February 28, 2003

The Honorable Charles H. Taylor
Chairman
Subcommittee on Interior
 and Related Agencies
Committee on Appropriations
U.S. House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

Enclosed is the *Fuel Cell Report to Congress*. The Conference Report (House Report 107-234, page 120) accompanying Public Law 107-63, enacted November 2001, making appropriations for the Department of the Interior and Related Agencies, requests the Department of Energy to report to the House and Senate Committees on Appropriations, on the technical and economic barriers to the use of fuel cells in transportation, potable power, stationary, and distributed generation applications. The Conference Report also requested that the Department provide an interim assessment that describes preliminary findings about the need for public and private cooperative programs to demonstrate the use of fuel cells in commercial-scale applications.

The enclosed report combines our response for both the interim assessment and the final report. This comprehensive report on fuel cell technology stresses the importance of hydrogen and establishes timeframes consistent with the President's newly announced Hydrogen Fuel Initiative. The enclosed report describes the following findings:

- Fuel cell technologies offer the Nation unique opportunities for unprecedented reductions in both energy use and emissions for transportation and stationary power applications.

- Public and private cooperative programs are needed to overcome major technical, institutional, and economic barriers to realize potential fuel cell benefits of reducing dependence on imported oil, improving air quality, and reducing greenhouse gas emissions.

- Cost and durability are the primary technical barriers to commercializing fuel cells. Considerably more government and industry cooperative research is required to overcome these barriers. Lack of codes and standards necessary for safe and reliable use of hydrogen and fuel cells represents a large institutional barrier which also must be overcome by a public and private cooperative effort.

- Hydrogen, the fuel for fuel cells, opens a clear path to increasing energy feedstock diversity utilizing domestic fossil, nuclear, and renewable resources.

- A new hydrogen production, delivery, and refueling infrastructure is necessary for transportation fuel cell technology to achieve its potential energy and environmental benefits. Because of the large economic implications of a change in motor fuel infrastructure, a cooperative approach that includes energy and auto industries, as well as the United States and other government organizations, is essential.

Based on these findings, the Department recommends the following:

- Core Technology Development should focus more attention on advanced materials, manufacturing techniques, and other advancements to lower cost, increase durability, and improve reliability of fuel cell systems.

- More emphasis must be placed on hydrogen production and delivery infrastructure, storage, codes and standards development, and education.

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

- Stationary and Distributed Generation Partnership to continue robust research activities to lower costs and improve durability, and to establish necessary field evaluations leading to commercialization.

- Transportation and Infrastructure Partnership to test fuel cell vehicles and evaluate critical cost, performance, and reliability information; and to address safety, cost, and standardization issues associated with a hydrogen infrastructure for fuel cell vehicles.

Government and private sector commitment of resources is necessary due to the large capital investment required to achieve increased energy security and dramatically reduced emissions; to provide an independent assessment of technological progress; and to manage the risks and expectations on behalf of taxpayers and investors. Government commitment is critical to assure private industry investment over the long term.

If you have any questions concerning the report, please feel free to contact me or Mr. Michael Bloomer, Office of Management, Budget and Evaluation, at (202) 586-8526.

Sincerely,

David K. Garman
Assistant Secretary
Energy Efficiency and Renewable Energy

Enclosure

The Honorable C.W. Bill Young
Chairman
Committee on Appropriations
U.S. House of Representatives
Washington, DC 20515

The Honorable David R. Obey
Ranking Minority Member
Committee on Appropriations
U.S. House of Representatives
Washington, DC 20515

The Honorable Charles H. Taylor
Chairman
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The Honorable Norman D. Dicks
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The Honorable Ted Stevens
Chairman
Committee on Appropriations
United States Senate
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The Honorable Robert C. Byrd
Ranking Minority Member
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The Honorable Conrad Burns
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The Honorable Robert C. Byrd
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United States Senate
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February 2003

Fuel Cell Report to Congress

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Fuel Cell Report to Congress

Executive Summary

Congress has asked the Department of Energy (DOE) to prepare two reports describing the status of fuel cells. The Interior & Related Agencies Appropriations Conference Report (House Report 107-234) that accompanies Public Law 107-63, enacted in November 2001, requests that the Department report within 12 months to the House and Senate Committees on Appropriations on the technical and economic barriers to the use of fuel cells in transportation, portable power, stationary, and distributed power generation applications. It also requests that the Department provide, within six months after enactment, an interim assessment that describes preliminary findings about the need for public-private cooperative programs to demonstrate the use of fuel cells in commercial-scale applications by 2012. The aim of this report is to respond to these requests.

Potential Benefits

Fuel cell technologies offer unique opportunities for significant reductions in both energy use and emissions for transportation and stationary power applications.

- Efficiency improvements over conventional technologies that are inherent to fuel cells could lead to considerable energy savings and reduction in greenhouse gas emissions.

- The use of hydrogen in fuel cells, produced from diverse, domestic resources, could result in reduced demand for foreign oil in transportation applications.

- Widespread use of fuel cell technology could make a significant improvement in air quality in the United States. This would be a result of near zero emission vehicles and clean power generation systems that operate on fossil fuels, and zero emission vehicles and power plants that run on hydrogen.

For the purposes of this report, the Department did not attempt to quantify benefits of fuel cell commercialization and compare them to the expected public and private sector costs necessary to achieve commercialization.

Barriers to Commercialization

Significant additional fuel cell research and development (R&D) would need to be conducted to achieve cost reductions and durability improvements for stationary and transportation applications.

Additional barriers to commercialization vary by application and fuel cell type; however, cost and durability are the major challenges facing all fuel cell technologies. (See Figure 1.)

Figure 1: Barriers to Fuel Cell Commercialization

Application	Barriers	Difficulty
Transportation	Cost	High
	Durability	High
	Fuel Infrastructure	High
	Hydrogen Storage	High
Stationary-Distributed Generation	Cost	High
	Durability	Medium - High
	Fuel Infrastructure	Low
	Fuel Storage (Renewable Hydrogen)	Medium
Portable	Cost	Medium
	Durability	Medium
	System Miniaturization	High
	Fuels and Fuels Packaging	Medium

For fuel cell vehicles, a hydrogen fuel infrastructure and advances in hydrogen storage technology would be required to achieve the promised energy and environmental benefits.

Efficient, clean and economical processes for producing and delivering hydrogen from a variety of domestic feedstocks, including fossil, nuclear and renewable sources, is critical to increased energy resource diversity and energy security.

Recommended Program Adjustments

Our assessment is that potential national benefits of fuel cell technology (such as reduced dependence on imported oil) suggest a federal role is appropriate in researching and developing fuel cell technology. Market forces alone are unlikely to result in large-scale use of fuel cells in the next few decades. Conventional power and vehicle technologies meet or exceed customer requirements and expectations, electricity and refueling stations are readily available, and power and fuel are relatively inexpensive. Absent other incentives, or a dramatic change in economics or availability of petroleum, the customer has very little reason to try an unproven new technology.

Industry is investing heavily to develop and deploy fuel cell systems. Industry's goal is to provide customers with a clean, energy-efficient technology that performs as well as, if not better than, the commercially available product and at comparable cost. However, major technical and institutional barriers must be overcome. Because of the high cost and risk involved with overcoming these barriers, no single company or consortia of industry partners could be expected to make the huge investments that would be required (such as the investments to create a hydrogen infrastructure for fuel cell technology).

Program adjustments as recommended below are being initiated as an outcome of internal program reviews as well as a result of the latest input from a broad spectrum of stakeholders.

Core Technology Development and Supporting Initiatives**:** The ongoing core technology development efforts need to focus more attention on advanced materials, manufacturing techniques, and other advancements that will lower costs, increase life, and improve reliability for all fuel cell systems. These activities will need to address not only core fuel cell stack issues but also balance of plant (BOP) subsystems such as fuel processors, hydrogen storage, power electronics, and heat exchangers. More emphasis also must be placed on hydrogen production and delivery infrastructure research, codes and standards development, and education.

Public-Private Cooperative Partnerships**:** Public-private cooperative programs, where government and industry work together in a collaborative manner, provide a means to overcome commercialization barriers so that the national benefits can be realized. The Federal role in such partnerships should focus on the research and development needed to enhance the prospects for commercialization. After extensive consultations with stakeholders, the Department recommends the initiation of new and/or broadening of existing government-industry partnerships to address the diversity of markets and technologies. The kinds of cost-shared partnerships envisioned by the Department include the following:

- ***Stationary and Distributed Generation Partnership.*** Government-industry R&D partnerships will continue to be used as a strategy for accelerating the use of fuel cells in stationary power generation for residential applications and commercial buildings, as well as larger distributed generation. There is a need to continue robust, cooperative R&D programs, such as the Solid-State Energy Conversion Alliance (SECA), to reduce fuel cell technology costs, and to increase durability and reliability. Additional cooperative, field evaluation programs, which include end users such as utilities, should be used to continually focus the R&D. These partnerships should also plan and implement a cooperative program to establish interconnection standards for fuel cell powered systems, address safety codes and standards, and develop a dual use infrastructure that supports transportation applications in cases where hydrogen is the primary fuel.

- ***Transportation and Infrastructure Partnership.*** FreedomCAR, a partnership between the U.S. Council for Automotive Research and the Department of Energy, addresses fuel cell technology research challenges. Similar partnerships to test fuel cell vehicles under real operating conditions would yield valuable cost, performance and reliability information that would focus future research. Transitioning the current fuel supply infrastructure to the production and delivery of hydrogen would be a massive undertaking from a technology and economic standpoint. A public-private cooperative program to evaluate and overcome hydrogen infrastructure commercialization barriers would help to develop and demonstrate efficient, clean and economical hydrogen production and delivery processes; on- and off-board hydrogen storage systems; standardized vehicle-refueling interface requirements; and acceptable safety practices, codes and standards. Over the last year, the Department worked with industry and other stakeholders to develop a national vision to transition to a hydrogen economy. Recently, a National Hydrogen Energy Roadmap has been completed (November 2002) as an "action plan" to fulfill the vision of a hydrogen economy. This key document could serve as the basis for a cooperative program demonstrating fuel cell vehicle and hydrogen infrastructure technologies.

Codes and Standards**:** The Federal government is in a unique position as a neutral third party to catalyze and coordinate the work of professional societies, trade associations, and international organizations in codes and standards development. The development of a complete set of codes and standards would foster mass-market acceptance of fuel cell technologies because of the safety and liability aspects of introducing a new technology. Codes and Standards would also help guide R&D programs to ensure technology compliance prior to deployment. The scope of ongoing codes and standards programs would need to be expanded to include a broader range of applications, system architectures, and technology options.

Education: Educational materials would be developed to introduce hydrogen and fuel cell systems, and clearly communicate the hydrogen vision to potential end users, local governments, and others. These educational materials would address the National Energy Policy recommendation to communicate hydrogen benefits, safety, and utilization information to key stakeholders. In collaboration with industry and education organizations, a curriculum and training program for elementary and secondary school teachers will be created. The effort would pair teachers with local industry experts and involve practicing teachers in the development of a usable curriculum for education about hydrogen and fuel cells, as well as a training program for teachers to use the curriculum. Building on current Department efforts, university programs would be expanded to provide more students opportunities to research hydrogen and fuel cell technologies.

Regional, state, and local networks would be established to involve code officials, building engineers, energy regulators, and consumers in regional hydrogen technology demonstrations including education on installation, codes and standards, and safety issues. These regional programs would provide information exchange and networking to seek solutions to local hydrogen implementation barriers.

Conclusion

The recommended program adjustments and public-private cooperative programs to develop and validate technology described in this report would produce the information necessary to determine if commercialization of fuel cell technology over a wide range of applications is viable by 2015. Even if technology development is successful, market factors and advancements of competing technologies will influence industry's decision to begin commercialization in 2015. Commercialization and widespread deployment could contribute to the achievement of increased energy security and dramatically reduced carbon dioxide and criteria pollutant emissions. Government and private sector commitment of resources would be necessary due to the large capital investment required to overcome major technical and institutional barriers, to provide independent evaluation of technology progress, and to manage the risks and expectations on behalf of taxpayers and private investors. Government resources can be critical in securing the commitment of private investors, while the investment of the private sector is an indication to the government of the industry's willingness and commitment to commercialize the technology.

The Department believes that the Federal involvement should be reduced as technologies progress along the research-development-demonstration-commercialization continuum. The Department also recognizes that, while demonstration of currently uneconomic technologies may provide useful information to help identify R&D needs, the proportion of funding dedicated to such demonstrations must be carefully monitored so as not to detract resources needed for the long-term success of its programs. The Department will strive to maintain an appropriate balance in its R&D portfolio, focusing on long-term, high-risk activities, and will strictly adhere to cost-sharing guidelines for all of its activities. In addition, these program efforts continue to be coordinated between DOE's Office of Energy Efficiency and Renewable Energy and Office of Fossil Energy as well as with other Federal agencies.

