrate fuel cells that capture the heat produced in a fuel cell and use it to create hot water for a residence.

- Many automotive and energy companies have partnered with various smaller and independent fuel cell makers, choosing to take equity positions instead of acquisitions. They continue to invest money in internal R&D programs, but it is difficult for an outsider to judge whether these programs are creating significant advances that may be revealed in a few years or whether they are a means for these firms to remain technically competent in case some other company delivers significant technology breakthroughs.

- Overall, the PEM fuel cell industry consists of a core group of companies—e.g., Ballard (Canada), Plug Power (U.S.), and UTC Fuel Cells (U.S.)—engaged in commercializing the technology. Each company has large partners on both the demand side (automotive and utility companies) and the supply side (chemicals and specialty materials companies).

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[6]U.S. Fuel Cell Council Federal Fuel Cell Funding Chart.

Obstacles Impeding Commercialization of PEM Stationary Fuel Cells

- There remains a large gap between today's costs of fuel cell technology versus comparable existing energy technologies. For PEM stationary fuel cells to be commercially viable, installed costs must be reduced by a substantial factor. The exact number is difficult to quantify because production efficiencies cannot be estimated until large-scale production begins. A 2001 study by the Energy Information Agency assumed that fuel cell capital costs then equaled approximately $3 625 (1998$) per kilowatt (kW) of electricity with 40 % efficiency versus gas turbine capital costs of $900 per kilowatt of electricity with 29 % efficiency.[7] The agency's model assumes a price drop to $3 000 per kilowatt by 2009, to $2 450 per kilowatt by 2014, and to $1 750 per kilowatt by 2019. These numbers may be somewhat optimistic regarding the current cost of producing a residential fuel cell, but the trajectory of cost reductions needed for commercialization to become a reality are the same regardless of today's cost.

- The near-term commercial potential of fuel cells is limited to portable applications and niche markets such as, for example, uninterruptible power supply. Larger markets may take a very long time to deliver the returns needed to justify the large investments being made now and over the next several years. Although fuel cell companies are attempting to develop products designed for those larger, more potentially lucrative, markets, these companies may not be able to support themselves before these markets develop. Given the times needed to develop these technologies and the financial positions of most small fuel cell companies, it is likely that some type of consolidation will occur; otherwise, companies will need to find more commercially salable products now—perhaps at the expense of developing truly revolutionary technologies.

- Safety and standards issues must be addressed. DOE recently awarded several new projects in this area, and the National Institute of Standards and Technology is developing standards using a residential fuel cell supplied by Plug Power. More DOE funds are being allocated to safety and testing as well as to public education.

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[7]Boedecker, Cymbalsy, and Wade (2001).

Contents

I. Introduction to the Study

The motivation for this study came from a request by the Organization for Economic Cooperation and Development (OECD) to study the U.S. national innovation system's impact on energy technologies, which focused primarily on emerging fuel cell technology developments. Our mission was to study developments of residential/stationary fuel cell technology in the United States and, in particular, the influence of the national innovation system on its development.[1] We were asked to answer certain questions by OECD. For example, what are the drivers of innovation? In what manner do governments and universities assist in this effort? What is the role of public-private partnerships?

We answered these questions at an industry level, but in order to understand innovative processes, we believed it was necessary to examine the experiences of individual companies. We determined that the scope of fuel cell development was enormous, even though there are only a few commercial products available in the marketplace. Therefore, besides researching broad-based industry trends, we focused our efforts on an individual company, Plug Power, in order to highlight its experience with the national innovation system and, hopefully, to gain some insights. We felt that it would be helpful to illustrate how research and development (R&D) in this field has progressed to date and to explore marketplace issues by citing experiences of one of the major players in the field. Plug Power, an Advanced Technology Program (ATP) awardee, was willing to share considerable detail about its fuel cell experiences, and so we include the information in the report. Citing this example, as well as similar information regarding other fuel cell companies, does *not* constitute endorsement of those firms or their products by the National Institute of Standards and Technology (NIST).

These topics are organized into the following structure. Section II contains a description of the fuel cell, the types of fuel cells available, and their potential commercial application. Section III describes the drivers of innovation within the fuel cell industry. Section IV describes knowledge creation within the fuel cell industry. Section V focuses on commercialization issues. Section VI presents several conclusions drawn from the study.

The purpose of this publication is several-fold:

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[1]The OECD mission statement can be found at www.oecd.org/dataoecd/25/45/2495364.pdf.

- The study provides a snapshot of the state of the fuel cell industry in 2004 as it relates to the national innovation system, private sector players, and the intellectual property arena.
- The study provides a detailed explanation of efforts by ATP and NIST in the fuel cell area.
- Conclusions for this study were used in the comprehensive OECD study covering nine other nations' efforts in fuel cell development.
- This study will be summarized into a 15-page report, which will then be combined with similar summaries from the nine other nations.
- The conclusions from the comprehensive fuel cell study will be combined with other large multi-country studies related to biotechnology and knowledge-intensive services in order to create a comprehensive "lessons learned" document, summarizing the knowledge gained from all three large studies.

Since its beginning, the U.S. Government has enacted policies and laws that encourage innovation. The national innovation system is not a formal institution per se, but a set of policies designed to advance science and technology and to commercialize new discoveries. Some examples of the national innovation system from history include the following:

- The Constitution provided for a national patent system.
- Alexander Hamilton promoted government tariffs as a way to protect new industries from competition.
- The Morrill Act of 1862 created land-grant colleges.[2]
- The Federal Government provided free land to build canals and railroads.

Although circumstances and times have changed considerably, the U.S. Government continues to pursue policies that encourage and support innovation.

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[2]In 1862, Congress's first Morrill Act granted each state 30 000 acres of federal land for every senator and representative. Each state was to sell the land and invest the proceeds in an endowment in order to establish at least one college whose mission was—and continues to be today—to incorporate the traditions of the liberal arts and sciences with those of the practical, mechanical, and industrial.

One of the greatest innovations in human history was the ubiquitous deployment of electricity. Thomas Edison understood that large amounts of capital were needed to commercialize new technology, which is why he placed his first electric power station in the Wall Street district of New York in 1882. Edison envisioned a world of distributed power wherein the power was generated at the plant that used the energy or in the home. However, by the 1920s, the electric power industry followed a model that relied upon centralized power generation and distribution across wires. By the 1980s, the efficiency gains from building ever-larger power plants dissipated, and the trend of larger plants and declining prices reached a sudden end.[3] Another technology that generates electric power, the fuel cell, has experienced steady technical advances over the last four or five decades. This study examines the development of the fuel cell through the U.S. national innovation system.

[3]Dunn (2000), p. 6.

II. Overview of Fuel Cells

This section describes the fuel cell, the different types of fuel cells available, and their commercial applications.

A. Description of Fuel Cells

A fuel cell is an electrochemical device that produces electricity silently and without combustion. A fuel cell consists of two electrodes, an anode and a cathode, with an electrolyte sandwiched in between. Figure 1 is a diagram of a typical fuel cell. Oxygen passes over one electrode and hydrogen over the other, generating electricity, water, and heat. Unlike other electrochemical devices such as batteries, a fuel cell only requires a continuous flow of hydrogen and does not run down or require recharging. It will produce energy in the form of electricity and heat as long as fuel is supplied.

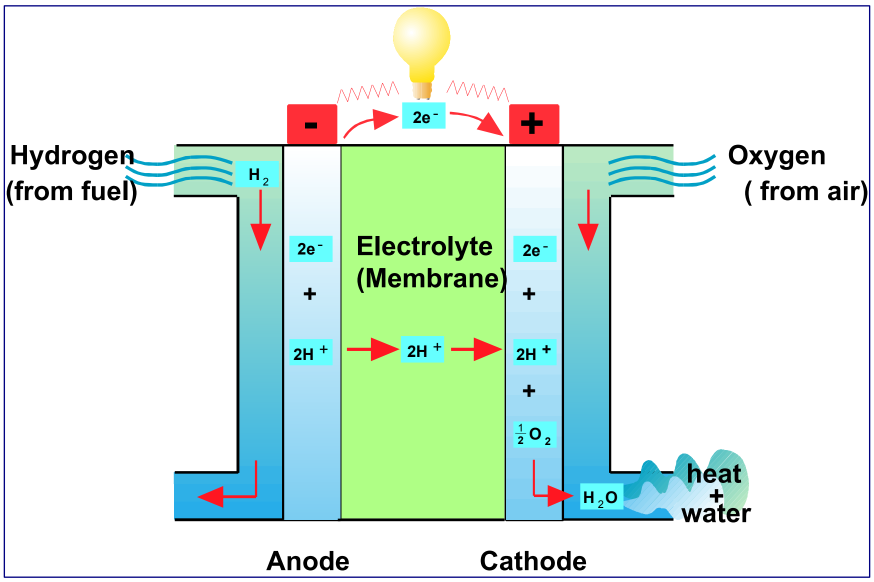

Figure 1. A fuel cell membrane electrode assembly operation. Adapted from Fuel Cell World Council (1999).

Fuel cells thus make usable energy in the form of electricity and heat by combining hydrogen and oxygen from the air in an electrochemical reaction. For stationary applications, hydrogen is typically made on site from natural gas by means of a reformer. Fuel cells are highly energy efficient, extracting two to three times more useful energy from fuels than other generation methods.[1] Since a fuel cell has no

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[1]U.S. DOE (2003), p. 1.

moving parts in its core system, its reliability can be high. Because fuel cells do not involve combustion, the device produces no air pollutants when operating with pure hydrogen as a fuel, and greatly reduces air pollutants when operating with reformed hydrogen.

As shown in figure 2, a fuel cell system consists of three main components that work together: a fuel reformer, a fuel cell stack consisting of many membrane electrode assemblies, with gas and water distribution manifolds and electronic controls and power conversion equipment. The reformer is responsible for producing a hydrogen-rich stream, typically from a fossil fuel source, which is then fed into the stack containing the membrane assembly to be combined with oxygen from the air. This catalytic reactive combination of hydrogen and oxygen produces electricity. Reformers can be designed to convert a number of everyday fuels into hydrogen, including natural gas, propane, coal-bed gas (sour gas), landfill decomposition gas, and gasoline. The reformer converts the hydrogen from the hydrocarbon molecule, generally using the steam or heat captured from the operating fuel cell. Alternatively, hydrogen can be produced in bulk at a separate facility and then transported and stored on site in a compressed gas form or bound in a metal hydride.

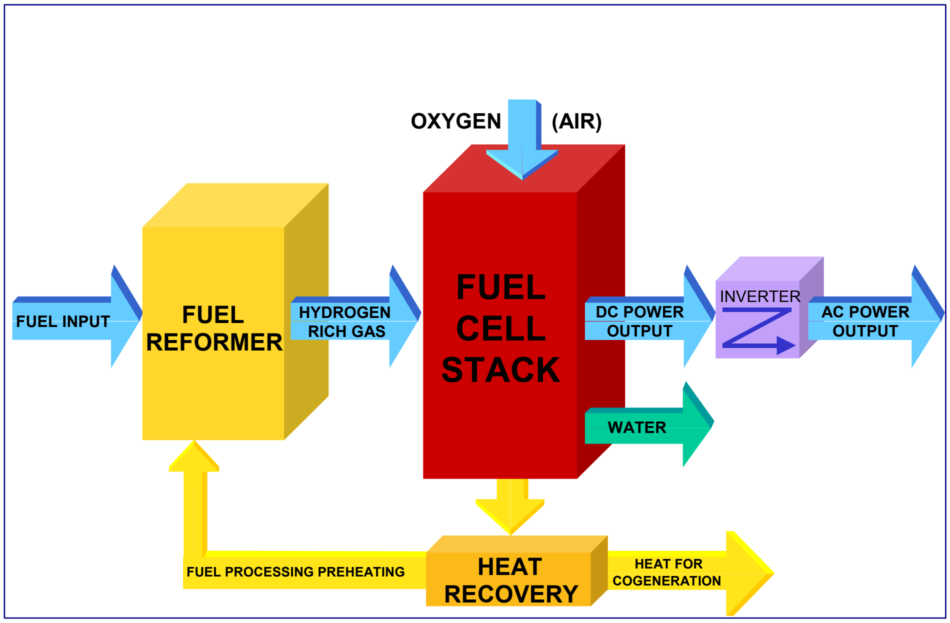

Figure 2. Fuel cell system components and flow diagram. Adapted from Fuel Cell World Council (1999).