Fuel Cell Report to Congress

Scope Note

From the Conference Report (House Report 107-234) that accompanies Public Law 107-63, which makes appropriations for Interior and related agencies:

> The Department should report to the House and Senate Committees on Appropriations, within twelve months of the date of enactment of this Act, on the technical and economic barriers to the use of fuel cells in transportation, portable power, stationary, and distributed generation applications. The report should include recommendations on program adjustments based on an assessment of the technical, economic and infrastructure requirements needed for the commercial use of fuel cells for stationary and transportation applications. Within six months of the date of enactment of this Act, the Department should also provide an interim assessment that describes preliminary findings about the need for public and private cooperative programs to demonstrate the use of fuel cells in commercial scale applications by 2012.

This appropriations law was enacted November 5, 2001 and provided the fiscal year 2002 funding for the Department of Energy's Fossil Energy and Energy Efficiency and Renewable Energy fuel cell programs. As agreed to by House Interior Appropriations Subcommittee staff, this report fulfills the request for both the six-month interim assessment and the twelve-month full report.

In the course of preparing this report, the Department consulted extensively with stakeholders in the public and private sectors. These consultations included four workshops: the Auto Industry Workshop on December 13, 2001 in Sacramento, California; the Fuel Cell Portable Power Workshop on January 15-17, 2002 in Phoenix, Arizona; the Energy Industry Workshop on February 11, 2002 in Herndon, Virginia; and the Integrated Workshop to obtain industry input to the Interim Assessment on February 21-22, 2002 in Washington, DC. Also, this report has been prepared in conjunction with a parallel effort to develop a National Hydrogen Vision and Roadmap. (National Hydrogen Energy Vision Document published February 2002; National Hydrogen Energy Roadmap published November 2002.)

While the Department alone is responsible for the content of this report, the Department is grateful to the participants of these workshops for providing input and for reviewing the various drafts of this report. Workshop participants and other reviewers include representatives from the following organizations:

Air Products and Chemicals, Inc.
Alliance to Save Energy
American Council for an Energy-Efficiency Economy
American Green Network
American Honda Motor Co, Inc.
American Public Power Association
Arthur D. Little, Inc. (now TIAX LLC)
Argonne National Laboratory
Avista Laboratories, Inc.

Ball Aerospace Corporation
Ballard Power Systems, Inc.
BP
Business Council for Sustainable Energy
California Fuel Cell Partnership
California Air Resources Board
CENTRA Technology, Inc.
ChevronTexaco
DaimlerChrysler
DCH/Enable Fuel Cell
Delphi Automotive
Duracell (part of The Gillette Company)
Electric Vehicle Association of the Americas (EVAA)
Energetics, Inc.
Energy Conversion Devices, Inc.
Engelhard Corporation
Environmental and Energy Study Institute
ExxonMobil Corporation
Ford Motor Company
FuelCell Energy, Inc.
General Electric Company
General Motors Corporation
Giner Electrochemical Systems, LLC
Greenpeace USA
H Power Corporation
H2Gen Innovations, Inc.
Honda R&D Americas, Inc.
Hydrogen Technical Advisory Panel
IdaTech Corporation
International District Energy Association
Jet Propulsion Laboratory, California Institute of Technology
Kyocera Wireless Corporation
Los Alamos National Laboratory
Market Facts Motoresearch, Inc.
Materials & Systems Research, Inc.
McDermott Technology, Inc.
Methanol Institute
Methanex Corporation
Microcell Corporation
Millennium Cell
Motorola, Inc.
MTI Micro Fuel Cells Inc.
National Energy Technology Laboratory
National Hydrogen Association
National Renewable Energy Laboratory
Natural Resources Defense Council
Nissan Motor Company, Ltd.
Nissan North America, Inc.
Nuvera Fuel Cells, Inc.
OMG Corporation
Pacific Northwest National Laboratory
Panasonic Technologies
PDVSA/Citgo
Philips Petroleum Company
Plug Power, Inc.
Polyfuel, Inc.
Praxair
Princeton University
Proton Energy Systems, Inc.
Protonex Technology Corporation
Quantum Technologies
Renewable Energy Policy Project
Renewable Fuels Association
Sandia National Laboratories
Saudi Aramco
SENTECH, Inc.
Shell Hydrogen
Siemens Westinghouse Power Corporation
Sierra Club
South Coast Air Quality Management District
Stuart Energy USA
Sunline Transit Agency
Teledyne Energy Systems, Inc.
Toyota Motor North America
Union of Concerned Scientists
University of Florida
University of Michigan
U.S. Army - Communications and Electronics Command (CECOM)
U.S. Army - Construction Engineering Command (CERL)
U.S. Army - Tank Automotive and Armaments Command (TACOM)
U.S. Army - National Automotive Center
U.S. Department of Energy
U.S. Department of Transportation/ Federal Transit Administration
U.S. Environmental Protection Agency
U.S. Fuel Cell Council

U.S. Naval Research Laboratory
U.S. Office of Naval Research
U.S. Public Interest Research Group
UTC Fuel Cells
W. L. Gore & Associates, Inc.
World Wildlife Fund
Zetek Corporation

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Introduction

Fuel cell technologies offer unique opportunities for significant reductions in both energy use and emissions for transportation and stationary power applications.

Fuel cells represent a radically different approach to energy conversion, one that could replace conventional power generation technologies like engines and turbines in applications such as automobiles and power plants. Like batteries, fuel cells produce electrical energy electrochemically. But unlike batteries, fuel cells do not require recharging; instead they use fuel to produce power as long as fuel is supplied. Fuel cells operate quietly and are relatively compact. Largely because of these characteristics, fuel cells promise:

- Efficiency improvements that could lead to considerable energy savings and reduction in greenhouse gas emissions. This includes more than a 50 percent reduction in fuel consumption for vehicles when compared to a conventional vehicle with a gasoline internal combustion engine, on a well-to-wheels basis; more than a 30 percent reduction in natural gas consumption for power generation; and increased co-generation in buildings and small businesses, leading to a significant reduction in energy use for heating and cooling.

- Increased energy security and electric grid reliability — the use of hydrogen produced from diverse, domestic energy resources could result in reduced demand for foreign oil, especially for transportation applications. Distributed energy systems using fuel cells could be an alternative to centrally generated power. In addition, they could take the load off of the electric power grid in critical situations when the transmission system is not capable of meeting the demand, e.g. during blackouts fuel cells can serve as backup power.

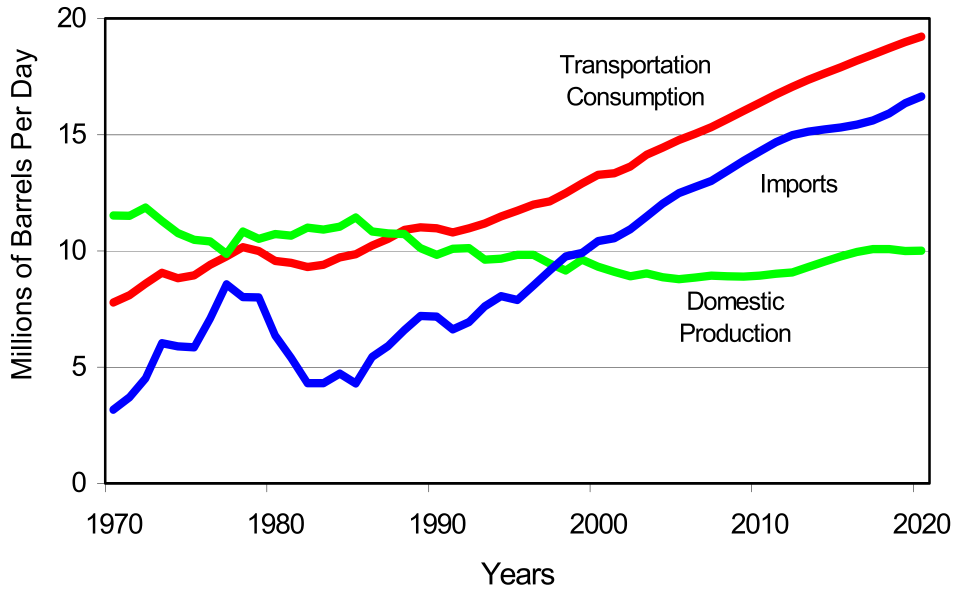
- A significant improvement in air quality in the United States, resulting from near zero emission vehicles and clean power generation systems that operate on fossil fuels, and from zero emission vehicles and power plants that run on hydrogen.

- Modular power —fuel cells have the potential to be used in a wide range of applications ranging in power level from a few watts to more than a megawatt.

For the purposes of this report, the Department did not attempt to quantify benefits of fuel cell commercialization and compare them to the expected public and private sector costs necessary to achieve commercialization.

America's need for increased energy supply and diversity will only grow as the economy grows, expanding the demand for petroleum at a pace that almost certainly will exceed our best efforts to expand traditional sources of domestic production. While estimates vary, credible industry assessments place the total volume of U.S. petroleum imports at some 15 million barrels per day by 2020, assuming no dramatic breakthroughs are introduced in vehicle technology. The transportation sector remains the primary driver of petroleum demand. The introduction of fuel cell technologies at a level that would significantly impact petroleum consumption will require significant technology advances. (See Figure 2.)

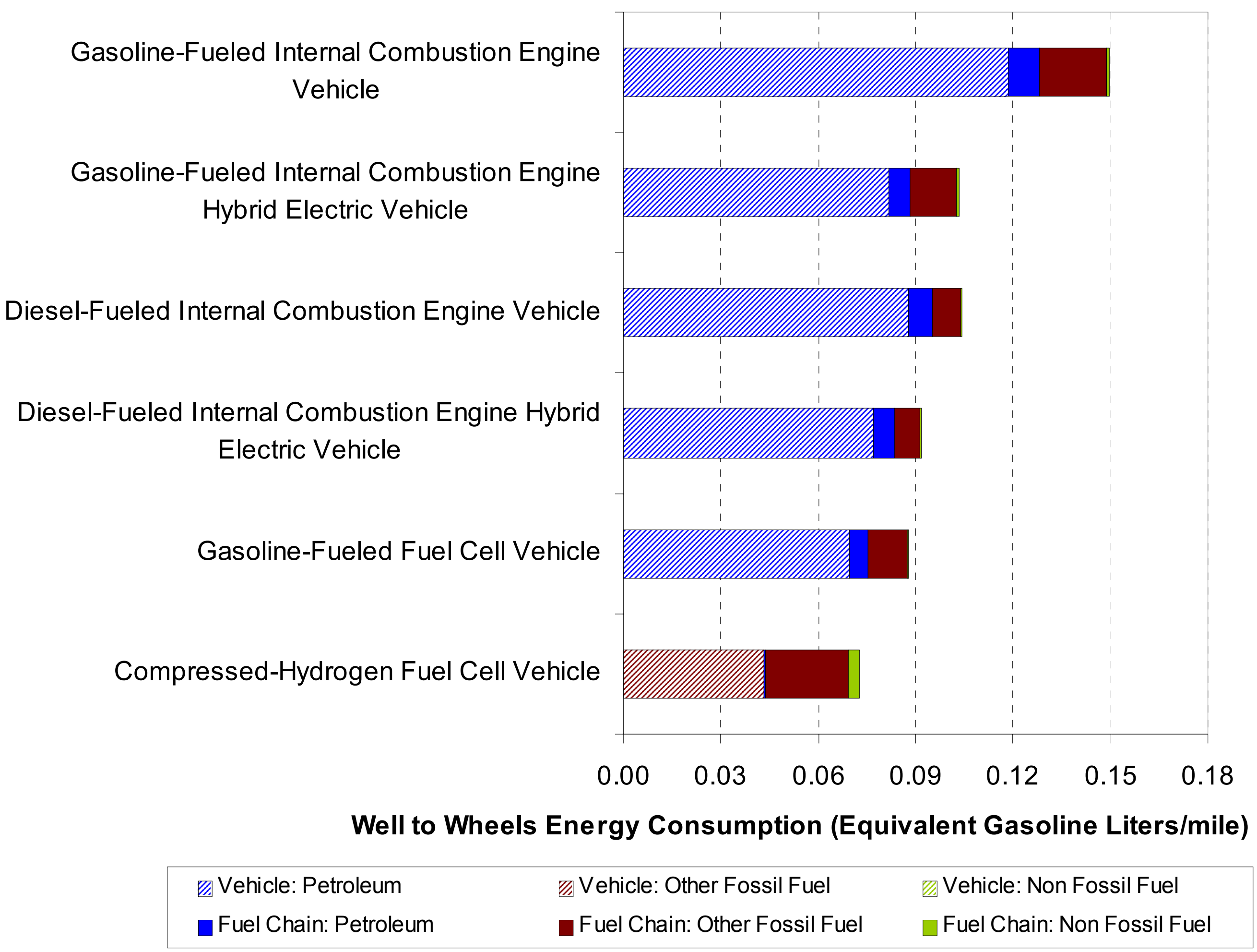
Figure 2. U.S. Petroleum Dependence and Transportation



Source Data: Energy Information Administration
Note: Does not show petroleum use by other sectors

The Department believes that successful development efforts can lead to a commercialization decision in 2015, and fuel cell vehicles could hit the showrooms by 2020. While successful development of hydrogen fuel cell technology would have virtually no impact on trends through 2020 (shown in Figure 2), reductions in oil imports and transportation consumption would be expected to begin after 2020. In fact, if mass penetration of fuel cell vehicles were achieved by 2040, light-duty oil use could be reduced by 11.6 million barrels per day. (This reduction represents approximately the amount imported today.) Due to the increased efficiency of fuel cells and the anticipated use of nuclear and renewable sources, this penetration also should significantly reduce the production of greenhouse emissions, on a per-mile-driven basis, compared to conventional internal combustion engines. (See Figure 3.)