The heart of the fuel cell is the membrane electrode assembly, composed of an anode, cathode, electrolyte, and associated channels to deliver hydrogen and oxygen and to remove water and heat. The anode and cathode have to be electrically isolated from each other, but with a membrane in between that allows hydrogen ions catalytically produced at the anode to migrate to the cathode to combine with oxygen from the air, producing water. The electric current flows from one electrode to the other thru the electrical load. The fuel cell system (figure 2) contains a fuel cell stack, so called because it is a stack of the fuel cells shown in figure 1. The size of the stack determines how much power and voltage can be produced by the system. The third part of a fuel cell system consists of the electronic controls and power conversion equipment. Integral to efficient design, electronic controls balance the inflows and outflows of fuel, air, and cooling agents. Power conditioning equipment is also needed to convert the direct current (DC) power produced by fuel cells into the U.S. standard 110 V, 12 A at 60 Hz power source (alternating current—AC) required by most residential and commercial users. This process, represented by the inverter box in figure 2, is approximately 96 % efficient, causing a slight dip in the overall efficiency of the fuel cell.

B. Types of Fuel Cells

Table 1 lists the different types of fuel cells. The primary difference between each is the type of materials used in the fuel cell stack to generate the chemical reaction (electrolyte) needed to make electricity. Not only do fuel cells emit fewer pollutants than other forms of energy generation, they also have the potential to use 50 % less energy than internal combustion engines and 30 % less energy than conventional gas-fired power plants.[2]

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[2]U.S. DOE (2003).

Table 1. Types of Fuel Cells

Type	Electrolyte	Operating temperature (°C)	Commercial applications	Commercialization
Proton Exchange Membrane (PEM)	Solid polymer, proton-conducting electrolyte	50 to 90	Transportation, stationary, portable power	Out of 1 900 small stationary fuel cells deployed as of 2003, 75 % are PEM. Currently, Plug Power has installed over 400 PEM stationary fuel cells for demonstration. Ballard has produced PEM fuel cells for cars and trucks over the last decade.
Direct Methanol	Solid polymer, proton-conducting electrolyte	40 to 100	Portable power, transportation, stationary	Of the 3 500 portable fuel cells deployed so far, about 45 % are fueled with methanol.
Solid Oxide	Yttria-stabilized Zirconia	800 to 1 000	Transportation, stationary, portable power	25 % of the 1 900 small stationary fuel cells deployed as of 2003 are solid oxide.
Phosphoric Acid	Phosphoric acid	190 to 210	Stationary	More than 200 fuel cell systems have been installed worldwide, including at hospitals, hotels, and office buildings.
Molten Carbonate	Potassium carbonate	630 to 650	Stationary	Carbonate fuel cells for stationary applications have been successfully demonstrated in Japan and Italy.

Sources: Breakthrough Technologies Institute, www.fuelcells.org/fctypes.htm; Cropper (2003) et al.

C. Fuel Cell Applications

1. Stationary (Residential Systems 1 kW to 20 kW Units, Target Cost <$1 000 per Kilowatt)

Stationary fuel cells, as their name implies, generate power from a unit that remains in a single fixed location. Stationary fuel cells come in a variety of sizes. The smaller on-site stationary fuel cells (between 1 kW and 10 kW) may power a home, business, or stand-alone remote electric application such as a cell telephone tower. For example, Plug Power's residential fuel cell generates approximately 5 kW of power. Since the technology is modular and easily permits units to be added together, such distributed power units can be used to power hotels, hospitals, or industrial establishments that require hundreds of kilowatts of power. The larger PEM stationary fuel cells generate between 50 MW and 200 MW of power and are more suitable for central power generation. Any large consumer of electricity may use these fuel cells. One advantage of distributed on-site stationary fuel cells is the capability to sell any extra electricity that is generated but not consumed back to the "grid." To compete with electricity coming from the grid, fuel cell power units have to cost less than $1 000 per kilowatt.

2. Transportation (Target Cost <$50 per Kilowatt)

Ballard fuel cells have powered buses in Canada since 1993. All the major automotive manufacturers have fuel cell vehicles under development and in testing right now—General Motors, Ford, Daimler-Chrysler, Honda, Toyota, Hyundai, and Volkswagen. To compete with the internal combustion engine, fuel cell power trains have to be made small, lightweight, and extremely cost effectively at less than $50 per kilowatt—that is, more than 20 times cheaper than stationary units.

Market penetration of fuel cells likely will begin in markets where cost sensitivity is not as great an issue as it is for vehicles. These new markets will include stationary distributed power units for commercial and residential electricity and micro fuel cells. It is widely speculated that the fuel cell vehicle will not be commercialized until 2010 at the earliest.[3]

3. Portable Power (Electric Appliances <1 kW, Target Cost <$3 000 per Kilowatt)

Miniature fuel cells will enable consumers to talk for up to a month continuously on a cellular phone without recharging. Fuel cells will change the telecommuting world, powering laptops and Palm Pilots and other personal digital assistants (PDAs) hours longer than batteries. Many of these miniature fuel cells will run on methanol, an inexpensive alcohol used in windshield wiper fluid. Since consumers pay more than $5 000 per kilowatt for rechargeable batteries with their limited run times, significant markets are expected to develop over the next 10 years, first for micro fuel cells where higher costs per kilowatt can be supported by the market, and then for stationary distributed power as the system cost point comes down to below $1 000 per kilowatt. Stationary and micro-power fuel cells will serve to catalyze the building of a fuel cell manufacturing industry infrastructure that will be important to automotive uses, where far more stringent cost points and robust technology targets need to be met.

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[3]This estimate was provided by one of the companies involved in a partnership with the Advanced Technology Program on a fuel cell project. Section IV.C.2 contains a description of ATP and its role in fuel cell technology development.

III. Drivers of Innovation in the Fuel Cell Industry

The first subsection describes the historical drivers of innovation in the fuel cell industry. Much of this information is drawn from a book about the founding and subsequent development of Ballard Power, a well-known Canadian fuel cell manufacturer.[1] The second subsection focuses on how public policy affects the development of fuel cell technology including federal energy R&D expenditures, public-private partnerships, environmental regulation, deregulation of energy markets, and the facilitation of standards. The third subsection explores the drivers of innovation for a single company, Mechanical Technology Inc. (MTI), and the subsequent creation and spin-off of Plug Power from that company. The sources for this material include interviews with three former and current Plug Power employees who were present at its founding.[2] In addition, Plug Power's 10-K Securities and Exchange Commission filings provided important financial information as well as verification of historical timelines.

As a historical driver of innovation in the fuel cell arena, the role of the government space program cannot be minimized. The space program proved the first viability of fuel cell technology, albeit for limited application and at low power levels. On the other hand, the role of government in advancing the fuel cell from an expensive item with a single mission in outer space to a less expensive item with large-scale commercial applications on earth cannot be tied to a single government program. It is undeniable that in the 1980s fuel cell technology needed government funding to advance. However, it was not a single government program, agency, or company that is responsible for the PEM fuel cell innovation that occurred during this and subsequent periods. Certain programs have made key funding decisions or produced new forms of knowledge at key moments. Often, these funds or knowledge have been fortuitous enough to provide the impetus for private actors to continue their pursuit of the technology. Since large-scale commercialization of fuel cells is yet to come, the development of this technology is still a work in progress.

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[1]Koppel (1999). The material presented by Koppel was supplemented by interviews with Plug Power employees as well as the expertise and experience of one of the authors of this paper, Gerald Ceasar.

[2]These employees are William D. Ernst, current Vice President and Chief Scientist; Glenn Eisman, former Chief Technology Officer; and Wayne Huang, former Director of Chemistry and Materials.

A. Historical Drivers of Innovation

1. Early Fuel Cells

During the first 100 years of fuel cell development, much of the innovation originated from small groups of scientists. In 1839, Sir William Robert Grove, a Welsh judge, inventor, and physicist, created the first fuel cell. He reacted hydrogen and oxygen at catalytic platinum electrodes in the presence of an electrolyte to produce electricity and water. The invention did not produce enough electricity to be useful, however.

In 1889, Ludwig Mond and Charles Langer improved on Grove's design to make the world's first working fuel cell. They are also credited with originating the name "fuel cell." However, they decided their device had little commercial application due to the high cost of platinum.

In 1932, engineer Francis T. Bacon began his vital research into fuel cells. Early cell designers used porous platinum electrodes and sulfuric acid as the electrolyte bath. However, using platinum was expensive, and using sulfuric acid was corrosive. Bacon improved on the expensive platinum catalysts with a hydrogen and oxygen cell using a less corrosive alkaline electrolyte and inexpensive nickel electrodes. Bacon continued his work for three decades and eventually transferred his knowledge to the Pratt and Whitney Division of United Aircraft Corporation in Connecticut. This company subsequently became United Technologies Corporation (UTC), which is today one of the world's largest manufacturers of fuel cells.

2. GE and the PEM Fuel Cell

Tom Grubb of General Electric (GE) explored fuel cell research in the early 1950s, and, in 1954, he developed the first PEM fuel cell. In the late 1950s, government funding began to affect fuel cell development. U.S. Army contracts provided $1.1 million in funding for GE's fledgling PEM fuel cell program; ultimately, this led to work with the newly formed National Aeronautics and Space Administration (NASA) and the development of PEM fuel cells that powered several Gemini missions.[3]

Typical of many technologies in the 1960s, fuel cell development accelerated with its selection as a technology for powering U.S. spacecraft. The GE fuel cells, using large amounts of platinum and pure gases, were very expensive to produce. Cost was not, however, an issue. Although GE spent $8.5 million of its own money over the 1960s and 1970s trying to develop fuel cells using cheaper materials, it ultimately stopped

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[3] Koppel (1999), p. 46.

pursuing that research and instead sold the technology. During this period, the biggest improvement in GE's fuel cells came from the adaptation of a new membrane known as Nafion from the DuPont Corporation.

3. Drivers of Innovation in the 1980s

In the 1970s and early 1980s, most government and industry money in the United States was spent on the development of phosphoric acid and ceramic electrolyte fuel cells. Los Alamos National Laboratory was the only organization conducting PEM fuel cell research, and its funding was very modest.[4] In 1983, a Canadian company called Ballard Research (founded by Geoffrey Ballard; now Ballard Power), of Vancouver, British Columbia, received the first Canadian government grant for PEM fuel cell research. By this time, many of the GE patents related to PEM fuel cells had expired, thereby allowing the technology to be exploited by other companies. The advantage of PEM fuel cells over the other types was their ability to run on low-purity hydrogen. Their biggest disadvantage was their cost, particularly for the Nafion membrane and platinum electro-catalyst.

James Huff led the Los Alamos team that conducted PEM fuel cell research in the 1980s.[5] The Los Alamos group consisted of approximately a dozen people and had an annual budget of close to $1 million. About the same time that Ballard was starting its contract to build a fuel cell for Canada, researchers at Los Alamos and Texas A&M showed that the amount of platinum required for the fuel cell could be reduced by a factor of 10. Their work convinced the people at Ballard that a PEM fuel cell might become economically feasible. For the remainder of the 1980s, Ballard and Los Alamos watched each other's progress; sometimes, breakthroughs by one group would encourage the other to keep pursuing this embryonic technology.

By the mid-1980s, Ballard had produced continuous improvements in its fuel cell. Working with limited resources, the Ballard researchers came to believe that a shoestring budget had helped, not hindered, their early progress. Sometimes, small changes in one area precipitated substantial leaps in performance. For example, the flow field design to channel how hydrogen flows through a stack of cells to produce electricity used GE's old parallel design. When Ballard changed its flow field pattern on the graphite plates that support the membrane electrode assembly, it achieved between two- and fourfold increases in performance in a few weeks' time. Geoffrey Ballard observed this about PEM fuel cell technology: "It has been a very forgiving

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[4]Koppel (1999), p. 49.

[5]Interestingly, James Huff was, in 1959, head of catalysts for the Allis-Chambers farm equipment company, which produced the first tractor to run on a fuel cell.

technology…the system gets simpler, not more complex—which is the other measure of a good technology."[6]

Another hurdle that Ballard needed to cross in the mid-1980s was to reduce the cost of the membrane. A breakthrough occurred when a Ballard scientist obtained a piece of membrane developed by DuPont rival Dow Chemical in 1986. Dow had developed an experimental polymer membrane of its own which had lower resistance than Nafion. The new membrane produced four times as much power as the Nafion membrane.[7] It proved to be a "eureka" moment for the Ballard scientists. When Ballard showed its progress to the Los Alamos scientists, the results convinced the latter that PEM fuel cells might be a potential power source for electric vehicles. This conclusion demonstrates the synergy of the parallel research efforts. It was Los Alamos research that had convinced Ballard that the platinum problem could be solved; now, Ballard research convinced Los Alamos scientists that the membrane could potentially produce sufficient power to operate a motor vehicle.

Thus, the innovative drivers of PEM fuel cell research in the 1980s emerged primarily from two places, Ballard Research in Canada and Los Alamos National Laboratory in New Mexico. Each group worked with relatively few resources. All of Los Alamos's money came from public funding, as did all of Ballard's initial Canadian funding. Ballard eventually received private venture capital money in the late 1980s.[8]

B. Public Policy as a Driver of Innovation

1. Government Support of Energy R&D

The rationale for government support of basic R&D is well known and widely accepted. Recent research also indicates that private companies underfund early-stage technology development R&D.[9] Overall, the amount of federal R&D dollars devoted to energy R&D has steadily declined in real terms over the last 20 years (figure 3).