Figure 3. Energy Consumption by Vehicle Type



Source: ADL-DOE Fuel Choice for Fuel Cell Vehicles Study Results, February 2002

Fuel cells are expected to be suitable for a wide range of applications. (See Figure 4.) Transportation applications include vehicle propulsion and on-board auxiliary power generation. Portable applications include consumer electronics, business machinery, and recreational devices. Stationary power applications include stand-alone power plants, distributed generation, cogeneration, back-up power units, and power for remote locations.

Figure 4. Fuel Cell Technologies and Their Applications

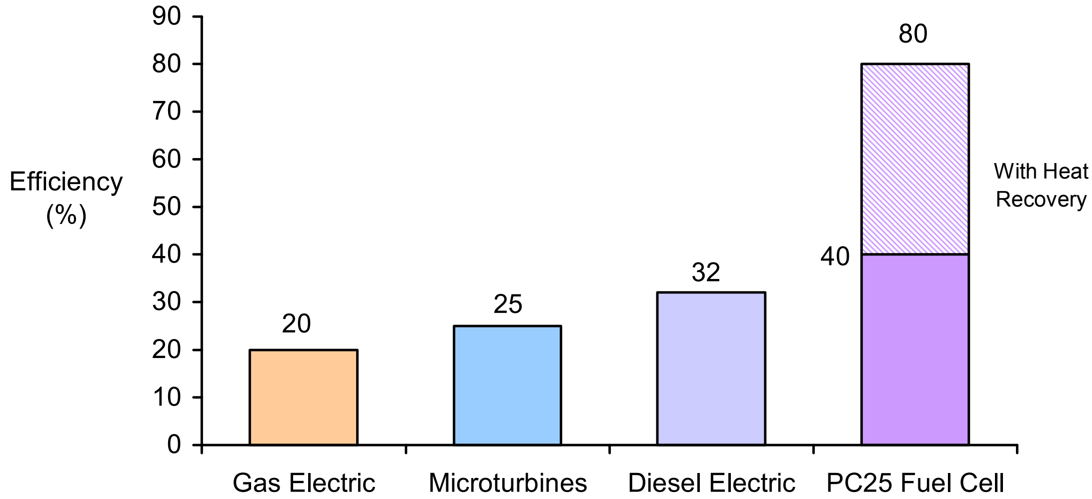
Target Applications				Polymer Electrolyte Membrane Fuel Cell (PEMFC)	Alkaline Fuel Cell (AFC)	Phosphoric Acid Fuel Cell (PAFC)	Molten Carbonate Fuel Cell (MCFC)	Solid Oxide Fuel Cell (SOFC)
	Stationary-Distributed	Grid Sited	Central	○	○	○	●	●
			Distributed	○	○	○	●	●
			Re Powering	○	○	●	●	●
		Customer Sited Cogeneration	Residential	●	◒	○	◒	●
			Commercial	●	◒	●	●	●
			Light Industrial	◒	◒	●	●	●
			Heavy Industrial	○	○	●	●	●
	Transportation	Propulsion	Light Duty	●	○	○	○	○
			Heavy Duty	●	○	◒	◒	◒
		Auxiliary Power Unit	Light & Heavy Duty	●	○	○	○	●
	Portable	Premium	Recreational, Military	●	○	○	○	●
		Micro	Electronics, Military	●	○	○	○	○

● Likely
◒ Under consideration
○ Unlikely

There are several different fuel cell technology paths being pursued. These divide into low temperature and high temperature technologies. Low temperature technologies, including phosphoric acid and polymer electrolyte membrane fuel cells (PAFCs and PEMFCs), target transportation, portable power, and lower-capacity distributed power applications; while high temperature technologies, including molten carbonate and solid oxide fuel cells (MCFCs and SOFCs), focus on larger stationary power applications, niche stationary and distributed power, and certain mobile applications. A combination of technology developments and market forces will determine which of these technologies are successful. Currently, phosphoric acid fuel cells are the only commercially available fuel cells. More than 200 of these "first generation" power units are now operating in stationary power applications in the United States and overseas. Most are the 200-kilowatt PC25 fuel cell manufactured by UTC Fuel Cells.

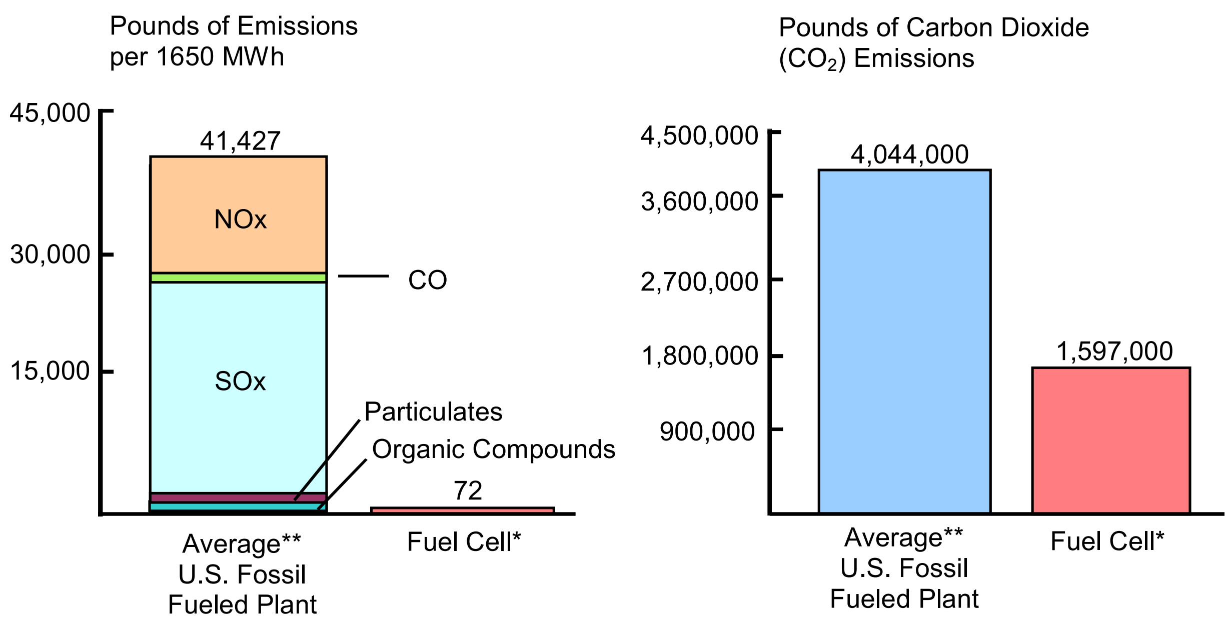
In the long run, fuel cells could increase the efficiency of electric power generation and reduce emissions, thereby providing environmental and health benefits. (See Figures 5 and 6.)

Figure 5. Phosphoric Acid Fuel Cell Efficiency Comparison



Source: United Technologies

Figure 6. Phosphoric Acid Fuel Cell Emissions for One Year of Operation



Sources[i]: United Technologies, 1994 and US DOC, 1993

* Fueled by Natural Gas, without sequestration
**An "average" fossil fueled plant consisting of 83% coal, 11.5% natural gas, and 5.5% oil[ii]

Fuel cells may also provide national security benefits: fuel cells could be among the technologies that support the planned transformation of the U.S. military into a more mobile and stealth precision strike force. Portable fuel cells may be well suited to extended field operations, as battery replacements, or as auxiliary power units. Moreover, low-temperature fuel cells produce little heat signature and can operate quietly. (Appendix A describes how fuel cells work.)

By 2020, fuel cell applications could benefit all key energy-related interests. The public stands to gain from greater national, economic, and energy security, and from lower emissions; industry stands to gain from numerous commercial opportunities, assuring itself a share of what may be an enormous business globally; and the individual consumer stands to gain from the introduction of a vast array of new power sources. Notwithstanding the potential future national benefits, high costs and unproven long-term performance have limited fuel cell commercialization to date. It is for this reason that governments—in the United States and abroad—have played a role in fuel cell development by funding research and development and demonstration projects to prove commercial viability. (See Appendix B for a description of international efforts.)

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Technical and Economic Barriers to Commercialization

Significant additional R&D would need to be conducted to achieve cost reductions and improved durability—the key technical barriers to the commercialization of fuel cells.

Over the past ten years, cost-shared fuel cell R&D funded primarily by the U.S. Department of Energy at U.S. national laboratories, universities and private companies, has improved several fuel cell technologies through significant size and cost reductions (each by a factor of ten). However, the cost of fuel cells still remains high and has made them unaffordable for most consumers, and very few products are available with full commercial warranties and a track record for reliable operation. Additional cost reduction (by a factor of ten) through technology development programs, such as the Solid State Energy Conversion Alliance (SECA) and FreedomCAR, would be required to help assure their commercial viability in each of the markets. Ultimately, mass-production of fuel cells would further reduce manufacturing cost.

Proving full performance and reliability of fuel cell systems over the required life in field applications is a prerequisite for all applications. Figure 7 shows the major barriers to commercialization according to the application in which the technology is employed.

Figure 7. Barriers to Fuel Cell Commercialization

Application	Barriers	Difficulty
Transportation	Cost Durability Fuel Infrastructure Hydrogen Storage	High High High High
Stationary-Distributed Generation	Cost Durability Fuel Infrastructure Fuel Storage (Renewable Hydrogen)	High Medium-High Low Medium
Portable	Cost Durability System Miniaturization Fuels and Fuel Packaging	Medium Medium High Medium

In stationary applications, especially, a long system life—twenty years or longer—is key to commercial viability. Components such as stacks that must be replaced during 5-10 year periods must be available at low costs and be compatible with earlier generations. Durability testing of some early fuel cell technologies has been very promising, but given the significant cost reduction still required (through lower cost materials and high volume manufacturing), durability will continue to be a major challenge.

In transportation applications, private enterprise commercialization will require massive investments in supporting infrastructure, including the development of large-scale hydrogen fuel production, distribution, and storage systems. The risks for private enterprise are compounded further by a lack of common codes and standards that would ensure fair trade opportunities, compatibility with zoning and safety requirements, and consistent regulations essential for high-volume, low-cost manufacturing.

Portable power applications require operating characteristics that are not required by larger power plants such as miniaturization, shock and vibration resistance, orientation insensitivity, and passive operation.

The use of hydrogen for fuel cells opens a path to increased energy resource diversity, including increased use of renewable energy sources, as they become cost-effective.

Hydrogen has great potential as a fuel but is not itself an energy source. Like electricity, hydrogen is an energy carrier. Since hydrogen can be produced from a wide variety of resources, it is an attractive fuel for fuel cells in transportation and eventually in stationary applications, if centralized production and distribution are feasible. In the near term, it is likely that hydrogen would be produced from fossil fuels (for example, petroleum feedstocks and natural gas) or from electricity using an electrolyzer; improving the cost and efficiency of these conversion methods is a major goal for current programs. Electrolyzer production of hydrogen may be practical in the near term (from a distribution standpoint) but would not result in net energy and environmental benefits using the current electric grid. Sequestration of carbon dioxide, as it becomes feasible, could be applied to generation of hydrogen from fossil fuels, leading to greater reductions of greenhouse gas emissions.

The longer-term strategy, however, is to derive an increasing portion of the hydrogen needed for fuel cells from renewable sources, such as converting water by electrolysis using wind or solar power, producing hydrogen from bio-mass or photo-catalytically using sunlight. Production of hydrogen from coal (with carbon sequestration) and nuclear power (by thermo-chemical process or electrolysis) is also feasible, and can improve energy security by increasing energy diversity. Many of the technologies developed for a near-term fossil-based hydrogen infrastructure would be applicable to a renewable hydrogen infrastructure, easing the transition to a sustainable hydrogen economy.

If hydrogen is to succeed as the fuel of choice because of its energy resource diversity and environmental benefits, safe and cost effective means of hydrogen storage would have to be developed for vehicle applications. Storage is a problem because of hydrogen's low volumetric energy density. Current storage systems are either too heavy, too large, or both. Hydrogen storage is also an important aspect of renewable energy production. During off-peak hours, electricity can be transformed into hydrogen through electrolysis, and the hydrogen is then re-converted by a fuel cell into electricity on demand. Safety and regulatory issues are also substantial barriers to hydrogen utilization.

A new hydrogen refueling infrastructure would be required for automotive fuel cell technology in order to achieve the potential energy and environmental benefits.

Structured fuel chain analyses undertaken by DOE and others increasingly lead to the conclusion that the preferred long-term fueling option for fuel cell vehicles is to store hydrogen on-board the vehicle. However, a hydrogen refueling infrastructure, which includes production, delivery, and refueling, along with the necessary codes and standards, would need to be developed in order to provide hydrogen for vehicles. This involves the development of new technologies and entails significant investment risk and regulatory barriers for the participants in this industry. Although production of hydrogen on-board the vehicle from a hydrocarbon or alcohol fuel has been proven feasible in principle and can reduce refueling infrastructure investments, the on-board storage of hydrogen, assuming acceptable vehicle range can be achieved, results in potentially greater energy independence because of increased feed stock flexibility.

However, storage of hydrogen on-board the vehicle shifts some of the risks from the vehicle to the infrastructure. The energy and environmental benefits depend greatly on how the hydrogen is manufactured and on carbon sequestration feasibility (for fossil feed stocks). Therefore, critical "well to wheels" analyses have to be applied to pathways for hydrogen production, delivery, and storage to ascertain the potential for "net" energy and environmental benefits compared to conventional fuel and vehicle technologies.

If hydrogen can be generated efficiently on board the vehicle from gasoline and alcohol fuels, the infrastructure barriers would be greatly diminished and significant energy and environmental benefits could still be realized. On-board generation is an important transition strategy to get around the current hydrogen storage problem and the lack of hydrogen infrastructure. However, fuel-processing technologies, for vehicle applications, have yet to achieve the performance necessary to supply hydrogen with the purity levels to ensure adequate life of the fuel cells. Therefore, durability is a greater issue with vehicle fuel cell systems that require on-board fuel processing or reforming rather than those using hydrogen directly. In transportation applications, fuel processors are also currently incapable of rapid start-ups or of quick response to fluctuating fuel demand—risking system shutdown or catalyst contamination. Fuel processor downsizing is required before commercial use can be established in transportation, portable, and small stationary applications.

The clear need for further research and development to overcome these obstacles highlights the substantial business risks associated with transportation and stationary fuel cell systems development. Although cost reductions may be obtained through the eventual development of high-volume manufacturing technologies, production volume alone will not suffice to reduce costs to a competitive level. Substantial research and development is required for new materials and simpler, more durable systems that can withstand the variable operating conditions that will be found in real world environments.

The investment risk on long-term research and development is, in practice, difficult for private enterprises to absorb. In many applications, immediate gains can be realized in the incremental improvement to existing technologies that directly compete with fuel cells even though these technologies cannot ultimately achieve the public benefits desired. Therefore, in order to meet these high-risk technology challenges while achieving the desired public benefits, continued support for R&D from the U.S. Government for industry is key.

Liability and safety concerns add to the business risk and make it difficult to define warranty terms and to obtain insurance from underwriters for fuel cell systems. Liability concerns are partly an outgrowth of a lack of coordinated codes and standards. The timely establishment of common codes and standards would help ensure compatibility with zoning and safety requirements, reducing business risk and making the returns to research and development more obvious. Appropriate codes and standards are difficult and time-consuming to develop for new technologies, and especially for vehicle applications that require large-scale investment in complex infrastructures, but early efforts to develop common codes and standards could moderate business risks substantially through insurability. International coordination to obtain uniform codes and standards would help in the export of fuel cell products and enhance the ability to compete globally, and accelerate the adoption of fuel cell technologies.

For additional information on the technical and economic barriers facing hydrogen and fuel cell technologies, please see Appendix C.

Recommendations on Program Adjustments

The National Energy Policy Report, issued in May of 2001, directs the Secretary of Energy "to develop next generation technology - including hydrogen…" and to "focus research and development efforts on integrating current programs regarding hydrogen, fuel cells, and distributed energy." Thus, DOE has since been planning and implementing a comprehensive integrated hydrogen/fuel cell program, and in the process identified program adjustments that are being incorporated. In addition, these program efforts continue to be coordinated between DOE's Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy, Office of Nuclear Energy, and Office of Science, as well as with other Federal agencies.

As a part of the planning process, DOE organized a National Hydrogen Energy Roadmap Workshop, held in Washington DC in April 2002, to obtain stakeholder input for outlining key issues and challenges in hydrogen energy development and suggesting paths that government and industry can take to expand use of hydrogen-based energy. A critical component of this Roadmap, released by the Secretary of Energy in November 2002, addresses fuel cell technology as an efficient way of utilizing hydrogen to produce electricity. While this activity was underway, DOE was responding to the Congressional request for a Fuel Cell Report to Congress. The inputs received from industry and other key stakeholders in development of the roadmap were integrated with the four workshops held with industry to develop this Fuel Cell Report to Congress. The aim of all adjustments is to implement an integrated focused R&D program to aggressively pursue the development and field testing of the critical technologies needed to accelerate the commercial introduction of fuel cells.

Current DOE Fuel Cell R&D Programs

DOE supports the largest budgets for fuel cell R&D, although other agencies (e.g., DOD, NASA) continue to make significant investments as well. Fuel cell R&D responsibilities at DOE now reside in two organizations. One of these, the Office of Fossil Energy (FE), supports the development of high-temperature fuel cell systems, operating on natural gas and syngas (derived from a variety of fuels including coal) for primarily stationary and distributed generation applications. Fuel cell technologies that are supported through this program are solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC). The total funding request for FY 2003 is $47.0 million, of which approximately $11.5 million is allocated towards the Vision 21 projects that develop clean central station generation technologies. The remainder is allocated to technologies that are more focused on distributed generation applications. A cornerstone activity of the FE fuel cell program is the Solid State Energy Conversion Alliance (SECA), a partnership between DOE, the National Laboratories, and industry. The aim of SECA is to develop and demonstrate planar solid oxide fuel cells for distributed generation applications. Performance and cost goals for the SECA Program are shown in Figure 8.

Figure 8. SECA Performance & Cost Goals

<table>
<tr><th></th><th colspan="2">Fuel Cell System</th><th>Fuel Cell/Turbine Hybrid System</th></tr>
<tr><td>Capital Cost</td><td colspan="2">$400/kW</td><td>$400/kW (includes turbine)</td></tr>
<tr><td>Maintenance Interval</td><td colspan="2">3,000 hours</td><td>3,000 hours</td></tr>
<tr><td rowspan="2">Electrical Efficiency (Full Load, LHV)</td><td>Auxiliary Power Unit</td><td>50%</td><td rowspan="2">60-70% (adaptable to coal gas)</td></tr>
<tr><td>Stationary</td><td>60%</td></tr>
<tr><td rowspan="2">Design Life</td><td>Auxiliary Power Unit</td><td>5,000 hours</td><td rowspan="2">40,000 hours</td></tr>
<tr><td>Stationary</td><td>40,000 hours</td></tr>
<tr><td>Emissions</td><td colspan="2">Near Zero</td><td>Near Zero</td></tr>
</table>

DOE's Office of Energy Efficiency and Renewable Energy (EERE) develops fuel cell technologies with an emphasis on the polymer electrolyte membrane (PEM) fuel cell for both stationary and transportation applications. In general, PEM technology, a low temperature fuel cell system, has attractive performance characteristics for smaller scale systems, while the high temperature systems developed under the Fossil Energy program are most attractive in larger sized systems. The FreedomCAR partnership between DOE and USCAR (a pre-competitive research organization consisting of General Motors, Ford and DaimlerChrysler) is the vehicle through which PEM fuel cells are being developed for use in automotive applications. EERE also has the responsibility for developing PEM fuel cells for portable and distributed generation applications as well as the technologies required for the hydrogen energy infrastructure that is important in the long-term for large scale use of PEM fuel cells. Until recently, these different responsibilities resided in separate organizations within EERE.

The recent reorganization within EERE addressed a recommendation in the National Energy Policy to integrate hydrogen and fuel cell activities by creating the Hydrogen, Fuel Cells & Infrastructure Technologies Program. The reorganization recognizes the direct linkage between the need for a robust cost-effective hydrogen infrastructure and the effective utilization of fuel cell technologies. This new office consists of three teams: Hydrogen Production, Hydrogen Storage, and Fuel Cells. Similarly, the FreedomCAR Partnership now includes a Hydrogen Storage and Refueling Interface Technical Team, a Fuel Cell Technical Team, and a new team being formed to address hydrogen production and infrastructure issues. The teams will consist of automotive and energy industry professionals along with DOE personnel to ensure adequate industry inputs in the planning and evaluation of program activities.

The FY 2003 budget request for the integrated EERE program is $97.4 million, split between PEM fuel cell R&D ($57.5 million), and hydrogen production, infrastructure, and storage R&D ($39.9 million). Figure 9 presents performance and cost goals for the FreedomCAR partnership.

Figure 9. FreedomCAR Performance & Cost Goals (all 2010 except as noted)

	Efficiency	Power	Energy	Cost	Life	Weight
Fuel Cell System	60% (hydrogen) 45% (w/reformer)	325 W/kg 220 W/L		$45/kW $30/kW (2015)		
Hydrogen Fuel/ Storage*/ Infrastructure	70% well-to-pump		2kW-h/kg 1.1kW-h/L 3.0kW-h/kg 2.7kW-h/L	$5/kW-h $2/kW-h $1.50/gal (gas equiv.)		
Electric Propulsion		≥55kW 18s 30kW cont.		$12/kW peak	15 years	
Electric Energy Storage		25kW 18s	300 W-h	$20/kW	15 years	
Materials						50% less
Engine Powertrain System	45% peak			$30/kW	15 years	

*Due to a recent assessment of hydrogen storage needs, technology goals have been revised and are currently under review.

Proposed Program Adjustments

Core Technology Development

The critical technology development areas are advanced materials, manufacturing techniques, and other advancements that will lower costs, increase durability, and improve reliability and performance for all fuel cell systems and applications. These activities need to address not only core fuel cell stack issues but also balance of plant

(BOP) subsystems such as: fuel processors; hydrogen production, delivery, and storage; power electronics; sensors and controls; air handling equipment; and heat exchangers.

Research and development areas include:

Polymer Electrolyte Membrane Fuel Cells

- Slightly higher temperature (80-120°C), lower cost membrane materials for more efficient waste heat utilization for cogeneration in stationary/distributed applications or as process heat in a fuel reformer, reducing radiator size for transportation applications and for reduced carbon monoxide (CO) management requirements. The result would be a simplified balance of plant and increased life (due to reduced sensitivity to reformate impurities).

- New, low-cost catalyst materials (reducing or possibly eliminating precious metals) that achieve useful power densities and are resistant to damage from CO or sulfur compounds would benefit both fuel cell and fuel processor technologies.

- A go/no go decision for on-board fuel processing work is scheduled for June 2004. The primary criteria for this decision will be the identification of a credible path to achieve 30 second start-up time target.

- Long life, low cost, and high efficiency air handling equipment to allow operation within weight, volume and cost requirements.

Solid Oxide Fuel Cells

- Stack material and architecture combinations that allow for effective sealing and reduction in life-limiting thermal stresses during thermal cycles.

- Electrolyte/electrode/separator plate material combinations allowing high (over 500 mW/cm^2) power densities at the stack level (not just cells) for achievement of low cost goals.

- Long life, high effectiveness, high temperature heat exchangers for process flow heat recovery subsystems for high system efficiency.