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[6]Koppel (1999), p. 86.

[7]Ibid, p. 90. Dow Chemical and Ballard eventually collaborated on a joint venture, which is discussed more completely in section IV.

[8]Koppel (1999), pp. 114–15.

[9]Branscomb and Auerswald (2002). Early-stage technology development R&D is characterized as research that is more commercially advanced than basic research, but not yet at the point of product development.

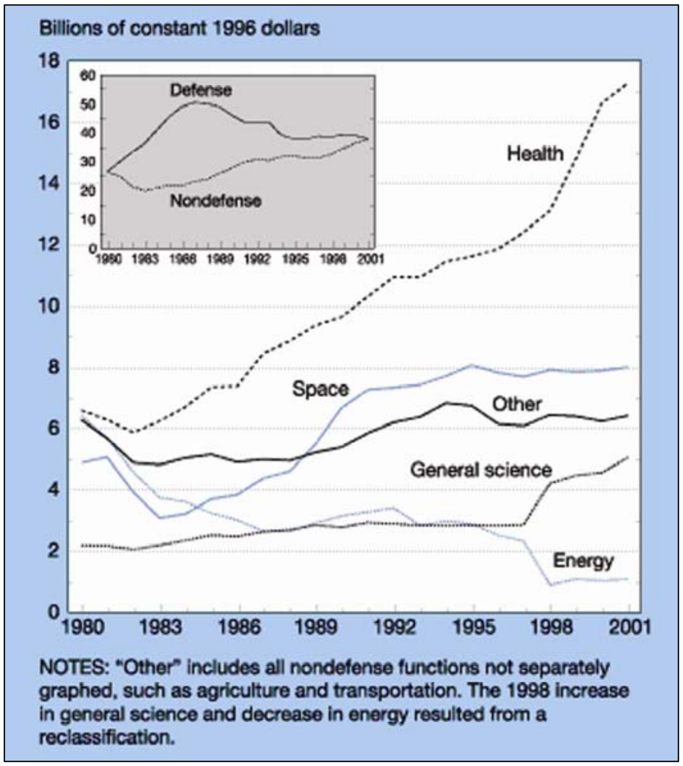

Figure 3. Federal R&D funding by budget function. Source: NSF (2002).

Decaux (2003) finds that funding for R&D in alternative energy technologies is inadequate and inconsistent. She also finds that throughout OECD countries, overall energy R&D is declining and shifting from long-term to near-term projects. This trend has been exacerbated by utility deregulation. Her recommendations for an improved policy environment include providing direct incentives for energy R&D, targeting long-term projects, and clearly mapping the process from the technology drawing board to commercialization.[10] While the Departments of Energy (DOE) and Defense (DOD) provide direct incentives for basic research and for demonstration projects, programs such as the Advanced Technology Program support Decaux's recommendation of providing platforms for moving the technology from the drawing board to commercialization.

2. Public-Private Partnerships and the Advanced Technology Program

The U.S. Department of Commerce oversees ATP through the National Institute of Standards and Technology. ATP shares the cost of high-risk R&D projects with private companies in order to accelerate the development of innovative technologies for broad national benefit.

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[10]Decaux (2003).

ATP partners with companies of all sizes, universities, and nonprofits, encouraging them to take on greater technical challenges with potentially large benefits that extend well beyond the innovators—challenges they could not or would not undertake alone.[11] ATP awards are selected through open, peer-reviewed competitions. The ATP selection process does not discriminate across technologies as long as projects meet the technical and economic criteria. This last point is important, because ATP has not favored one approach over another. It has funded research projects focused on PEM, Direct Methanol, and Solid Oxide fuel cell applications.

ATP awarded its first fuel cell project in 1997. In 1998, ATP supported the development of premium power technologies through a competition focused on that technology area. The portfolio of 13 projects and $47 million in funding that emerged from this solicitation were aimed at accelerating the development of the technologies in step with the changes taking place in the ways electricity is generated and used—distributed electric generation on site and free from the grid, and wireless portable power. Through the 1998 premium power solicitation, ATP became the first government agency to provide significant funding of R&D aimed at development of small, distributed, stationary power technologies such as fuel cells that could be used for generating electricity on site for homes and businesses. This continues to be a dominant theme in its most recent fuel cell awards. In the last two years, ATP has also emerged as a leading enabler of micro fuel cell technology that can meet the ever-increasing functionality and power needs of wireless electronics and, e.g., power a cell phone for a month before recharging. Overall, ATP has funded 25 projects in the fuel cell area. Table 2 shows the total number of awards in fuel cell projects and the total amount of government and industry cost-share funds committed.

Table 2. ATP's 25 Fuel Cell Projects, 1997–2003

Total number of active or completed projects	25
Estimated ATP share of funding	$60 million
Industry cost-share of funding	$54 million
Total funding	$114 million

Source: Gerald Ceasar, ATP.

The following section and table 3 provide a brief description of the knowledge gained from three early fuel cell projects from the ATP Premium Power Focused Program. These projects involved competing approaches to PEM fuel cells by Plug

[11] ATP (2003).

Power, Avista Labs,[12] and H Power–Nuvera. Each company approached the market and its PEM fuel cell design from a different perspective, with the goal of meeting different needs in the short term: Plug Power targeted residential, mass market applications; Avista targeted off-grid, backup power and power quality; and the joint venture between H Power and Nuvera targeted telecommunications.[13] The role ATP plays in the U.S. national innovation system is illustrated by these three projects. Each company is small and has limited funds to conduct longer-term research. ATP allows companies to conduct early-stage research development projects that might not otherwise be funded because the private venture capital market demands relatively short-term payback and may not adequately optimize technology development because of the extended time horizon needed for high-risk research.[14]

Table 3. Fuel Cell Case Study Compilation Chart

	Plug Power	Avista	H Power
Amount of total funding	$9 737 848	$3 224 510	$6 376 772
Award period	2 years (5/99–5/01)	2.5 years (11/98–4/01)	2 years (1/99–1/01)
Research focus	High temperature membranes	Modular, self-hydrating fuel cell cartridges	Simplified one-piece membrane assembly and reformer integration
Employee growth (1998–2003)	22 to 339	7 to 45	50 to 135
Target market	3 kW to 7 kW residential, on-grid applications	Uninterrupted power source and remote, off-grid applications	Backup and primary telecom power and residential units
Initial public offering (IPO) status	IPO completed in November 1999 $58 million stock offering completed 10/13/03	Avista Labs is now a privately funded Washington corporation with several venture capital funds as investors	Plug Power buys company on 5/15/03
Strategic partners	DTI, General Electric Power Systems, Vaillant, Advanced Energy Systems, Engelhard, SRI, Polyfuel, Celanese	UOP, Black & Veatch, 3M, Airgas	Nuvera, formerly Epyx, is focused on distributed and vehicle uses of fuel cell power systems

a. Plug Power

Plug Power of Latham, New York, was founded in 1997, and in six years has grown from 22 to over 300 employees. Plug Power's early investors formed the company as

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[12] Avista Labs is an independent company, of which Avista Corp. is a minority shareholder.

[13] Plug Power prospectus and company interviews, spring 2000.

[14] David Morgenthaler, cited in Branscombe, Morse, and Roberts (2000), p. 107.

a joint venture between Detroit Edison (DTE) Energy Company, Michigan's largest electric utility, and Mechanical Technology Inc., an early developer of fuel cell technologies. Now a stand-alone, publicly traded company, Plug Power added General Electric Company and Sempra Energy, a subsidiary of Southern California Gas Company, as major investors in 2000.[15] Plug Power has built and deployed over 400 PEM fuel cell systems to date, including GenSys prime power and GenCore backup power 5 kW units.

The ATP-funded $9.7 million project allowed Plug Power and its partners (Polyfuel/SRI and Celanese) to attack the problem of carbon monoxide poisoning of the catalyst head-on by pursuing higher temperature polymer membranes, as well as by designing the fuel cell stack for higher operating temperatures.[16] This is desirable because increased temperatures reduce the poisoning effect of carbon monoxide in the fuel cell systems. PEM fuel cells produce their fuel—hydrogen—by reforming common fuels such as natural gas and propane. However, this reformate fuel stream is contaminated with trace levels of carbon monoxide because the decomposition of hydrocarbons from the original fossil fuels is not 100 % complete. Fuel cells operated at lower temperatures with the current generation of polymer (i.e., Nafion) membranes are less robust, with as little as 50 μL/L of carbon monoxide shutting the system down. With the Celanese high-temperature, non-fluoropolymer membrane, which is chemically different from Nafion, Plug Power has succeeded in operating a PEM-based fuel cell system at temperatures above 150 °C, demonstrating 20 000 μL/L carbon monoxide tolerance over a period of more than 5 000 h. This breakthrough should result in more reliable operation with simpler reformers and would also allow for more efficient use of the leftover heat and reduce the complexity and size of the overall system.

b. Avista

Avista Labs was created in 1996 as a full subsidiary of Avista Corporation, formerly Washington Water Power of Spokane, Washington, to commercialize new energy technologies. Making quick progress on its new responsibility, Avista Labs unveiled its fuel cell generator prototype at the International Fuel Cell Seminar in 1998. By March 2000, Avista was issued a comprehensive patent covering 162 claims for its PEM fuel cell power system. The summer of 2000 brought the first alpha test units to the field. Avista's rapid development speaks to the need for innovation and timely financial support. Avista currently has fuel cells installed in over 80 locations in the United States and abroad, and counts among its customers major

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[15] PRNewswire, Plug Power press release, March 16, 2000.

[16] Interview with Wayne Huang, Plug Power, April 2000.

telecommunications providers, uninterruptible power system providers, government communication sites, utilities, and railroad suppliers.

ATP funding came at a crucial time for Avista Labs. In 1997, the Fortune 500 parent company, originally Washington Water and Power (renamed Avista Corporation), was in the midst of a transition from the status quo guard of regulated power markets to the new deregulated markets. In preparation for deregulated power markets, Avista was involved in several research projects aimed at diversifying its value-added business units, including fuel cells. The new unit tasked with fuel cell development was Avista Labs, which started with only seven scientists and engineers, and a concentration on the design of modular PEM fuel cells. In 1998, Avista applied for and won an ATP award in the Premium Power Focused Program. The 2.5-year project began in November 1998 and allowed Avista Labs to pursue its unique technical approach toward the development of a commercially viable PEM fuel cell at a faster pace and with more flexibility than it otherwise would have been afforded. Avista Labs president Kim Zentz commented that "ATP allowed us to bring prototypes to decision makers much more quickly. Without ATP it would also have been much harder to prove the modular design concept."

Investors, including internal decision makers, require a "proof-of-concept" for new technologies before they are willing to fund the more costly product development phase. ATP funding helped Avista Labs prototype design ideas rapidly and speed up the cycle time of developing a new modular approach to PEM fuel cells. As a result of the more timely achievement of a proof-of-concept of modular fuel cells, the introduction of this technology to the residential market was accelerated by three years. ATP support filled the gap left by internal funding constraints and a lack of outside equity sources.[17]

Avista Labs engineers opted to take a different approach to PEM fuel cells using a modular, cartridge concept instead of a stack of cells.[18] Cartridges can be replaced

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[17]Interview with Kim Zentz, President, Avista Labs, April 11, 2000.

[18]In fuel cell architecture, there are two basic configurations for holding the membranes: the stack and the cartridge. In both designs, hydrogen must flow to one side of the membrane and air to the other, and multiple membranes are required. In stacks, the membranes are stacked together to achieve a particular output and power density. The membranes are usually separated by a complex set of precisely machined plates, made with minute channels that direct hydrogen, air, humidification, and cooling fluids to the membranes. This requires compressors, fans, and other balance-of-plant equipment. In the event of a failure of any one of the stack seals, equipment components, or membranes, the entire stack ceases to operate.

In the Avista Labs cartridge system, the PEM membranes are housed within an inexpensive plastic cartridge that is air-cooled and self-humidifying. There are no pumps or compressors to fail. Hydrogen enters one side of the cartridge; air the other. The only moving part without interrupting generation and can use the water produced in conjunction with fan-forced air to promote cooling and self-hydration. These features simplify system performance by reducing balance-of-plant to a minimum. The advanced cartridges incorporate embedded control functions to protect the membrane electrode assemblies from conditions leading to loss of life or failure. A simple, retractable ballpoint pen was the inspiration for the hydrogen valves, which where crucial to making the cartridge design workable. Using injection-molded, extremely cheap parts for the valves, Avista engineers developed cartridges that click into place and safely keep the volatile hydrogen fuel within the cartridge. The alpha test units incorporate these features and utilize leftover water from the reactions in the fuel cell to keep the membrane wet. This self-hydrating technology increases reliability, reduces maintenance, and is ultimately more consumer-friendly because cartridges last longer. Estimated to last for five years or more, the individual cartridges are easy to change and require no more skill than replacing a book on a bookshelf.

Avista Labs is the only fuel cell developer that uses hot-swappable, modular power cartridge architecture. This patented technology offers high reliability. In part this is because it requires less balance-of-plant (Avista fuel cells have only one moving part, a high-efficiency fan) and also because any service needs can be accomplished quickly and easily by simply swapping out one cartridge for another, while the unit continues to create reliable power.

c. H Power and Nuvera

The H Power Company of Belleville, New Jersey, was founded in 1989 with the goal of commercializing PEM fuel cells. In 2000, the company employed approximately 70 people at its Belleville R&D and manufacturing facilities, and 15 in its Clifton, New Jersey, administrative offices; it also maintained a project office at McClellan Air Force Base in Sacramento. H Power has a subsidiary company, H Power Enterprises of Canada, in Ville St. Laurent, Quebec, which employs an additional 50 people. On March 25, 2003, Plug Power purchased H Power in a stock-for-stock exchange.

H Power was attempting to commercialize sub-kilowatt fuel cell systems for a variety of telecommunications and backup power applications. Typically, these products require a few watts to 1 kW of power. Sub-kilowatt systems are also suitable for many mobile applications involving light utility vehicles and auxiliary power units used in conjunction with other power-generating systems, e.g., on-board battery chargers in electric vehicles.

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is a high-efficiency fan. If a cartridge fails, the system shunts around it and continues to operate as before. The system automatically bypasses the cartridge with the problem and continues to provide power to the load. Cartridge replacement takes only a few seconds and requires no tools.

The core innovation that H Power developed for the ATP project is a one-piece membrane electrode assembly which eases assembly and lowers cost. A new bipolar plate design improves the distribution of hydrogen fuel to the membrane and incorporates channels for cooling and hydrating the cell. The metallic plate design is projected to further reduce manufacturing costs and increase the reliability of the fuel cell stack. Work continues to improve the electrical performance and the corrosion resistance of the bipolar plates.

H Power received two patents for work done during the ATP-sponsored project. These advances have allowed H Power to move more quickly into the alpha test phase for larger PEM fuel cell units, thereby reducing the time to market. H Power had success with smaller output units as demonstrated by a New Jersey Department of Transportation contract to replace solar-powered variable message highway signs with fuel cell power systems. The systems provide backup power for the state's fleet of variable-message road signs. More than 60 of the systems have been deployed and operate daily.

Nuvera Fuel Cells was formed in April 2000 when ATP-funded Epyx Corporation (a former subsidiary of Arthur D. Little, Inc.) merged with Italy's De Nora Fuel Cells, SpA, and Amerada Hess Corporation, a leading U.S. East Coast energy company. Nuvera combines Epyx's reformer process to produce hydrogen feed for fuel cells with De Nora's leadership in electrochemical, membrane, and fuel cell technology. A 5 kW fuel cell power system running on propane and specifically tailored to the needs of the telecommunications industry was designed and built. In March 2001, this first-of-a-kind unit was delivered to Verizon to test for powering a remote cell telephone tower. Such systems could be used in the future to provide primary or backup power for cell towers and telecom switch nodes that could benefit from on-site, reliable generation of DC electricity.

3. Environmental Regulations

Although the expected service life requirements and reformers in automotive and stationary residential applications are different, the PEM fuel cells at the heart of the systems are quite similar. Together, automotive and stationary applications of fuel cells have the potential to reduce U.S. carbon dioxide emissions by two-thirds.[19] When powered directly by hydrogen, fuel cells produce only water vapor as a byproduct. Even when using fossil fuels, PEM fuel cells result, because of their greater energy conversion efficiency, in reduced organic and nitrous oxide emissions that cause air pollution, which is a leading cause of lung-related diseases and ozone

[19] Lovins and Williams (1999).

depletion. Therefore, environmental regulations targeted at both automobiles and electricity generators have significant positive impacts on firms' incentives to invest in fuel cell R&D. In fact, California's zero emissions law has led virtually all car companies, even those initially skeptical of fuel cells, to consider PEM fuel cells.[20] Notwithstanding these insights, as discussed above, there remains under-investment in energy-related R&D due to a high level of technical and business risk, as well as appropriability issues and shortened investor time horizons.[21]

Although the U.S. administration's position on the reduction in greenhouse gases is uncertain, environmental regulatory policies may have relatively little direct impact on private investment in traditional electric utility production. Using event study analysis to examine 22 milestones, J. David Diltz found that events leading to the passage of the Clean Air Act Amendments in 1990 did not have a significant negative impact on investors' perceptions of electric utilities.[22] Combined, these factors suggest that environmental regulation has a positive impact on the demand for funds for investment and does not curtail the supply of investor funds. This is an important finding, as an increase in demand for funds accompanied by a decrease in supply could drive up investment costs and potentially lead to lower overall levels of investment.

An area where the utility industry has been responsive is air quality regulation, in that almost all of the new-generation capacity built in the 1990s uses large gas turbines running on cleaner natural gas. The adoption of these large gas turbines by utilities was aided by the fact that the technology matured and the costs dropped around the same time that the regulations became effective. It is a matter of conjecture as to whether utilities might have been more willing to resist the regulations had a relatively inexpensive substitute not been available. This point notwithstanding, environmental regulations mandating a certain level of compliance are always subject to political pressures unless reasonable substitutes are available and the costs are not prohibitive. In terms of fuel cells, if, several years from now, there is increasing political pressure to reduce greenhouse gases and the price of delivering emission-free fuel cells is still substantially more than current emission-emitting technologies, how much will the body politic be willing to subsidize fuel cells, or other emission-reducing technologies, in order to reduce emissions?

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[20] *The Economist* (2001).

[21] Appropriability refers to the ability of private firms to appropriate profits from their innovations.

[22] Diltz (2002).

An unintended consequence of the switch to natural gas turbines is that shortages in natural gas are occurring. The North American gas supply is now declining.[23] This circumstance is troublesome, because many of the fuel cells being developed—including Plug Power's—reform their hydrogen from natural gas.

Although environmental policy has, on balance, spurred investment in fuel cells, fuel cell sales are unlikely to be similarly aided. Any environmental benefits offered by PEM fuel cells are a public good for which consumers are reluctant to pay an extra premium. Scott Samuelsen of the University of California–Irvine and director of the National Fuel Cell Research Center confirms the difficulty of using the environmental benefits of fuel cells as selling points. "That [fuel cells] have no plumes of smoke, no turning parts, no 700-foot-high dams, and no noise to upset people is bound to go unnoticed."[24]

4. Utility Deregulation

The confluence of technological development and changes in economists' thinking about so-called "natural monopolies" has led to a reevaluation of electricity regulation over the past 30 years.[25] Of all the federal environmental and regulatory changes, deregulation of electric and natural gas markets has had the most significant impact on the economic viability of stationary PEM fuel cells.[26] Such efforts are likely to have wide-ranging effects including a lowering of the nation's core rate of inflation. Although such regulatory changes enable small businesses to compete against the large power companies, they have at the same time increased the degree of competition with alternative fuel technologies and thereby limit the total overall R&D dollars in the energy sectors because companies believe they cannot appropriate their full investment.

The two most significant pieces of federal legislation in this regard are the Public Utilities Regulatory Policies Act of 1978 and the Energy Policy Act of 1992. The former promoted the use of cogeneration in independent power and industrial projects by exempting generators from federal and state regulatory control. This regulatory change was made in response to technological changes that allowed smaller scale generators to be combined with other applications that use the waste heat and energy from the generation process. The latter act promoted sweeping

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[23]www.simmonsco-intl.com/files/IP%20Week%20-%20London.pdf.

[24]*The Economist* (2002).

[25]Schiller (2001).

[26]Berry (2000).

changes in the generation and transmission of electricity. When coupled with Federal Energy Regulatory Commission orders enacted in response to this piece of legislation, the number of independent generators exempt from regulation was expanded, all interstate transmission lines were made available at the same cost for all power generators, and all generators were required to make information available regarding their generating capacity. Although federal legislation affected interstate electric markets, individual state deregulation efforts promoted consumer choice and competition. Over half the states in the country have enacted retail competition plans to emulate those pioneered by Massachusetts, Rhode Island, and California.[27]

One impact of this deregulation is that utilities are no longer guaranteed to recover their fixed investment costs, which has prompted utilities to become more risk-averse and choose smaller investments. For example, before deregulation, the typical utility owned the power plants that generated the electricity for the customers in their defined service area. When utilities prepared long-range R&D budgets, they knew that if they wanted to reduce the costs of power, they needed to improve the productivity at their own power plants. Now that utilities can purchase cheaper power on the open market, the incentive to innovate their own power infrastructure is diminished. Decaux finds that this has contributed to the shift to short-term R&D projects.[28] Deregulation may also have had a negative impact on utilities' investments in emission-reducing technologies as well. Roberts reports that by 1997 utilities had invested $894 million in energy-efficiency programs as compared to 1992 projections of $2.7 billion.[29]

5. Development of Standards

In order to assess the total costs of fuel cells relative to current utility costs, consumers need a better understanding of the energy efficiency and potential savings of small residential fuel cell systems across the range of environmental and seasonal conditions. To help meet this goal, Plug Power is participating in a NIST testing program outside of the ATP project to investigate the energy content of various fuel sources, the electrical power and electrical energy generated by the fuel cell, and the thermal output of the fuel cell under a variety of different load-demand conditions. This program will provide purchasers with a realistic estimate of annual

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[27]See Joskow 2003 and 2001 for a discussion of the outcome of the California electricity crisis.

[28]Decaux (2003).

[29]Roberts (1999).

electrical energy output, thermal energy output, and fuel usage.[30] In addition to electricity generation, the heat generated by this 5 kW unit will be captured to provide estimates of the space and hot water heating requirements that can be met by this system. These efforts continue NIST's history of collaborating with DOE and industry to develop metrology and standards that define the energy efficiency of heat pumps, water heaters, gas furnaces, and other household appliances.

A remaining regulatory hurdle with a major impact on the commercialization prospects of grid-connected stationary fuel cells is "net metering." Typically in residential electricity generation, utilities meter the amount of electricity supplied to the grid separately from that pulled from the grid. Federal legislation requires only that utilities purchase electricity from independent generators at an "avoided cost" basis, which facilitates utilities' use of separate prices for electricity flowing from house to grid and for electricity flowing from grid to house. In essence, owners of stationary fuel cells sell any excess power to the grid at wholesale prices. Yet should they need to purchase supplemental power from the grid, they must pay retail prices.

C. Plug Power

1. Drivers of Innovation for Fuel Cells at MTI and the Founding of Plug Power

In 1961, two entrepreneurial engineers founded Mechanical Technology Inc. For the next three decades, this small company pursued government research contracts in the area of precision instruments and energy-related research such as flywheels. In the late 1980s, the company was carrying out research on the Automotive Stirling engine for DOE in a project managed by NASA.[31] As this contract neared its conclusion, MTI tried to find new areas of system- and energy-related work to pursue, particularly since this program had employed many people. Because MTI's Stirling engine used hydrogen as a working gas and MTI was involved in non air-breathing underwater propulsion studies, PEM fuel cells were seen as a promising next phase of research that utilized MTI's core system expertise.

In 1992, MTI received a $160 000 grant from the New York State Energy Research Development Authority (NYSERDA) to deliver a PEM fuel cell for hybrid electric

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[30]Interview with Mark W. Davis and A. Hunter Fanney, Heat Transfer and Alternative Energy Systems Group, NIST.

[31]The Stirling is an external combustion engine and, in that respect, is similar to a steam engine. Fuel is not critical; it can run on anything that produces heat. It was invented in 1816 by Dr. Robert Stirling, a Scottish minister, and for many years competed with the steam engine. The program was the result of federal concerns over energy availability.

vehicles. William D. Ernst, current vice president and chief scientist at Plug Power, developed and directed the project. Dr. Ernst originally led the team working on the Stirling engine projects and flywheel research. While MTI had significant systems and mechanical engineering skills, it lacked critical electrochemical fuel cell expertise. To remedy this, MTI, during the 1992–94 time frame, attempted to purchase a fuel cell stack from Texas A&M, H Power, and other places, but could not find a stack that was large enough for its purposes and that would perform to its specifications. Ballard would sell them a stack, but the price was prohibitive. At this point, Dr. Ernst decided to have MTI develop its own fuel cell stack and, in early 1995, hired Wayne Huang. Dr. Huang brought to MTI critical expertise in electrochemistry and fuel cells. Previously, he had worked at the Los Alamos National Laboratory on fuel cell technology, where he learned the decal printing method from its inventor, Mahlon Wilson. Eventually, MTI licensed the decal printing technology from Los Alamos and started to build its own fuel cell stack.