- Stack architectures (including material combinations) that can realistically implement internal reforming leading to reduced costs and long life.

Molten Carbonate Fuel Cells

- Stack materials and configurations to significantly increase power densities above current levels to approach cost targets consistent with large markets.

- Advanced corrosion-resistant materials for stack construction that can result in stack lifetimes in excess of 40,000 hours.

Hydrogen Production, Storage and Infrastructure

- Production technology that enables hydrogen to be produced from domestic sources – initially natural gas and eventually clean coal, nuclear energy, biomass and other renewable sources.

- Compact, lightweight, and cost-effective hydrogen storage systems enabling greater than 300 mile range in all light-duty vehicle platforms.

- Delivery technology capable of providing hydrogen fuel so that when the fuel cell vehicles are commercially available, people can fill them up at their convenience.

Sensors

- Sensor and control technology with the proper ranges and selectivities for integrated fuel cell system application.

- Low cost sensors for detecting hydrogen leaks and other safety related requirements.

Codes and Standards Development

The Federal government is in a unique position as a neutral third party to catalyze and coordinate the work of professional societies and trade associations in codes and standards development. The development of codes and standards is of interest to all parties and is clearly pre-competitive in nature. It is important that appropriate codes/standards are in place as fuel cells approach commercial readiness in order to allow these technologies to successfully enter the market. A clear understanding of codes and standards would help to guide R&D programs to ensure technology compliance in advance. The scope of ongoing codes and standards activities would need to be expanded to include a broader range of applications, system architectures, and technology options especially regarding the use of hydrogen. The government should work with the appropriate organizations to create a centralized, coordinating authority to ensure the compatible development of a comprehensive and rigorous set of codes and standards.

Education

Educational materials would help to introduce hydrogen and fuel cell systems to consumers, and to clearly communicate the hydrogen vision to potential end users, local governments, and others. These educational materials address the National Energy Policy recommendation to communicate hydrogen benefits, safety, and utilization information to key stakeholders. In collaboration with industry and education organizations, a curriculum and training program for elementary and secondary school teachers would be created. The effort would pair teachers with local industry experts and involve practicing teachers in the development of a usable curriculum for education about hydrogen and fuel cells, as well as a training program for teachers to use the curriculum. Building on current Department efforts, the scope of university programs would be expanded to provide more students opportunities to research hydrogen and fuel cell technologies.

Regional, State, and local networks would be established to involve code officials, building engineers, energy regulators, and consumers in regional hydrogen technology demonstrations including education on installation, codes and standards, and safety issues. These regional programs would provide information exchange and networking to seek solutions to local hydrogen implementation barriers.

Proposed Government-Industry Partnerships

To ensure the proper federal role in the collaboration between government and private enterprise in fuel cell development, the Department over the last year has organized a series of discussions with industry stakeholders to determine cooperative program needs and objectives. Stakeholders representing each fuel cell application (transportation, stationary and distributed generation, and portable) provided input.

The challenges facing cooperative programs vary by application. Stationary, distributed generation, and portable—the so-called "early markets" —appear to be closest to commercialization but face cost challenges that may limit market penetration. At the other end of the spectrum, transportation applications and supporting hydrogen infrastructure are longer-term and entail the greatest complexity and uncertainty. Reaping the dividends from transportation fuel cell applications requires that stakeholders tackle complexity and uncertainty effectively; only then can the promise of reduced dependence on foreign oil be realized. However, this requires the development of near-, mid- and long-term strategies for production of hydrogen from primary energy resources.

The Department has been working with developers of fuel cell-related technologies, the automotive industry, energy providers, and the electric utility industry to accelerate the development of fuel cells. The strong partnerships that have been established to plan and support research and development should continue, but they alone may not be sufficient. For instance, the Solid State Energy Conversion Alliance (SECA) is a DOE-sponsored government-industry partnership seeking to lower the cost and improve the performance of fuel cell technology for a wide range of applications. Likewise, FreedomCAR is a cooperative research partnership between DOE and the U.S. Council for Automotive Research, to develop technologies that will enable the mass production of affordable hydrogen-powered fuel cell vehicles. Fuel cell technology is approaching the point at which limited "learning" demonstrations would be useful to focus ongoing R&D. New partnerships between the public and private sectors would help share the risks of this new activity. Moreover, the variety and scale of industry investments required for the successful commercialization of fuel cells require a coordinated effort among multiple companies.

A cooperative approach to the development of a hydrogen infrastructure involving the U.S. Government, the energy and auto industries, as well as other government organizations, would help achieve potential benefits.

Public-private cooperation is needed because of the magnitude of the technology challenges, and the associated regulatory and anti-trust issues. Anti-trust concerns of the energy industry as it develops and demonstrates the new infrastructure in a collaborative manner must be addressed, especially as it pertains to the initial placement of refueling stations to provide adequate coverage. The Department of Energy is working with energy providers to determine the form and function of a potential partnership to evaluate the merits of a hydrogen-based fuel infrastructure. An appropriate level of government involvement in targeted areas can assist industry in being competitive in global markets.

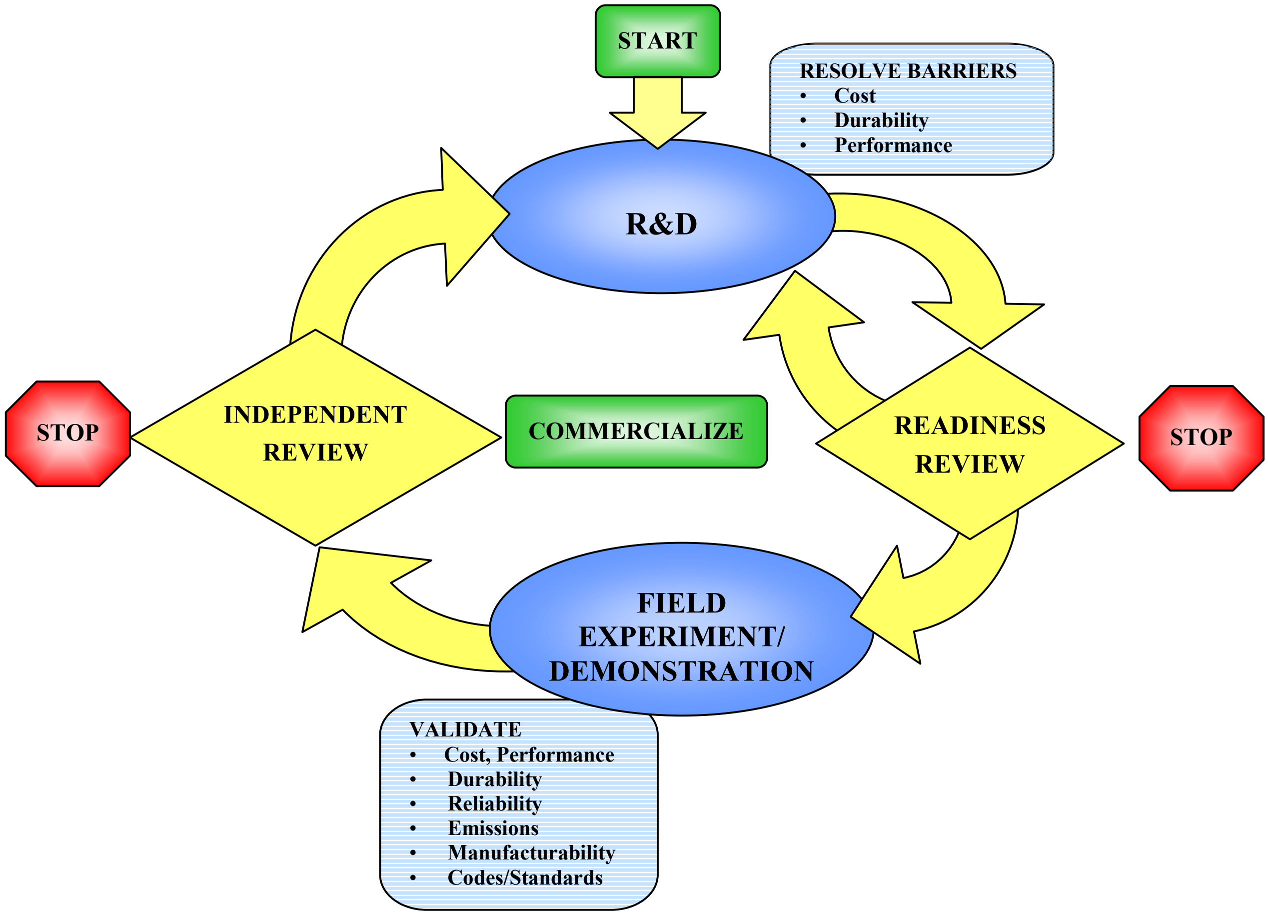
The targeted areas envisioned for public/private partnerships include:

- Continued investments in advanced R&D to support the development and deployment of improvements that address the technical and cost barriers to commercialization of fuel cells. Advanced R&D should focus on cost reduction and durability improvement for all applications. Hydrogen storage and fuel delivery infrastructure R&D, in particular, would be focused on vehicle applications. This R&D, if needed, would leverage the capabilities of the U.S. national labs and universities in fuel cell science and technology. Controlled field experiments should be conducted to verify technology characteristics and to provide better focus on what R&D is needed. (See Figure 10.)

- Demonstrating the validity of performance-based success criteria used.

- Rigorous and periodic supporting analysis and systematic assessment, the status of the technologies, their commercial prospects, their costs, their potential impacts. If necessary, the partnerships would be refocused on those options with the greatest potential impact. For example, one important area is for the government to work with energy providers to define and estimate the costs of installing hydrogen infrastructure for vehicle applications. Systematic analyses to evaluate the economics, emissions, energy use, and other secondary costs and benefits need to be conducted across all aspects of the life cycle.

Figure 10. The R&D – Field Experiment Cycle



Timing is critical; "due diligence" to evaluate economic and technical barriers would be essential prior to and after each R&D and demonstration phase. A key aspect of "due diligence" is that long-term cost and reliability targets must be truly feasible before proceeding to the next phase.

If the public-private partnerships are successful, industry would have the information necessary to make decisions regarding investment for commercialization of stationary and distributed generation fuel cell power systems, hydrogen infrastructure, and fuel cells for transportation applications. However, widespread commercialization of fuel cells depends on a variety of market factors, including the development of competing technologies.

The specific roles of the stakeholders will vary considerably, depending on the partnership and on the development effort that is being pursued. But they should follow the principles developed by participants in the four supporting workshops referenced in the Scope Note of this document. (See Figure 11.)

Figure 11. Principles for Government and Industry Stakeholders

The Federal Government's role should be guided by the following principles:

- *Provide a leadership role by setting realistic goals for Federal investments and tracking and reporting progress and performance.*
- *Utilize universities and the national laboratories where appropriate to continue to research and develop breakthrough technologies and to support industry through cost-shared research and development contracts.*
- *Where appropriate, conduct demonstrations, with appropriate industry cost-sharing, to validate performance of technologies and infrastructure, and assist industry in reducing manufacturing costs.*
- *Develop the Federal policy framework and where appropriate the regulatory structure for the new energy paradigm, and develop the codes and standards required for the new energy infrastructure.*
- *Educate the public and increase its awareness about the new energy technologies and manage expectations.*

The private sector's role should be guided by the following principles:

- *Continue a robust product development effort to meet application cost and performance targets.*
- *Cost-share in research, development, and demonstration projects, sharing the results of field validation efforts.*
- *Work closely with the public sector to develop consensus codes and standards.*
- *Share with the public sector, with appropriate confidentiality, performance data, cost information, and commercialization plans.*
- *Provide input to the Federal Government's effort to develop a policy framework.*

Public sector partners with the Department of Energy could include:

- Federal Technology Development Agencies. This group includes agencies such as the U.S. Department of Transportation, the U.S. Department of Defense, and the National Aeronautics and Space Administration, which are actively working with industry in developing fuel cell technology to meet their missions.

- Other Federal Agencies. This group includes agencies such as the U.S. Department of Commerce, U.S. Environmental Protection Agency, Federal Energy Regulatory Commission, and the U.S. Department of Treasury to facilitate technical information exchange.

- State Agencies, Local Agencies, and Federal Agencies/Military Field Activities. This group could have a critical role in establishing a positive environment for the demonstration of fuel cells. They can deter or facilitate technology evaluations. This group may also be early customers of fuel cell technology prior to full commercialization.

The primary partners from the private sector could include:

- Technology Developers. This group includes companies, research laboratories and others developing fuel cell, fuel processing, and hydrogen-related technologies, and would be responsible for achieving the required performance and cost targets established for research.

- Suppliers and Original Equipment Manufacturers. This group includes industrial entities that supply components and/or subsystems and the companies that integrate and build the final product for the consumer.

- Utility and Energy Providers. This group would be responsible for providing electricity and/or fuel (such as natural gas and hydrogen), to the consumer.

- Risk Managers. This group includes organizations that do independent testing of products and that verify quality and safety, that is, the insurance industry, which underwrites risks, and the investment banking industry, which generates the equity needed for such an effort.

Another group of important stakeholders includes environmental and other non-profit organizations, such as professional societies and trade associations that play an important role in developing industry consensus, and in establishing codes and standards.

Portable Power and Stationary-Distributed Generation Partnership

The "early markets," which are defined as high value markets where customers are already willing to pay a premium for the benefits that fuel cell systems can provide, will likely be the first markets to be commercialized. In these markets, fuel cells could be employed in a wide variety of applications, including defense applications.

Portable Power Applications. One class is commonly referred to as "portable applications." The fuel cell industry is actively developing small capacity units for a variety of portable and premium power applications ranging from 25-watt systems for operation of portable electronics to 10-kW backup power systems for critical commercial functions. Although these applications, by themselves, will not save significant amounts of energy, their development can assist demonstration and development programs in other applications through advances in technology, as well as regulations affecting fuel supply, transport, and storage, are areas in which a public sector role is appropriate.

Portable applications will provide early exposure of the public to fuel cell technology, thereby potentially facilitating a more rapid introduction of fuel cell systems by sustaining private investment. Most of these portable applications will use direct methanol or hydrogen as the fuel (hydrogen is critical to the longer-term success of transportation applications). Finally, the core technology platforms relative to materials and high-volume manufacturing techniques for portable applications are similar to (in some cases identical to) those that will be used for transportation applications.

Although no formal partnership is planned in the area of portable power, the government could assist commercialization by sponsoring research and coordinating the accelerated development of codes and standards that are needed to allow the use of these portable systems across a wide range of applications. When economically justified, government could also purchase and test significant numbers of systems showing commercial potential in order to provide independent verification of performance and benefits, thereby enhancing technology credibility with potential buyers. Further, selected support of technology research synergistic with transportation and stationary applications could reduce risks. Perhaps most important, government involvement could help assure continued momentum in commercial investment in portable applications.

Stationary and Distributed Power Applications. Another class of early market applications includes stationary and distributed generation for residential and commercial buildings. This sector consumes just over one-third of the Nation's electricity. As deregulation of the electric utility industry progresses, this sector may find that generating its own electric and thermal energy is a desirable option. A robust research and development partnership (such as SECA) can help to develop very low cost fuel cells. Commercialization may be accelerated by a public-private cooperative partnership to promote field testing and validation of system and component performance under actual operating conditions, and where needed, a program to establish interconnection standards, to address codes and standards, and to help develop a dual-use infrastructure that supports both transportation and stationary applications.

National electricity markets are evolving as deregulation is considered and implemented and as environmental pressures, including local air quality and global climate concerns, mount. Fuel cell systems may become increasingly attractive in an era of restructuring.

Implementation. The Department has formed cost-shared partnerships with industry to research and develop stationary and distributed fuel cell systems based in the near-term primarily on natural gas, but also using propane (for remote areas) and in the longer-term on coal-derived gas. The Department continues to work within these industry partnerships to develop road maps establishing well-defined technical targets, goals, and implementation strategies for stationary fuel cell systems that will result in reduced demand on the nation's energy resources. The technology developed will facilitate a multitude of stationary and portable applications, including power for commercial buildings, auxiliary power units, consumer electronic products, and uninterruptible power supplies. The benefits of stationary fuel cells include the ability to generate independent power, with clean, highly efficient fuel cell systems to generate high quality power, the potential to supply power back to the grid during peak loads, and the potential to provide emergency back up power for medical services, communication, and other basic needs during power outages.

Over the last several years, phosphoric acid, tubular solid oxide, and molten carbonate fuel cell systems have been demonstrated at greater than 200 kW. These stationary and distributed demonstrations have validated the current costs of $4,000-12,000 per kW, and reliability of 10,000-20,000 hours. As further research and development improves cost and reliability, Federal and State governments can team with private industry to share risks and costs of limited prototype tests, initially of systems in the 3-50 kW range. Cost reduction and technology improvement managed by partnerships like SECA are critical in the current phase of technology development. (See Figure 12.) Only technologies that have the potential to approach an installed cost target of $400/kW would be pursued through further research, development, and demonstration. This cost target is based on 5 kW modular systems at a production volume of 100,000 units. A more detailed study is planned to develop cost targets for specific applications.

If successful, the next phase, during 2005-2008, would involve continued emphasis on research to lower costs, improve reliability, and increase electrical efficiency. As the cost target of $400/kW is approached, increased numbers of stationary fuel cell systems could be sited by 2008 in residential building and distributed generation applications.

Figure 12. Stationary and Distributed Generation Timeline to Obtain Commercialization Information

	2000–2005	2005–2008	2008–2010	2010–2015
	Phase 1 **Cost Reduction/ Technology Improvement** **Small System**	**Phase 2** **Cost Reduction/ Technology Improvement/ Limited Commercialization** **Small System**	**Phase 3** **Large Scale Commercialization/ Multiple Applications** **Small System**	**Large System Demonstration and Commercialization** **Fuel Cell/ Turbine Hybrids Distributed Generation** **Coal Based Central Generation**
Objectives	• Develop stack design • Develop manufacturing methods	• Incorporate lower cost, robust materials	• Optimize system, thermal integration	• Use small system technology in larger hybrid and coal based systems • Hybrid efficiency - 60-70% • Coal based efficiency – 60%
	R&D to establish initial performance and reliability Limited 3 to 50 kW prototype tests	R&D to improve cost, durability and efficiency Target 2 to 25 MW sited by 2008	R&D to improve cost, durability and efficiency Target: 500 MW sited by 2012	Investment to establish full manufacturing capacity and product warranty to successfully compete in the market
Go/No Go Decision Points	**Proposed Decision Criteria**: R&D and limited demonstrations results in acceptable durability, 35-55% efficiency, and potential to approach $400/kW. (Projection based on 100,000 units production, exact cost targets depend on specific applications.) Verified by independent audit and testing	**Proposed Decision Criteria:** Validated Phase 2 systems achieve improved durability, 40-60% efficiency, and assurance that $400/kW can be achieved (Projection based on 100,000 units production, exact cost targets depend on specific applications).	**Commercialization**: Goals of $400/kW, 40-60%, 5 years stack life and 25 year system life achieved. Industry decides on commercialization.	

If the partnership is successful in achieving technical targets for the second phase, a third phase, to be considered in the 2008-2010 timeframe, would continue research and development on smaller stationary and distributed systems where higher volume potential and improved materials performance would lead to achieving the goal of $400/kW based on the 5 kW module and production of 100,000 units. The system life requirement can be as high as 25 years with a stack replacement interval of 5 years. If the research and development is successfully completed in this phase, the government could partner with industry to install fuel cell systems in federal facilities such as military installations and office buildings. During this phase, government agencies could also educate the general public on the benefits of stationary fuel cells.

Upon successful completion of the third phase, which emphasizes small systems, larger systems, achieving efficiency greater than 60 percent by employing fuel cells and turbines operating in a hybrid configuration, could be demonstrated and commercialized if full manufacturing and product warranty can be achieved with confidence. Coal-based central hydrogen generation plants are also possible, which would take advantage of this abundant natural resource. If mandated and economically feasible, carbon capture or sequestration could be used to minimize carbon emissions in coal-based hydrogen generation.

It should be noted that, even if all phases were successful, other market factors and competing technologies would influence industry's decision to commercialize.

Transportation and Infrastructure Partnership

Without a significant public sector role, free market forces are unlikely to result in large-scale use of fuel cell powered light- and heavy-duty vehicles within the next few decades. Current conventional vehicles meet or exceed customer requirements and expectations, refueling stations are readily available, and fuel is relatively inexpensive. Absent other incentives or a dramatic change in fuel availability and price over an extended time, the average customer has very little reason to try an unproven new technology for which fueling infrastructure is generally unavailable. Furthermore, in the attempt to commercialize fuel cell vehicles, the automobile manufacturing and fuels industries face a "chicken and egg" dilemma. Due to large market uncertainties, neither industry is willing to be the first to make the massive capital investments necessary to begin commercial use.

Public sector involvement to promote and accelerate transportation fuel cell applications can help the Nation realize the public benefits (discussed earlier) of widespread fuel cell use. Partnerships such as FreedomCAR, and future or expanded partnerships that more effectively engage energy providers, can be used to address technology R&D needs such as hydrogen storage, hydrogen production infrastructure, and fuel cell cost reduction. FreedomCAR is focused on the development of long-range, high-risk technologies that will pave the way toward less dependence on foreign petroleum and emissions-free transportation. In parallel with FreedomCAR, the Department of Energy joined industrial and other organizations to draft a Hydrogen Vision for America's energy future – a more secure Nation powered by clean, abundant hydrogen. This "visioning" process was followed by publication of a "National Hydrogen Energy Roadmap," which identifies the research, development and demonstration activities necessary to overcome barriers and resolve issues associated with a future hydrogen economy.

Development of fuel cell vehicles for transportation applications will require controlled fleet test and evaluation (of personal and commercial vehicles, buses, and off-road vehicles) to validate performance, cost and servicing and maintenance requirements, and to develop a better understanding of vehicle and hydrogen refueling infrastructure interface issues. Data from tests and demonstrations can be used to refine research and development programs; gain a clear understanding of remaining technology barriers; illustrate the safety standards and practices required for fuel cell vehicles to store hydrogen on board; and support a public education campaign to promote the advantages of fuel cell powered vehicles. In addition, targeted cost-shared, commercial-scale vehicle and the supporting refueling infrastructure demonstrations would allow industry to produce enough vehicles and refueling stations to fully illuminate fuel life cycle cost and performance issues, evaluate manufacturing materials or techniques, assess safety and reliability issues, and gauge the public acceptance of this new technology. With information from these demonstrations, industry could develop a concrete commercialization plan for fuel cell powered vehicles.

Transitioning the current fuel supply infrastructure to the long-term production and delivery of hydrogen as a primary fuel will be a large and complex undertaking. Fuel cell designers for transportation applications face a critical choice between generating hydrogen off-board the vehicle or generating hydrogen on-board the vehicle from another fuel, such as gasoline, methanol, ethanol, or other hydrocarbons. While storing hydrogen fuel in the vehicle has the appeal of simplicity and offers better vehicle fuel efficiency, it poses entirely different and apparently more significant demands on fuel infrastructure. Furthermore, solving the hydrogen storage problem (that is, limited vehicle driving range) is a necessary condition prior to investment in the installation of a hydrogen infrastructure. There is, however, considerable synergy between automotive and stationary technology development for hydrogen generation systems.

The public sector role in guiding the transition to a hydrogen economy should also involve developing codes and standards for the fuel infrastructure, and addressing anti-trust concerns of the fuels industry as they develop and demonstrate the new fuel infrastructure in a collaborative manner. The government role should be to utilize public resources to assist industry in implementing this massive transition and in educating the public about fuel cell vehicles' safety, reliability, cost and performance.

The transportation and hydrogen infrastructure partnerships will be synergistic: progress realized in the transportation partnerships will assist the infrastructure transition by making the commercial feasibility of fuel cell vehicles more obvious to market participants. Furthermore, as a hydrogen infrastructure develops, there will be additional opportunities to utilize hydrogen for stationary and distributed power systems.

Implementation. The Department believes that public-private partnerships, such as FreedomCAR, could assist in the development and demonstration of vehicles and of supporting hydrogen fuel infrastructure technologies. (See Figure 13.) Government and industry should jointly work out precise success criteria for a phased approach to implementation.

A Technical Feasibility phase is now underway at the California Fuel Cell Partnership (CaFCP), in which auto manufacturers, energy companies, fuel cell technology companies, and government agencies have joined to demonstrate approximately 50 fuel cell vehicles under day-to-day driving conditions, and to examine fuel infrastructure issues. Smaller demonstration activities are also underway at the SunLine Transit Agency in Southern California and in Las Vegas.

In this Technical Feasibility phase, infrastructure activities are aimed at analyzing the feasibility of different fuel choices for providing hydrogen to fuel cell vehicles, developing codes and standards for hydrogen refueling, demonstrating the technical feasibility of the refueling technology, and identifying any major stumbling blocks to any of the fuel infrastructure options.