In 1995, the project work for NYSERDA led to a 30-month, $2 million contract with DOE to develop and build a stand-alone, proof-of-concept 50 kW PEM fuel cell system. Power of this magnitude would be comparable to a small gasoline internal combustion engine and would be an important first step in demonstrating that PEM fuel cell stacks could produce sufficient power for electric vehicle applications. This project was followed by several smaller demonstration projects with NYSERDA to continue work on fuel cells. As a result of these programs, Dr. Ernst received the Partnership for a New Generation of Vehicles award as part of a government-industry team for demonstrating the first fuel cell system that was run on reformed gasoline. Other pertinent awardees were from Epyx (Nuvera), Los Alamos National Laboratory, and Argonne National Laboratory.

Other developments were concurrently unfolding in the energy industry to drive innovation in fuel cells. In particular, deregulation of energy markets was about to hit the electric utility industry. Deregulation meant that energy markets that were previously restricted to one regulated monopolistic supplier would now be opened up to competition. However, only markets for power generation were opened up to competition; power distribution was still considered a natural monopoly in a centrally distributed world. In theory, utility companies could no longer pass on bad business decisions to customers for reimbursement but instead would be held accountable for these decisions due to increased competition. In practice, problems emerged in certain deregulated markets, especially in California.[32] During the

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[32]According to a Federal Energy Regulatory Commission investigation of Western energy markets, the staff "concluded that an underlying supply-demand imbalance and flawed market design combined to make a fertile environment for market manipulation" (FERC 2003).

summer of 2001, the prices paid by utilities in that state for power surged in the newly deregulated spot power generation market, while those same utilities were prevented from raising prices enough to cover costs in the still-regulated power distribution market. Once revenue shortfalls threatened the utilities' ability to borrow, the California governor intervened with a rescue plan—thereby demonstrating that electric power may be too much of a public good to ever be traded in a completely private market with little government intervention.

Another effect of deregulation was to motivate companies to think of alternative business models. In particular, deregulation allowed utilities to sell power outside of their traditional service areas. Certain executives at Detroit Edison, a public utility, saw deregulation as an opportunity to expand business opportunities and convinced their board to pursue alternative energy strategies. One executive in particular, Gary Mittleman, saw MTI and its fuel cell capabilities as an attractive new business venture. This led to DTE's investing in MTI and to the formation of Plug Power, LLC, with Gary Mittleman as its first CEO.

The new management team embarked on a serious reorganization of MTI. In 1997, Plug Power was formed as a separate limited liability joint venture spin-off company owned by DTE Energy and MTI. Plug Power's mission was to design, develop, and manufacture on-site electric power generation systems utilizing PEM fuel cells for stationary applications.[33] Later, in 2000, MTI further diversified its fuel cell technology, creating another company called MTI MicroFuel Cells to develop small fuel cells for the portable electronics market, e.g., laptops, cell phones, and PDAs.

2. Public-Private Partnerships and Their Impact on Accelerating Plug Power's Fuel Cell Development

Project managers at Plug Power understood the funding hurdle in acquiring the breadth and depth of R&D investment commitments needed to bring PEM fuel cells to market. The enormous expense, high technological risks, and long time horizons posed huge challenges for Plug Power. Federal funding opportunities that recognize that the development of new, high-payoff technologies is a risky proposition were particularly valuable. Through two cooperative agreements with ATP, Plug Power has been able to pursue next-generation PEM fuel cell technology and projects carrying more technical risk than private investors were willing to absorb. Dr. Wayne Huang, senior research engineer at Plug Power, commented that the research undertaken as part of the ATP project would have been set back by a "number of years" were it not for the awards. Private investors demanded that Plug Power spend a large share of its capital on the development of a manufacturing line for

[33]Plug Power, Inc. (2003a).

more proven, first-generation technology and on making incremental improvements on initial products. The amounts the government expends on R&D projects like this are 20 to 50 times smaller than the amounts needed to establish even the initial manufacturing infrastructure.

Under its first ATP award, Plug Power developed and demonstrated a PEM fuel cell stack running at above 150 °C using a novel high-temperature membrane. The advances in membrane electrode assemblies and fuel cell stacks solved the carbon monoxide poisoning problem, allowing for operation with 200 times higher than today's carbon monoxide tolerances. This singular breakthrough will enable Plug Power to produce simplified PEM fuel cell systems. Such systems incorporate simplified reformers, simplified thermal and water management, and simplified systems integration. Through a new ATP award, Plug Power is developing a simpler fuel processor to work with the high-temperature stack developed under the first cooperative agreement. Since the processor is a separate component from the fuel cell stack, this ATP award is a completely separate project from the high-temperature membrane project.

Through its acquisition of H Power, Plug Power has acquired the research outputs of a third ATP-funded research project. A small company focused on small PEM fuel cells for remote telecommunications applications, H Power used ATP support to engineer an integrated, simplified membrane electrode assembly for PEM-type stacks running on propane. Subsequent to this acquisition, Plug Power has introduced one of the first fuel cell products for the telecommunications market. The GenCoreTM5T is designed to provide extended-run backup power specifically for the telecommunications industry in the demanding outside plant market. This application is a direct hydrogen fuel cell enabling potential future products in the cable broadband and uninterruptible power supply industries.[34] Plug Power has additional ongoing work with DOD, NIST, NYSERDA, the Texas Railroad Commission, and other government agencies. In addition to performance of research, the outputs of these projects include consumer testing and development of standards and validation.

[34]Plug Power, Inc. (2003b).

IV. Knowledge Creation and the Use of Intellectual Property in the Fuel Cell Industry

This section focuses on knowledge creation within the fuel cell industry. The first two subsections briefly discuss the historical roles of government and universities, respectively, in fuel cell knowledge creation. The third subsection focuses on current government programs designed to create knowledge in the fuel cell arena. The section concludes with a discussion of the dynamics of the fuel cell innovation arena, presenting economic concepts of knowledge creation and applying these to the current intellectual property environment within the fuel cell industry.

A. Historical Government Support for Knowledge Creation in PEM Fuel Cells

Since the early 1960s, government programs have significantly influenced the development of fuel cells. A notable initiative was a series of contracts to purchase working fuel cells for the U.S. space program. Since operating performance was important but cost was not, the recipient companies were able to develop technology without proving its commercial feasibility for terrestrial markets. Ballard Power started with a Canadian government contract to build a PEM fuel cell. Another example of government funding is the DOE-sponsored effort, which started in the 1960s and continues to the present day, to develop large Molten Carbonate and Solid Oxide chemical plant-type systems for central utility electricity generation.[1]

Throughout the 1980s, much of the U.S. Government research money on small fuel cells focused on the Phosphoric Acid fuel cell rather than the PEM fuel cell. However, Los Alamos and General Motors formed a major engineering development partnership in 1988 and worked together for nearly eight years to perfect a PEM fuel cell and improve fuel processing.[2] Through the partnership, which also involved Dow Chemical and Ballard Power, Los Alamos developed diagnostic equipment for single fuel cells, stacks, and other components. These high-quality measurements made possible further developments in PEM fuel cells, including operation of a 10 kW demonstrator. Delphi Corp. currently is assembling a 150-person team to advance the General Motors–Los Alamos fuel cell concept. Much of the diagnostic

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[1]DOE was established in the 1970s under the Carter administration, but the programs began in agencies that eventually became part of DOE.

[2]Los Alamos National Laboratory (2002).

equipment developed by Los Alamos to test fuel cell performance is employed by Plug Power and other firms to test their fuel cells.[3]

Los Alamos created another piece of new knowledge through its discovery of how to operate PEM fuel cells on impure hydrogen fuel. Traces of carbon monoxide in hydrogen fuel, which are generated in processing liquid fuels such as gasoline or methanol, reduce fuel cell performance. By forcing low levels of air into the fuel feed stream, Los Alamos researchers removed the carbon monoxide catalytically within the cell, allowing fuel cells to run as well on contaminated hydrogen as on highly pure hydrogen. Though this development is far from a perfect solution, it did help to open the way for the use of PEM fuel cells with realistic hydrogen fuel feed streams derived from the processing of liquid fuels.

B. University Support of Fuel Cell Research

Historically, universities have conducted significant amounts of R&D for certain scientific disciplines related to the area of fuel cells. Table 4 shows the amount of historical R&D spending by universities in 1980, 1990, and 1999 in disciplines related to fuel cell research, including electrochemical, mechanical, polymer, ceramic, fluid flow and controls engineering, physics, chemistry, and materials science.

Table 4. Total University R&D Spending in Nine Scientific Disciplines Related to Fuel Cell Research for the United States and Selected States

	1980		1990		1999	
State	Dollars (millions)	Rank	Dollars (millions)	Rank	Dollars (millions)	Rank
Total U.S.	1 003	–	3 196	–	4 668	–
California	138	1	384	1	652	1
Georgia	39	7	142	7	201	8
Illinois	43	6	126	8	203	7
Maryland	84	4	271	3	315	2
Massachusetts	117	2	274	2	305	3
Michigan	28	11	96	10	171	10
New York	100	3	252	4	297	4
Ohio	34	9	122	9	178	9
Pennsylvania	39	8	154	6	254	6
Texas	50	5	183	5	290	5

Source: NSF (2003).

[3]The parameters that affect fuel cell performance include fuel, electrical load, thermal load, and environmental conditions. The types of tests used to measure the effects of the parameters on fuel cell performance include steady state, thermal load, and transient and start-up test (Davis 2002).

It is difficult to present reliable conclusions about the relative quality of various university research efforts. Based on the anecdotal evidence collected for this study, Case Western Reserve, Texas A&M, Ohio State, Rensselaer Polytechnic Institute, and California–Irvine are some of the academic institutions that conduct significant amounts of fuel cell research.

C. Government Support for Knowledge Creation in Fuel Cells (Outside of the Advanced Technology Program)

In his 2003 State of the Union address, President Bush called for a significant increase in research for the hydrogen economy and fuel cells. Specifically, President Bush announced a $1.2 billion hydrogen fuel initiative for developing the technology for commercially viable hydrogen-powered fuel cells to power cars, trucks, homes, and businesses. His hydrogen fuel initiative includes $720 million in new funding over the next five years to develop the technologies and infrastructure to produce, store, and distribute hydrogen. Combined with the FreedomCAR (Cooperative Automotive Research) initiative, President Bush proposed a total of $1.7 billion over the next five years to develop hydrogen-powered fuel cells, hydrogen infrastructure, and advanced automotive technologies.

1. Department of Energy

Several government agencies currently support fuel cell research and the generation of new knowledge. The largest supporter in terms of research dollars is the Department of Energy. DOE supports fuel cell research through two separate departments.[4] The Office of Fossil Energy supports the development of high-temperature ceramic-based fuel cell systems, which operate on natural gas. This program primarily supports the development of Solid Oxide and Molten Carbonate fuel cells. Much of that work is done through the Solid State Energy Conversion Alliance, a partnership between DOE, the national laboratories, and industry.

The other part of DOE performing fuel cell research is the Office of Energy Efficiency and Renewable Energy. This office supports research in the PEM fuel cell area. It also manages the FreedomCAR project, which is a partnership between DOE and a consortium of U.S. automakers. FreedomCAR supports the development of PEM fuel cell technology for automotive applications.

Table 5 shows the distribution of research dollars for total hydrogen research, which is divided between fuel cell applications and infrastructure.

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[4]U.S. DOE (2003), p. 46.

Table 5. Total DOE R&D Funding for Hydrogen, Fuel Cell, and Infrastructure Development (thousands of dollars)

Application	FY 2002	FY 2003	FY 2004 (request)
Fuel cell applications, total	46 482	55 300	77 100
Transportation systems	7 466	6 400	7 600
Distributed energy systems	5 500	7 500	7 500
Fuel cell processor	20 921	24 700	19 000
Stack component R&D	12 595	14 900	28 000
Technology validation	–	1 800	15 000
Infrastructure applications, total	29 092	42 081	87 982
Production and delivery	11 148	11 760	23 000
Storage	6 125	11 325	30 000
Infrastructure validation	5 696	10 000	13 160
Safety	4 486	4 786	16 000
Education	1 437	2 000	5 822
Total	**75 574**	**97 381**	**165 082**

Source: DOE Hydrogen, Fuel Cells and Infrastructure Technologies Program.

Based on the requests for funding in FY 2004, the Bush administration supports significant investment in the hydrogen economy. The total amount of requested funding for FY 2004 exceeds the 2003 figure by 70 %.[5] Hydrogen production and delivery and hydrogen storage are slated for 100 % and 200 % increases in funding, respectively. On the fuel cell application side, stack component R&D and technology validation are the gainers. A key item to conclude from table 5 is that the Bush administration has increased support for the building blocks of the fuel cell technology such as the stack and technology validation as well as the supporting hydrogen infrastructure while freezing the amounts that support the actual building of fuel cells.

2. National Institute of Standards and Technology

NIST, which develops standards and measurements for a broad range of products and technologies, contributes to the creation of knowledge in the fuel cell industry through its Residential Fuel Cell Test Facility. NIST built this facility to accomplish three goals: (1) accelerate the widespread commercialization of fuel cells in building applications; (2) provide consumers with accurate, easy-to-understand information on the financial costs and benefits of fuel cells; and (3) provide feedback to fuel cell manufacturers on the overall performance of fuel cell systems under varying environmental, thermal, and electrical load conditions.

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[5]Ultimately, Congress granted $158 million for FY 2004 and the president has requested $190 million, which would represent a doubling of funds in only two years.

NIST plays a key role in the development and commercialization of new technology. Not only must new standards be developed for new technologies but often the equipment and tests needed to measure the standards must be developed as well. For fuel cells, NIST will develop a methodology for determining the seasonal performance of residential and small commercial fuel cell systems. This methodology will aid the purchaser of a residential fuel cell in determining the economic impact of such a system. NIST will supplement the efforts of many consensus standards, such as those of the American Society of Mechanical Engineers (ASME) and the American National Standards Institute (ANSI), with a test procedure and rating methodology that accounts for any change in performance as a function of environmental conditions, electrical load, and thermal load. The fuel cell used by NIST in its test facility was purchased from Plug Power. Section V.B.5 provides a more specific description of Plug Power's role in developing fuel cell standards.

3. Department of Defense

The U.S. Department of Defense supports fuel cell demonstration and development in two separate programs. One program is the Fuel Cell Demonstration Program managed by the U.S. Army Construction Engineering Research Laboratory (USACERL) to demonstrate that small fuel cells can work in the field. USACERL's specific tasks include installing turnkey packages, devising site criteria, screening DOD candidate installation sites against selection criteria, evaluating viable applications at each candidate site, coordinating fuel cell site designs, installation and acceptance of the power plants, and performance monitoring and reporting. Although the program initially focused on Phosphoric Acid fuel cell systems, PEM fuel cells are now the program's main focus, with over 20 PEM installations (more than half from Plug Power) established in the last two years with no concurrent new deployments of Phosphoric Acid fuel cells.

The second DOD program is the Defense Advanced Research Projects Agency's fuel cell research conducted under the Advanced Energy Technologies Program.[6] The current program, Palm Power, is focused on projects that will produce electric power in the field for individual soldiers or small groups of soldiers. The program is developing compact fuel cell and thermal-to-electric energy conversion technologies and is primarily focused on 20 W to 500 W portable power systems using Solid Oxide fuel cell systems that can perform under military conditions and run on jet fuel.

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[6] www.darpa.mil/dso/thrust/matdev/advancet.htm.

D. Intellectual Property in Fuel Cells

Older science-based industries such as semiconductors, pharmaceuticals, and chemicals developed extensive knowledge markets over the years. These markets are characterized by intra-firm knowledge *generation* through R&D activity and by inter-firm knowledge *trading* through licensing and cooperative R&D.

In the relatively new industry of fuel cells, the market for knowledge is less developed than in more mature industries. Because the technology base is relatively unexploited compared to more mature technologies, a certain "land grab" mentality exists in terms of patenting activity. Since it is difficult to determine which patents will prove most valuable in the long term, the incentive is to patent often. Fuel cell makers employ two strategies that maximize value in their knowledge generation process. First, they create proprietary products that integrate many different processes into a single unit. Then, they patent many of the processes and integration strategies. In addition, the process of building the fuel cell and integrating its components creates a lot of tacit knowledge that companies accumulate and use to differentiate themselves and their products from the competition.

It is helpful to divide the fuel cell industry into three types of companies. There are the fuel cell makers, which integrate components around a fuel cell stack. This category includes companies such as Ballard, Plug Power, and UTC Fuel Cells. Second, there are the fuel cell component makers, which make components such as the membranes and catalysts. This category includes companies such as Johnson Matthey, DuPont, 3M, Gore, and Englehard. Finally, there are the large manufacturers that hope to sell fuel cells in their predominant power, automotive, and portable electronic device markets. This category includes companies such as GE and General Motors.

Figure 4 illustrates the patenting activity of five fuel cell makers. This figure shows that Ballard and UTC have generated the most patents—not surprisingly, as they have been patenting much longer than has Plug Power. Overall, each of these three companies is now averaging between 10 and 20 of the new patents granted each year. To put that in perspective, the whole fuel cell area only produced an average of 60 patents a year through the 1970s, 1980s, and early 1990s.

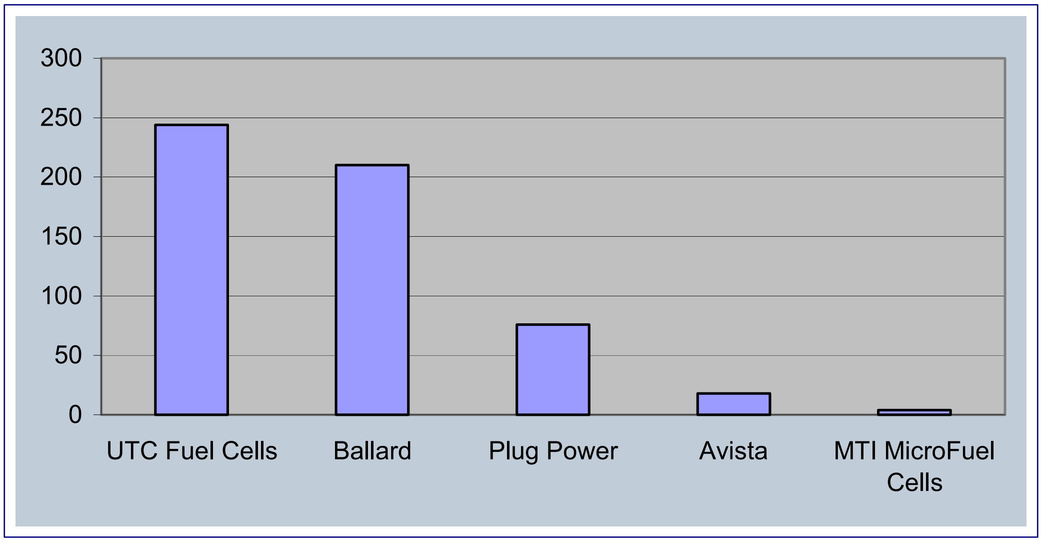

Figure 4. Number of full cell patents held by five selected fuel cell companies. Source: U.S. PTO (2003).

Table 6 shows the patenting activity of the fuel cell component companies and downstream distributors.

Table 6. Fuel Cell Patents of Selected Companies

Company	2003	2002	2001	2000	1999	1998	1997	Pre-1997
California Institute of Technology		5	7					
3M	2	6	5	3	3			
Avista	1	5	1	2				
Daimler-Chrysler		1	2	1		1		
Delphi	4	3	1					
Dow	1		3	1				
DuPont	1	1	1	0	2	2	1	
Energy Conversion Devices	1	2						3
Ford		5	3					3
Fuel Cell Energy	2	6	1	1	1			5
Gore	0	2	5	3	1			
Grafttech	4	1						
H Power (now owned by Plug Power)				4	3	2	1	1
Honda	7	9	7	2	1	4		
Hydrogenics	2	1			1	1		
IdaTech	4	5	1					
Johnson Matthey	2	3	1	2	3			2
Manhattan Scientifics	1		1					
Matsushita	4	3	1	1				

Company	2003	2002	2001	2000	1999	1998	1997	Pre-1997
Mitsubishi	3	1						
Motorola	2	6	3	3	1	1	1	
Nissan	2	3						
Nuvera		2		4				2
OMG		1	1	4	2	1		1
Proton Energy Systems		4	2	2	1			
Sanyo	2	3	1					
Stuart Energy Systems (Canada)		4	2	2				
UOP, LLC	2	2	3					

Source: Hydrogen & Fuel Cell Investor newsletter.

The overall business strategy of fuel cell makers has been to develop strategic partnerships with both component suppliers and downstream distributors. This strategy makes sense from a practical standpoint, because large companies dominate both upstream supplier and downstream distribution markets. What has emerged from these interlocking strategic relationships is that each fuel cell company concentrates its intellectual property strategy around its core area of expertise. For example, figure 5 shows the distribution of Plug Power's fuel cell patents by component area. The plate, stack, and water management components account for 56 % of the company's total patents. These three areas also represent the core of Plug Power's technical expertise.

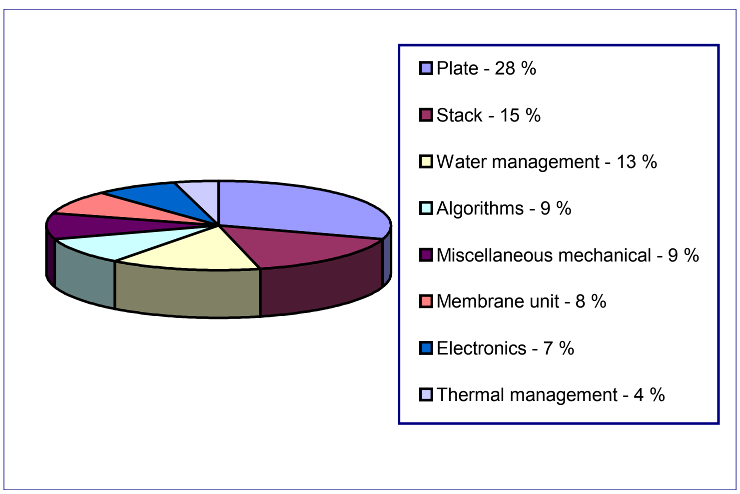

Figure 5. Plug Power's distribution of patents by fuel cell component area. Source: Plug Power.

In the fuel cell industry, it is difficult to find data on the size of the licensing market for fuel cell technology. What is known is that fuel cell companies often license technology from the national laboratories and universities. Celanese received an exclusive license to Case Western Reserve's high-temperature membrane and, in turn, has licensed the technology to Plug Power for stationary applications.

Based on data from 13 ATP fuel cell projects, three companies reported that some portion of the technology for their ATP project was licensed from a government national laboratory; one company reported that a portion came from two universities; and another reported that a portion came from a small private company.[7] Of the three companies that reported receiving their technology from a national lab, one reported that some of its technology also came from a large company, and another reported that some of its technology came from a second national laboratory. The main conclusion that can be drawn from this admittedly limited sample is that private firms use the knowledge generated by national laboratories. Moreover, one of the best methods to diffuse publicly generated knowledge is to have that knowledge embedded in a commercial product such that it can enter the marketplace.[8]

Firms do license technology when appropriate. However, until the fuel cell industry begins to deliver significant volumes, the demand to license technology is low. What has emerged is a significant degree of cooperative R&D and joint marketing, since a fuel cell involves several technologies and will ultimately need to be sold in mass markets such as the car and the home.

Despite the lack of profits and revenue to date, it appears that fuel cell companies are creating "moats" around their technologies. In other words, as fuel cell technologies evolve and become more commercially viable, it appears that fuel cell companies want to protect their intellectual property position with the broadest patenting claims available. Therefore, as commercial markets expand, each company will be in a better position to license its technology or use its patent portfolio as a bargaining chip in a cross-patenting negotiation.

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[7]Information on ATP's Business Reporting System may be found at www.atp.nist.gov/eao/ir-6491.pdf.

[8]Jaffe (1997).

V. Technological Innovation Leads to Commercialization of Stationary Fuel Cells

Technologies often face obstacles in moving from the lab to the marketplace. At its inception in the late 19th century, the electric industry was not particularly efficient. However, the incumbent technology, kerosene oil for lighting, was even more inefficient. As more uses of electricity were developed, economies of scale in production emerged and the price of electricity dropped. The average capacity of generation units rose from 80 MW in 1920 to 600 MW in 1960, and to 1 400 MW in 1980. Electric industry production began on a more or less equal footing with the incumbent technology, and only through growth in scale was it able to achieve technical and price dominance. In contrast, the computers of the 1950s competed against only rudimentary technologies such as the abacus or crude mechanical adding machines. Therefore, due to clear technological dominance, computers faced fewer obstacles in gaining marketplace acceptance.

The path from lab to marketplace for fuel cells is likely to be more arduous than those followed by either of these technologies. Fuel cells may not benefit from virtuous cycles enjoyed by electricity and computers. For electricity, it was a matter of initial adoption activity. Once electrification took hold, inventions run on electricity emerged in the marketplace, and the demand for electricity rose. This justified building larger electric plants, which produced cheaper electricity, which in turn made electricity an increasingly viable source of power. In computing, Moore's Law drove the whole process. As computers became faster and cheaper, more applications could be "computerized," which led to increased demand for computers.

Fuel cells face a rather difficult challenge as they enter the marketplace, since they appear to offer only a novel way of producing electricity and face stiff competition from an efficient technology that continues to receive a tremendous amount of investment. Therefore, fuel cells must overcome a much higher set of marketplace hurdles than either electricity or computers in order to gain commercial acceptance.

This section contains a review of the different actors and forces that exist within the fuel cell industry. These forces have played key roles in creating the incentive for the private sector to invest in PEM stationary fuel cell technology and affect the ultimate commercial success or failure of the technology as PEM fuel cells are brought to market in the near future. The first subsection presents a schematic of the industry and the forces driving innovation and adoption. The second subsection reviews the likelihood of commercial success and those areas that might help or hinder their ultimate acceptance in the commercial marketplace.