Figure 13. Transportation and Infrastructure Timeline to Obtain Commercialization Information

	2000 – Phase 1 Technical Feasibility	2004 – Phase 2 Controlled Fleet Test and Evaluation	2009 – Phase 3 Commercial Readiness Demonstrations	2015 – Commercialization Phase
Vehicles Objective	Test FC vehicle performance and feasibility	Evaluate use of FC vehicles under real-world conditions	Demonstrate commercial viability of FC Fleet vehicles	Investment to establish manufacturing plants and sales/service
Infrastructure Objective	Demonstrate H_2 fueling station; Analyze fuel options	Onsite generation from multiple feedstocks	Sufficient stations to provide consumer convenience	Investment for substantial numbers of all stations to be H_2 capable
Hydrogen Source	Primarily trucked in liquid	Renewable & fossil fuels	Most cost effective sources by region	
Go/No Go Decision Points				

Proposed Decision Criteria – Phase 1: Hydrogen vehicles achieve 1000 hrs durability, $200/kW cost (projection based on 500,000 units production), R&D results project 2000 hrs durability, $125/kW, $3.00/gallon gasoline equivalent (untaxed).

Proposed Decision Criteria – Phase 2: Hydrogen vehicles achieve 2000 hrs durability, $125/kW cost (projection based on 500,000 units production) & hydrogen at $3.00/gallon. R&D results project 5000 hrs durability, $45/kW, $1.50-$2.60/gallon gasoline equivalent (untaxed), and 120 g/mi greenhouse gases..

Proposed Commercialization Decision Criteria: Based on capability to achieve 5,000 hrs durability, $30/kW fuel cell system cost (at 500,000 units), $1.50 /gallon gasoline equivalent (untaxed), 120 g/mi greenhouse gases, and other market factors. The decision to enter a commercialization phase will be made by industry.

R&D Continues Concurrently to address key cost and performance barriers

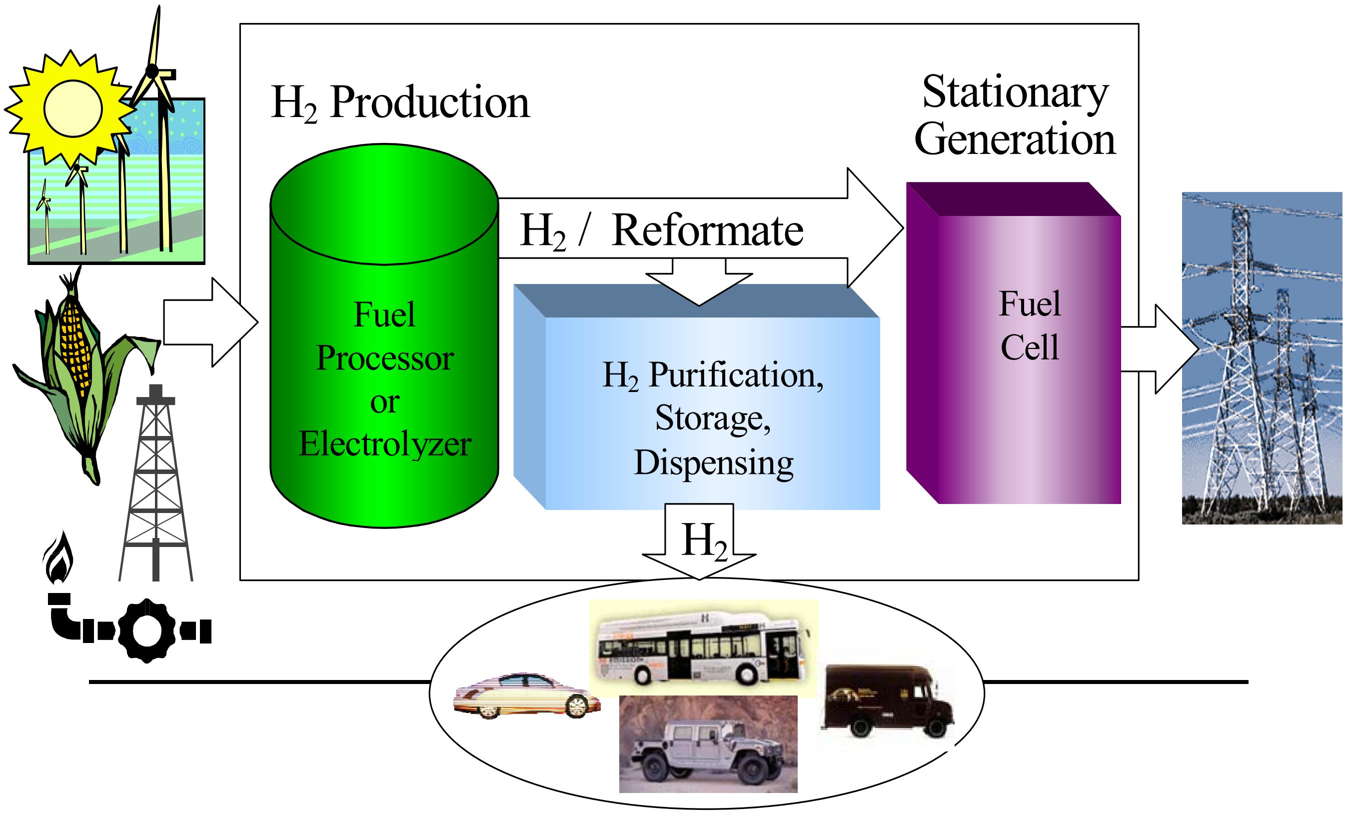
It is important to note that vehicle validation is projected to lag research and development results by approximately 3-4 years. During this phase, R&D will be carried out concurrently to improve fuel cell durability, and to lower fuel cell and hydrogen production costs. If technical decision criteria are met, then the Department will propose initiating a Controlled Fleet Test and Evaluation phase.

In the Controlled Fleet Test and Evaluation phase, vehicle demonstrations would consist of small "controlled" fleets of fuel cell vehicles supported by concurrent demonstration of hydrogen production and refueling technologies, and would include a range of fuel feedstocks. The vehicles demonstrated could be cars, light trucks, commercial delivery vehicles, buses, and/or off-road vehicles. Public utility plants or military installations could be attractive sites because they provide the controlled "environment" and central garaging, power generation capabilities for hydrogen production, and trained workforce knowledgeable of safety issues.

The Department, in developing this report to Congress, has discussed working with the National Automotive Center (NAC), which reports to the U.S. Army Tank-Automotive and Armaments Command, Tank Automotive Research Development and Engineering Center in Warren, Michigan in this Controlled Fleet Test and Evaluation phase. The NAC has been tasked by the Senate Committee on Armed Services to develop a plan for the establishment of a Defense-Industry Fuel Cell Partnership to leverage the investments of both the military and the private sector in fuel cell technology.

Since the number of vehicles would be limited, stationary power generation could be integrated with the distributed refueling stations for vehicles. The refueling stations would be powered by natural gas or other fuel (for example, gasoline, methanol, biomass ethanol) using a reformer, or by electricity (for example, grid, wind, solar) using an electrolyzer. (See Figure 14.)

Figure 14. Integrated Stationary Power Generation and Hydrogen Vehicle Refueling Station



If the Controlled Fleet Test and Evaluation phase meets technical success criteria the Department envisions a final demonstration phase to assess vehicle performance and refueling viability in terms of both technical and economic factors. By 2015, enough data would have been gathered for industry to make a commercialization decision. Industry and government should jointly establish technical success criteria for each phase of development and demonstration on the path to commercialization. The targets established would serve as decision points; the data flowing from the demonstrations would allow government and industry to gauge progress, establish research requirements leading into the next research cycle, and determine the investment necessary to carry out the next phase. In turn, the results from each phase would be used to define the requirements for further technology development and to help formulate R&D success criteria. The "due diligence" principle, employing independent assessments, for verifying costs and reliability would apply as it would in the case of stationary and distributed generation. It is envisioned that senior government officials and industry executives, not associated with the demonstration, and representatives from academia would be solicited to help in carrying out the "due diligence" process.

It should be noted that even if all phases were successful, other market factors (for example, world petroleum supplies) and competing technologies would influence industry's decision to commercialize. This final commercialization decision rests with industry alone.

Conclusions

The benefits from broad commercialization of fuel cells for the transportation, portable power, stationary and distributed power generation applications could provide "wins" for all key stakeholders. In stationary and distributed fuel cell applications, the nation as a whole could benefit from both increased energy efficiency and reduced emissions of air pollutants and greenhouse gases. In transportation applications, hydrogen as an energy carrier from a diverse number of feed stocks (fossil fuels, nuclear, and renewables) can provide significant energy security benefits, greatly reduced criteria emissions and reduced carbon emissions (with appropriate fossil fuel carbon sequestration). Comprehensive life cycle analyses must be carried out as technology developments progress to ensure that hydrogen production and utilization processes actually result in a "net" energy and environmental benefit. Participants in the fuel cell business value chain could benefit from new markets associated with the commercialization of fuel cells. Individual consumers could benefit from improved reliability of power from distributed fuel cells, and clean fuel-efficient cars. In addition, consumers will benefit from sustained, affordable power and fuels.

Since commercialization of fuel cells requires overcoming significant technical, economic, and regulatory barriers, this report recommends certain program adjustments that might aide in the development and introduction of fuel cell technologies. It also identifies targeted public-private partnerships to accelerate the generation of information necessary to determine if commercialization is warranted. These partnerships would help to reduce private sector development risks. They should also complement the ongoing government-industry collaborative research and development efforts to develop fuel cell technology. A public sector effort to develop and validate technology, increase public awareness, and reduce business and institutional barriers would assist industry in creating a basis for mass-market introduction of fuel cell systems. These program adjustments have been initiated, and future adjustments may be made based on ongoing feedback from stakeholders and progress toward achieving the program goals.

The Department believes that the Federal involvement should be reduced as technologies progress along the research-development-demonstration-commercialization continuum. The Department also recognizes that, while demonstration of currently available technologies may provide useful information to help identify R&D needs, the proportion of funding dedicated to such demonstrations must be carefully monitored so as not to detract from the long-term success of its programs. The Department will strive to maintain an appropriate balance in its R&D portfolio, focusing on long-term, high-risk activities, and will strictly adhere to cost-sharing guidelines for all of its activities.

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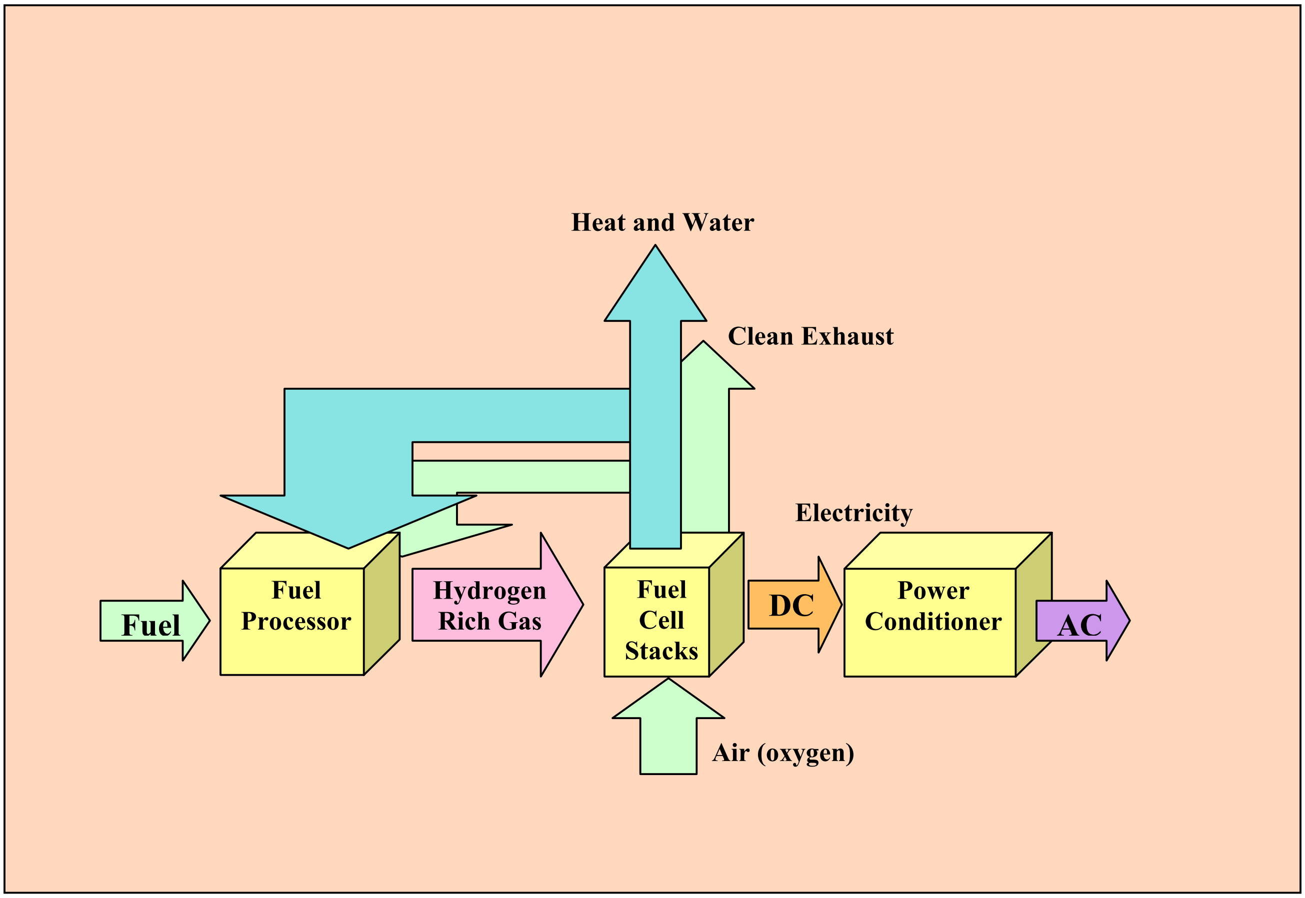
Appendix A