A. Analytical Framework

Figure 6 presents a schematic of the forces driving the innovation and adoption of stationary PEM fuel cells. The incentive for firms to dedicate resources to R&D of stationary fuel cells is affected by a variety of factors. These include the degree of difficulty of the research problem, the likelihood of commercial success, government policy, rivalry among PEM fuel cell developers, competition with alternative technologies for distributed generation of electricity—including other fuel cell technologies—competition with large-scale electricity generators, the availability of key resources, and the economic power of key resource providers.

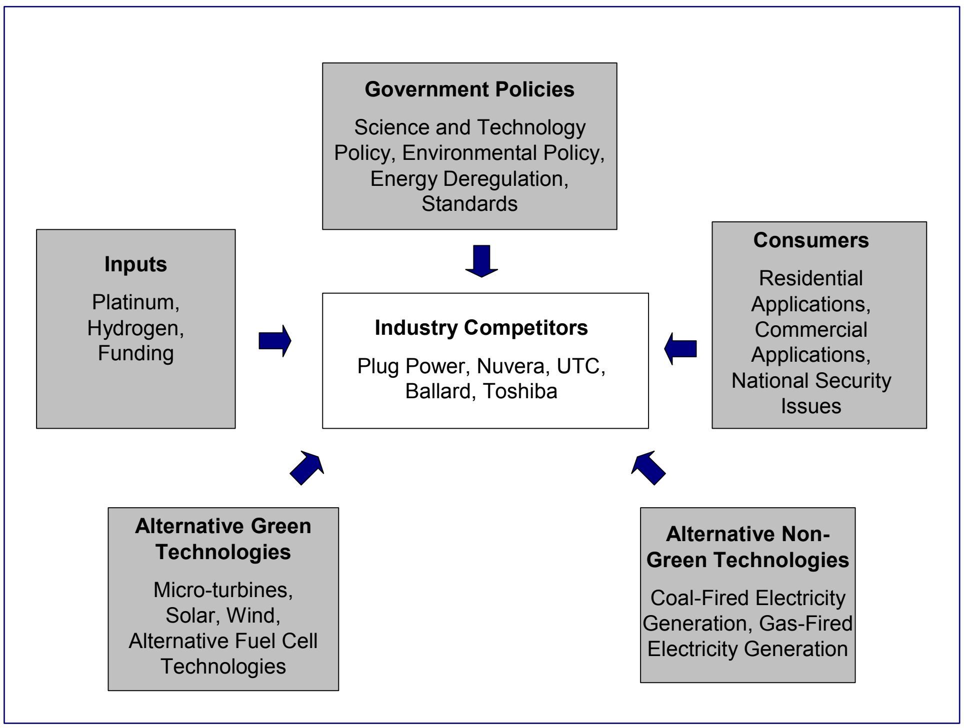

Figure 6. Forces driving stationary fuel cell innovation and adoption.

B. Likelihood of Commercial Success

Fuel cell companies face serious hurdles in attempting to achieve commercial success in the market. The following subsections present an overview of financial findings regarding fuel cell companies, followed by a brief discussion of five areas affecting the commercialization of fuel cells—platinum, hydrogen, consumer issues, target markets, and alternative energy forces. The discussion concludes with an outlook for the future.

1. Financial Overview

Table 7 shows the gross revenues of U.S. and Canadian fuel cell companies for the years 2001 and 2002. Table 8 shows the amount of R&D expenditures, net assets, and net cash flow for the same years. Total revenues rose from $128 million to $218 million—an impressive 60 % increase. However, as table 8 shows, the total R&D expenditures for 2002 for those same companies totaled $260 million, or almost $40 million more than their total revenue. A positive trend is suggested by the fact that the ratio of R&D expenditures to gross revenues dropped considerably, decreasing from 1.7 in 2001 to 1.18 in 2002.

Table 7. Gross Revenues for Selected Fuel Cell Companies (thousands of U.S. dollars)

Company	Country	2002	2001
Ballard	Canada	90 937	36 204
FuelCell Energy	United States	41 231	26 179
Quantum	United States	23 403	23 358
Hydrogenics	Canada	15 840	7 418
Global Thermoelectric	Canada	14 207	9 918
Plug Power	United States	11 818	5 742
Dynetek Industries	Canada	8 174	6 128
Stuart Energy Systems	Canada	5 052	6 255
Proton Energy Systems	United States	4 714	2 968
H Power	United States	2 576	3 643
Fuel Cell Technologies	Canada	709	443
Media Technologies	United States	192	-
Astris Energi	Canada	94	17
Energy Visions	Canada	50	141
Palcan Fuel Cells	Canada	–	–
Snow Leopard	Canada	–	–
Total		**218 997**	**128 414**

Source: PricewaterhouseCoopers (2003).

Fuel cell companies continue to rely heavily on government and industry research contracts for a significant proportion of their total revenues. The percentage of gross revenues from contract research, as opposed to product sales, increased from 35 % to 43 % between 2001 and 2002.[1]

As table 8 shows, total assets decreased $195 million from 2001 levels. The cause was a swing in net cash flow from a surplus of $215 million in 2001 to a deficit of $121 million in 2002. The largest contributor to the switch in net cash flow was the dismal equity environment for speculative capital in 2002, as shown in table 9.

[1]PricewaterhouseCoopers (2003), p. 4.

Table 8. R&D Expenditures, Total Assets, and Net Cash Flow for Selected Fuel Cell Companies (thousands of U.S. dollars)

		R&D expenditures		Total assets		Net cash flow	
Company	**Country**	**2002**	**2001**	**2002**	**2001**	**2002**	**2001**
Ballard	Canada	113 736	77 197	917 803	959 319	96 459	(40 325)
FuelCell Energy	United States	6 806	3 108	289 803	334 020	154 375	182 116
Quantum	United States	32 657	26 687	57 163	32 815	173	3
Hydrogenics	Canada	3 761	2 337	90 677	107 633	(644)	(80)
Global Thermoelectric	Canada	14 850	9 744	77 588	92 196	(34 476)	50 885
Plug Power	United States	40 289	60 600	108 683	151 374	(26 390)	(4 864)
Dynetek Industries	Canada	2 676	1 449	31 295	33 603	(7 399)	(4 602)
Stuart Energy Systems	Canada	11 019	8 864	85 746	102 111	(1 226)	(10 846)
Proton Energy Systems	United States	8 793	6 500	176 502	181 868	14 578	477
H Power	United States	18 905	13 466	73 752	105 350	(7 723)	38 129
Fuel Cell Technologies	Canada	1 592	2 505	5 209	4 954	(418)	1 274
Media Technologies	United States	4 161	4 251	66 894	69 894	37	3 114
Astris Energi	Canada	–	–	421	112	154	3
Energy Visions	Canada	678	678	167	1 377	(482)	461
Palcan Fuel Cells	Canada	315	240	584	145	165	6
Snow Leopard	Canada	115	134	56	981	22	(22)
Total		**260 353**	**217 938**	**1 982 343**	**2 177 752**	**(121 545)**	**215 723**

Source: PricewaterhouseCoopers (2003).

Table 9 shows the breakdown of cash flows by activity. Fuel cell companies continue to lose significant amounts of their net worth, as demonstrated by the increase in overall losses from operations from $199 million to $337 million between 2001 and 2002. Cash flow from financing dropped considerably from $615 million in 2001 to $158 million in 2002.

Table 9. Cash Flow by Activity (thousands of U.S. dollars)

Cash flow	**2002**	**2001**
From operations	(337 562)	(199 990)
From investing	57 330	(196 192)
From financing	158 687	611 905
Total	**(125 545)**	**215 723**

Source: PricewaterhouseCoopers (2003).

A number relevant to the near-term viability of fuel cell companies is their burn rate. For 2002, the average cash burn rate (cash plus short-term investments over operating cash flow) for the companies listed in tables 7 and 8 was 3.5 years. Six of the companies had an average cash burn rate of less than one year.[2]

2. Platinum/Catalyst Issues

One issue surrounding the commercial viability of fuel cells is their reliance upon precious metals as a catalyst. Borgwardt finds this to be a critical obstacle. Comparing projections of future platinum supply based on past trends to the amount of platinum required to replace the current U.S. automotive fleet with fuel cell–powered vehicles, the author concludes that "fuel cells alone cannot adequately address the issues facing the current U.S. system of road transport."[3]

There are several factors that suggest this view may be overly pessimistic. First, as Borgwardt notes, the historical trend is declining global prices and increasing global annual output of platinum ore. Second, compared to known global reserves of 47 500 tons of platinum, fuel cells currently use about 25 g.[4] Taken together, these facts suggest that the long-term elasticity of supply may be sufficient to meet future demands as fuel cells experience commercial success. Other tempering factors are based on current research efforts to decrease the usage of platinum in each fuel cell and examine alternative catalysts. There has been remarkable recent success in the first area, with a 100-fold decrease in the usage of platinum. This decrease has in turn helped to reduce the cost of platinum in a PEM fuel cell used to power an automobile from $30 000 to around $150.

DOE industry consultants have recently found that, although large fuel cell demand may drive higher platinum prices in the short run due to a lack of short-term supply, the price will likely return to its long-term mean as more mines come into operation. These short-term price spikes may result from either short-term real supply rigidities or hold-up issues resulting from South Africa's near-monopoly position in known platinum reserves.[5]

3. Hydrogen

A key advantage that stationary fuel cells have relative to other commercial applications of fuel cells is as a ready-to-use initial hydrogen source. Although

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[2]PricewaterhouseCoopers (2003), p. 6.

[3]Borgwardt (2001).

[4]Ibid.

[5]Carlson (2003).

direct-to-hydrogen methods are not currently economically viable, most residential and commercial sites are connected to a natural gas network. Stationary PEM fuel cells can therefore reform hydrogen from the natural gas supplied through existing networks. This allows residential applications to avoid the costs hydrogen networks faced in automotive applications. In fact, Lovins argues that there are important strategic complementarities between automotive and stationary applications of PEM fuel cells in the area of hydrogen reformation.[6] Direct hydrogen automobiles could use reformers located alongside either home- or work-based stationary fuel cells as hydrogen sources. This would not only provide a convenient source of hydrogen but would also allow increased automobile efficiency, as automobiles would not have to carry on-board reformers. To meet this challenge, Plug Power has formed a cooperative agreement with Honda to use Plug Power's residential fuel cell system's reformer as the basis for a home hydrogen refueling station for fuel cell–powered automobiles.

4. Consumer Issues

While changes to the regulation of utilities have contributed to the viability of the distributed generation business model, there are a number of customer-driven factors affecting this transition. Consumer demand for greener technologies and technologies that increase national energy security are not accompanied by actual willingness to pay for increased costs of energy produced with these technologies. If a public consensus were to develop that the benefits of accelerating the use of fuel cells are significantly large, then it might be appropriate to consider public policies of tax credits or other incentives to encourage the rapid adoption of fuel cell technology.

Several demand-pull factors affect the potential commercial success of PEM fuel cells in residential applications. For example, fuel cells must meet residential electrical and thermal loads; their reliability must be equal to or better than grid-connected service; the volume and footprint of fuel cells and reformers must match current heating, ventilation, and air conditioning systems; they must comply with current building and product codes; and they must have low noise levels. Critical to providing electricity cost competitive with the grid is the achievement of total fuel cell system cost well below $1 000 per kilowatt with reliable, inexpensive operation over the 20-year life that consumers expect from stationary energy appliances.

The need for high-quality, uninterruptible power already exists in certain banking, computing, and medical applications. High-quality electricity is also needed by

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[6] Lovins (2003).

industries that employ microprocessor electronics for process control. The paper, chemical, textile, and automotive sectors are a few examples of sectors where electrical disturbances due to voltage sags, spikes, and outages can cause significant losses to manufacturing productivity. The modularity, low noise production, and cogeneration opportunities make PEM fuel cells nearly ideally suited for building applications outside of these niche markets. The excess heat from the fuel cells can be used for heating and air conditioning. The ultra-pure water produced as a byproduct and joint production of hydrogen offers further complementarities between fuel cell–generated power and certain applications such as semiconductors. Lovins and Williams report that such applications may provide an initial entry opportunity for fuel cells,[7] particularly as conventional heating/air conditioning systems are replaced either due to age or the need to reduce chlorofluorocarbon emissions.

A final important step for fuel cells to become acceptable in the marketplace is the ability of consumers to purchase and be able to interconnect products from different vendors. For example, if a consumer buys a Hewlett Packard printer, he or she wants to be able to connect it to a Dell computer. The same applies to fuel cells.

5. Target Market and Strategic Actions

The residential consumer is Plug Power's eventual target market. To promote customer collaboration, Plug has 130 systems installed in the field in demonstration programs. To penetrate the market rapidly and obtain an advantage over competitors, Plug Power has pursued a series of joint ventures and agreements with partner companies.

A huge hurdle for a small technology company is how to sell the product once it is developed. Plug Power has addressed this challenge by partnering with GE's Power Division, a leading maker of turbines and power plants for the central utility business. GE's MicroGen unit became the exclusive licensee of Plug Power PEM fuel cells below 35 kW in most of the United States.[8] The addition of a large manufacturer of household energy appliances to distribute and service the residential fuel cells was a huge step forward for Plug Power. Both brand recognition and the fleet of GE technicians to service products after the sale will greatly accelerate market acceptance and reduce the time to commercialization. Subsidiary distribution deals are now being pursued with local utilities. For example, GE MicroGen has signed an agreement with NJR Energy Holdings Corp. of Wall, New Jersey, and Flint Energies of Warner Robins, Georgia, to be the first two distributors for GE MicroGen's line of

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[7]Lovins and Williams (1999).

[8]DTE has the rights to sell in the Midwest.

residential and small commercial-sized fuel cell systems.[9] In addition to these distribution channels, DTE retains marketing rights to sell the Plug Power units in several Midwestern states. Timing these agreements before commercial release of a product also allows for additional field testing of pre-commercial units, again accelerating the time to market for a tested, robust product for residential use.

On the technical side, Plug Power has sought to leverage its PEM technology with complementary systems. The German-based Celanese, the supplier of the high-temperature membranes used in Plug's first ATP project, subsequently signed an agreement to develop a high-temperature membrane electrode unit exclusively for Plug Power's stationary applications.[10] The unit consists of membranes, electrodes, and gas diffusion layers and forms the heart of the fuel cell stack. It is also the key to increasing operating temperatures. Higher temperature stacks operating in the 150 °C range, up from 90 °C, ensure more reliable, carbon monoxide–tolerant operation, allow for better cogeneration efficiencies for heating air and water, and reduce the complexity and cost of the fuel processor due to the removal of the final carbon monoxide clean-up steps. An April 2000 agreement with Vaillant, also based in Germany, will capitalize on these higher temperatures by integrating a combination furnace and hot water heater. PEM fuel cells produce electricity at approximately 35 % efficiency, with the other 65 % of the energy in the fuel exiting as heat or exhaust gas. The addition of a cogeneration unit can capture the heat energy that would otherwise be wasted and raise the overall energy efficiency to as much as 85 % to 95 % by utilizing this excess heat. The efficiency gains through cogeneration offer environmental benefits amounting to an estimated halving of home and office energy costs.

Plug Power has also signed an agreement with Advanced Energy Systems to develop power conditioning equipment for its fuel cells. The partnership gives Plug Power a 28 % stake in Advanced Energy Systems and provides the right to self-manufacture or outsource the power electronics production.[11] Power conditioning is important for fuel cells because they produce low-voltage DC, which must be inverted to AC for home and office use. The goal of the agreement is to provide quicker product development for specific Plug Power fuel cell needs.

To establish a foundation in fuel processing, Plug Power purchased the leading-edge technology of a European company, Gastec, and acquired its employees. To further

[9]PRNewswire, GE press release, December 1, 1999.

[10]PRNewswire, Plug Power press release, April 18, 2000.

[11]PRNewswire, Plug Power press release, March 16, 2000.

its technology base, Plug Power has signed agreements with Engelhard Corporation, based in Iselin, New Jersey, to provide advanced catalysts for the fuel reformers.[12] Natural gas and propane are catalytically converted into hydrogen, which is then used as the fuel to make electricity. Improved catalysts can have an impact on overall efficiency, thus lowering the operating costs for an installed fuel cell since less fuel will be needed to produce the same amount of hydrogen.

This series of agreements and technical collaborations shore up Plug Power's technology position in each of the three main areas of a fuel cell: fuel processors, fuel cell stack (membrane and associated assembly), and power conditioning equipment. In each case, the collaboration may speed the development of a total package, commercial-ready, residential fuel cell.

6. Alternative Energy Forces

Fuel cells share a common set of benefits with all distributed generation technologies. These include the avoidance of electric transmission losses and the need for a grid, investment in new distribution capacity, and the avoidance of the financial risks associated with investment in large central generating facilities. Swisher notes that fuel cells also have a number of advantages relative to green and traditional distributed generation technologies.[13] Photovoltaic generation has capacity costs comparable to pilot study–produced fuel cells, yet produces electricity during fewer hours per year and has lower peak load availability. While wind turbines may have lower costs than fuel cells, they face siting constraints. These constraints arise either due to their negative visual impact, noise, or a lack of wind resources. Wind turbines' viability as a distributed generation option is limited by these factors, and it therefore fails to avoid distribution costs.

Traditional distributed generation approaches such as reciprocating engines, small turbines, and micro-turbines have lower costs than fuel cells. These approaches are currently used primarily as backup power. As primary power sources, however, they will likely face regulatory constraints on environmental, safety, and land use grounds. These technologies are cousins to that used in aircraft propulsion engines and would likely face difficulties with building codes and noise restrictions. Further, such projects would likely face utility regulations from which they have been insulated as backup-only power sources. Swisher believes that even gas turbines will face significant air quality difficulties under the existing Clean Air Act. Further, few alternative fuel cell technologies are as well suited for residential applications. Of

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[12]PRNewswire, Plug Power press release, June 6, 2000.

[13]Swisher (2002).

competing technologies, only PEM and alkaline fuel cells operate at ambient temperatures. This allows the rapid start-up demanded in residential and automotive applications. PEM fuel cells currently enjoy significant advantages relative to alkaline-based systems in terms of reliability.

7. Outlook

The regulatory environment is promoting the development of a distributed energy strategy, which has taken on added import due to heightened security concerns. The significant advantages of fuel cells over both renewable and nonrenewable energy sources have led *The Economist* to note that "it is clear that the electricity industry will be turned on its head by fuel cell 'micro power' units that are about to come on the market."[14] It is also apparent to *The Economist* that the PEM fuel cell is "the most promising type" of fuel cell for automotive and residential applications.

Companies that work with public sector agencies can undertake riskier research agendas encompassing a broader scope. The Plug Power example described in this report illustrates how companies can leverage technical achievement through public-private partnership agreements.

[14] *The Economist* (2001).

VI. Conclusions

The following conclusions can be drawn from this study.

A. Drivers of Fuel Cell Innovation

Government

- Early drivers of U.S. fuel cell innovation were the space and defense programs. Since the 1980s, the Department of Energy has been the primary source of funds for fuel cell research both in basic research and in financing prototypes and demonstration projects.

- National laboratories, in particular Los Alamos in the early days, continue to drive innovation in fuel cell research. State programs such as the New York State Energy Research and Development Authority provide significant support through research grants and demonstration projects.

- In November 2001, in response to recommendations within the National Energy Policy, DOE organized a meeting of 50 visionary business leaders and policymakers to formulate a National Hydrogen Vision. In March 2002, DOE followed up with a larger group of over 200 technical experts from industry, academia, and the national laboratories to develop a National Hydrogen Energy Roadmap. The Roadmap contains clear technical and commercial goals that must be met in order to achieve a hydrogen-based economy by 2030.

- Starting in 1998, the Department of Commerce's Advanced Technology Program awarded the first of 25 fuel cell projects as fuel cell commercialization prospects improved. ATP provides cost-share funds for high-risk R&D projects with commercial potential, thereby bridging the funding gap between basic science and product development.

Environment and Deregulation

- Fuel cells have been marketed as an emission-free technology. However, there are questions about using fuel cells as a means to reduce carbon emissions, particularly when one considers that the most economical methods for generating hydrogen produce carbon dioxide.

- Deregulation of energy markets spurred utility companies to pursue alternative business strategies. Detroit Edison created Plug Power, a leading maker of stationary fuel cells, partially as a response to deregulation.

- Long-term R&D by utility companies has dropped as a result of the decoupling of the power generation business from the power distribution business by utilities in many states.

Expenditures

- Since the early 1980s, federal R&D expenditures on energy dropped in real terms from $6 billion in 1980 to $1.5 billion in 2001 (constant 1996 dollars).

- This trend may be changing particularly in the area of fuel cells, which President Bush has specifically targeted for a $1.7 billion increase in funds available for research over the next five years.

B. Innovation in the Energy Sector: Knowledge Creation, Diffusion, and Exploitation

Knowledge Creation

- A significant amount of fuel cell research is funded by government but conducted by private firms or universities.

- Private firms aggressively patent in the United States. After averaging about 60 fuel cell patents a year from the early 1980s to the late 1990s, the number of fuel cell patents granted per year has recently almost doubled.

- In 1999, universities conducted over $4.6 billion of R&D in the scientific disciplines related to fuel cells.

Market Structure

- Fuel cell makers such as Plug Power, Ballard, and Nuvera fit the criteria of a small or medium-sized enterprise, but they need access to a large firm's capital and to their markets.

- Since fuel cells are at a pre-commercialization stage, large firms such as automobile, utility, and energy companies pursue fuel cell opportunities with some firm-sponsored R&D but also through strategic alliances with the fuel cell makers.

- U.S. fuel cell makers have strategic alliances with international firms to market their products and use them as partners for demonstration projects (e.g., Vaillant uses Plug Power fuel cells in a German demonstration project). The fuel cell makers include international firms in their strategic relationships with suppliers (e.g., Plug Power has teamed with Celanese to create a high-temperature membrane).

C. Public Policy for Innovation in Fuel Cells

Market Development

- There are limited tax incentives for fuel cells at the federal and state levels. The fuel cell tax credits that are available are not large enough to affect the decision to purchase a fuel cell.

- Government procurement of fuel cells has been limited to this point.

- At this stage of commercial development, demonstration programs appear to be the most effective method for government to spur the commercial development of fuel cells. The cost of fuel cells must be reduced before tax policy or government procurement can be justified as a means for spurring their introduction to the marketplace.

Public-Private Partnerships

- In July 2003, DOE awarded a total of $96 million in 24 new awards in support of the president's FreedomCAR and Hydrogen Fuel Initiative. These new projects include research in advanced fuel cell technology for vehicles, buildings, and other applications. In particular, the projects on hydrogen storage technologies support DOE's priority to develop methods to safely store hydrogen to enable at least a 300-mile vehicle range—a critical requirement for successful vehicle commercialization. The recipients of these awards have pledged an additional $40 million in cost sharing, bringing the total value of these projects to $136 million.

- ATP awarded three new fuel cell projects in September 2004, bringing the total number of fuel cell projects awarded by ATP since 1997 to 25. The recipients of these awards have pledged an additional $51.1 million in cost sharing, bringing the total value of these projects to $109.3 million.

Development of Standards

- The National Institute of Standards and Technology, which develops standards and measurements for a broad range of products and technologies, will perform a vital public good function through its

Residential Fuel Cell Test Facility. This program will provide purchasers with a realistic estimate of annual electrical energy output, thermal energy output, and fuel usage.

- In addition to practical operating standards, a more long-term question involves safety issues involving both fuel cells and particularly hydrogen, which can be very dangerous. The role of government is extremely important.

Commercialization Prospects

- The National Hydrogen Roadmap describes the period from 2003–15 as the technology development phase; decisions on commercialization may not occur until 2015. However, the prospect for commercialization of fuel cells for portable applications or backup systems appears to be much sooner, with some electronics firms talking about late 2004 or 2005.

- The financial situation confronting fuel cell makers is precarious. Several firms have burn rates of less than a year. Their near-term survival depends on continued access to equity markets.

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About the Advanced Technology Program

The Advanced Technology Program (ATP) is a partnership between government and private industry to conduct high-risk research to develop enabling technologies that promise significant commercial payoffs and widespread benefits for the economy. ATP provides a mechanism for industry to extend its technological reach and push the envelope beyond what it otherwise would attempt.

Promising future technologies are the domain of ATP:

- Enabling technologies that are essential to the development of future new and substantially improved projects, processes, and services across diverse application areas;
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- Technologies whose development often involves complex "systems" problems requiring a collaborative effort by multiple organizations; and/or
- Technologies that will go undeveloped and/or proceed too slowly to be competitive in global markets without ATP.

ATP funds technical research, but it does not fund product development that is the domain of the company partners. ATP is industry driven, and that keeps it grounded in real-world needs. For-profit companies conceive, propose, co-fund, and execute all of the projects cost shared by ATP; these projects often include universities, and other nonprofit organizations.

Smaller firms working on single-company projects pay a minimum of all the indirect costs associated with the project. Large, "*Fortune* 500" companies participating in single-company projects must pay at least 60 % of total project costs. Participants of joint venture projects pay at least half of total project costs. Single-company projects can last up to three years; joint venture projects can last as long as five years. Companies of all sizes participate in ATP-funded projects. To date, nearly two out of three ATP awards have gone to individual small businesses or to joint ventures led by a small business.

Each project has specific goals, funding allocations, and completion dates established at the outset. Projects are monitored and can be terminated for cause before completion. All projects are selected in rigorous competitions that use peer review to identify those that score highest against technical and economic criteria.

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