How Typical Fuel Cells Work



Fuel cells are devices that convert the chemical energy in a fuel directly into electrical energy. The Fuel Cell Handbook, issued by the National Energy Technology Laboratory, is an excellent reference for more in-depth information (see www.netl.doe.gov). In a typical fuel cell, hydrogen and oxygen react electrochemically at separate electrodes, producing electricity, heat, and water. Fuel cell power plants typically consist of a hydrogen generator (fuel processor), fuel cell stacks (or modules), and the balance of plant, which includes machinery to deliver fuel to the processor and convert the electricity generated by the stacks from direct current to alternating current. A water electrolyzer, instead of a fuel processor, is used in the case when hydrogen is generated from renewable electricity. Other conversion processes can be used for hydrogen generation from renewable and nuclear resources. The fuel cell types that have promise for commercialization include:

- Phosphoric acid fuel cells (PAFCs) are the only fuel cells commercially available, albeit at a price not competitive with alternative technologies. U.S. and Japanese suppliers have been marketing 50- to 200-kW PAFC systems. Over 300 PAFC units have been installed worldwide with a combined operating history of almost 5 million hours. Cost challenges have limited PAFCs commercial success.

- Molten carbonate fuel cells (MCFCs) are best suited for large power plants. Japanese, European, and US firms have demonstrated MCFC systems of 250-kW to 2-MW class. MCFCs can use natural gas directly without the need for an external fuel processor and have had some recent test successes. MCFC developers project commercialization within five years.

- Solid oxide fuel cells (SOFCs) have a comparable efficiency and the same power applications as MCFCs. Two major types of SOFCs are under development.

    - Tubular solid oxide fuel cells (TSOFCs) are further along in development and close to commercialization in stationary applications.

    - Planar solid oxide fuel cells (PSOFCs) are less mature but have the potential for higher power densities and lower production costs than TSOFCs, and foreign governments and corporations are focusing on the technology as an area of intense global competition. PSOFCs are still in an early state of development, with commercialization, across many market segments, projected to take place in about 10 years. One particular application of interest is auxiliary power units for heavy-duty vehicles.

- Polymer electrolyte membrane fuel cells (PEMFCs) are considered a promising fuel cell technology. The potential for PEMFC applications in the transportation and small stationary power markets has stimulated intense global R&D competition. Major world automakers are racing to develop PEMFC passenger vehicles.

- Alkaline fuel cells (AFCs) are successfully used in the US space program where they operate on pure hydrogen and oxygen. AFCs are less attractive for terrestrial applications, where the carbon dioxide in the air reacts with the alkaline electrolyte, reducing efficiency. However, since they have potential for using no precious metal catalysts and the cost of materials is low, they have attracted some industrial interest.

- Direct methanol fuel cells (DMFCs) with polymer electrolyte membranes directly convert methanol into electricity and heat without a reformer, and thus are an attractive alternative to PEMFCs for portable power. However, critical problems, such as high platinum requirements, low power densities, and fuel crossover from the anode to the cathode may restrict their use for higher power applications.

Appendix B

Foreign Fuel Cell Programs

Japan

Japan has supported the development and commercialization of fuel cells since 1981. That year, the Ministry of International Trade and Industry (MITI, now METI) began a 17-year, $520 million effort to support fuel cell R&D in the Moonlight Project, a government program aimed at developing energy efficient technologies. In 1993, the Moonlight Project and other energy and environmental projects were incorporated into the New Sunshine Program. In 2002, Japan nearly doubled its fuel cell R&D budget to $220 million from $119 million. It created a new large-scale Polymer Electrolyte Fuel Cell Development Program to develop PEM fuel cells for both transport and stationary applications, leaving molten carbonate fuel cell and solid oxide fuel cell R&D under the New Sunshine Program. Of the total fuel cell budget of $220 million, $32 million is spread across the two programs for development of fuel cell testing, measurement, and evaluation technologies that aim to increase safety and reliability and the establishment of standards for such technologies. It has submitted a budget request of $288 million for fuel cells and hydrogen research and development for JFY 2003 (April 1, 2003 – March 31, 2004).

The government of Japan will launch a three-year joint test of hydrogen and fuel cell vehicle (FCV) technology on the country's roads in April 2003.

Japan Electric Vehicle Association said the Japan Hydrogen and Fuel Cell (JHFC) demonstration project will be sponsored by Japan's Ministry of Economy, Trade and Industry and will examine the "effectiveness, environmental friendliness and safety of [FCVs]." Additionally, the project will promote public awareness about fuel cells and the use of hydrogen "as a safe and clean fuel."

- *Molten carbonate fuel cell (MCFCs).* Japan has been providing support to three companies to develop MCFC technology. Ishikawajima-Harima Heavy Industries and Hitachi developed 250-kW stacks and built a 1-MW MCFC pilot plant with an external reformer at Kawagoe, Mie Prefecture, consisting of four 250-kW stacks. The test operation started in July 1999 and ended in January 2000 after 5,000 hours of test operations. Since 2000, Japan has focused on commercialization and is supporting development of a pressurized 300-kW MCFC cogeneration system, followed by a 750-kW system to be completed in March 2004. Japan hopes to see commercialization start immediately thereafter, according to METI officials. Japan's budget was $17 million on MCFC R&D in 2002.

- *Solid oxide fuel cell (SOFCs).* Since 1989, Japan has been providing R&D funding to at least seven manufacturers (Fuji Electric, Toto, Mitsubishi Heavy Industries, Mitsui Engineering and Shipbuilding, Murata Manufacturing, Nippon Steel, and Sanyo Electric), two electric power companies, and three gas companies. Japan focused its initial effort on a planar SOFC (PSOFC) design that has the potential for higher power densities than the tubular SOFC design (TSOFC), using the "wet processing" that reportedly has the potential for lowering production costs. Japan's National Institute of Materials and Chemical Research (NIMC) developed the wet processing technology, according to METI officials. The early stage of Japan's SOFC effort (1989-1991) included development of module with metal interconnects (Sanyo), oxide interconnects (Fuji), and interconnects made from magnesium spinel and lanthanum chromite (Mitsui Engineering and Shipbuilding). Japan's SOFC budget for 2002 was $15 million.

- *Polymer Electrolyte Membrane Fuel Cell (PEMFCs).* METI has been sponsoring five companies to develop PEMFC technologies since 1992. Sanyo, Toshiba, and Mitsubishi Electric have been developing 2-kW, 10-kW, and 30-kW stacks, respectively. Asahi Chemical Industry and Asahi Glass are developing fuel cell components, including polymer membranes and separators, according to METI documents. In 2002, Japan nearly quadrupled its budget for PEMFCs to $156 million and created a 10-year Polymer Electrolyte Fuel Cell Development program, which aims to develop PEMFCs for both stationary and transport applications. Japan will now equally focus on both stationary and transportation applications.

Europe

Since the mid-1970's, the European Commission (EC) has supported fuel cell R&D within the context of non-nuclear energy technologies. After 1985, fuel cell R&D was administered as part of the non-nuclear energy field of the multi-year Framework Program, which in 1994 was given the acronym JOULE. In 1994, the program for demonstration of non-nuclear energy technologies, nicknamed THERMIE, was integrated with JOULE in the Fourth Framework Program. The total EC fuel cell R&D budget was $60 million in 2001. In October 2002, the EC announced ambitious plans to promote hydrogen, in which it plans to spend € 2.12 billion ($2.09 billion) from 2003 to 2006 on renewable energy development, mostly related to hydrogen. (In comparison to € 127 million spent between 1999 and 2002).

In the *Fourth Framework Program* (1994-1998), the EC allocated $54 million to support 35 fuel cell projects, many of which ran through 2000. Polymer electrolyte membrane fuel cell (PEMFC) R&D received the largest funding—about $30 million (55 percent)—with a major emphasis on fuel cell vehicle development, which included the following:

- The FEVER project (1994-1997). Renault designed, built, and tested the liquid hydrogen-fueled Laguna Break in partnership with Italy's DeNora (the fuel cell supplier) and Ansaldo (assembly of secondary systems), Air Liquide of France (the hydrogen tank), and Volvo of Sweden (simulations).

- The HYDRO-GEN project (1996-1999). French automaker PSA Peugeot Citroen led the effort to develop a hydrogen-fueled PEMFC vehicle using a Berlingo van, in partnership with Renault, DeNora, and Air Liquide.

- The CAPRI project (1995-2000). Volkswagen led the effort to fit a methanol processor into a VW Golf station wagon. CAPRI incorporates a Ballard PEMFC stack and a methanol reformer, developed by Johnson Matthey of the United Kingdom (UK), with the Netherlands' Energy Research Foundation (ECN) responsible for the systems integration and Volvo for fuel cell system modeling, testing, and the air compressor/expander development.

Also included were a 250-kW PEMFC stationary demonstration project in Berlin, a 250-kW PEMFC portable generator fueled by waste hydrogen from an industrial site, and three direct methanol fuel cell (DMFC) development projects aiming to reduce platinum loadings and develop methanol tolerant catalysts. Other projects accomplished as part of the Fourth Framework Program were development of solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) technologies, for which the EC provided \$9 million and \$8.6 million, respectively. R&D effort aimed at improving durability and reducing cost, with major participants including Risoe National Laboratory of Denmark and ECN of the Netherlands for planar solid oxide fuel cells (PSOFCs) and Ansaldo Richerche of Italy and Motorem und Turbinen Union Friedrichshafen (MTU) of Germany for MCFCs.

The *Fifth Framework Program* (1999-2002) sponsors 10 projects with a budget of \$27.8 million. The projects were selected in 1999, and many of them will be running beyond 2002. Fuel cell vehicle development again will receive a large part of the total—\$12.4 million (45 percent)—including a major \$10 million "FUERO" project that aims to develop a PEMFC vehicle with fuel cell processors for commercial-grade gasoline and bioethanol. Participants in the project include most major European automakers, PSA Peugeot Citroen, Renault, Volvo, and Volkswagen.

The MCFC effort includes a 500-kW MCFC demonstration plant coordinated by Ansaldo, the Netherlands' National Agency for New Technologies, Energy, and the Environment, AMG-Palermo of Italy, and PEP of Spain. The SOFC effort includes development of a multi-functional 20-kW class PSOFC module stack with participation from Rolls Royce and Imperial College of UK, Risoe National Laboratory of Denmark, and Gaz de France, and demonstration of a 5-kW PSOFC stack with participation from Alstom of UK and Forschungszentrum Julich of Germany. Also included is a joint EU-US demonstration project to prove the feasibility of a hybrid tubular solid oxide fuel cell (TSOFC) micro turbine power system, including a 1-MW Siemens Westinghouse TSOFC system with the balance of the plant to be developed in Europe, with planned start-up in mid-2003.

Canada

Canada has focused primarily on PEM fuel cell research and development over the last decade. To commercialize its PEMFC technology, Ballard Power Systems has developed a major international network of strategic partners, including DaimlerChrysler, Ford Motor Company, GPU international (US), Alstom SA (a UK company based in France), and Ebara Corporation (Japan). In 1997, Ballard formed an alliance with DaimlerChrysler and Ford Motor, which have invested $500-600 million in the company. As of March 2000, DaimlerChrysler owned 18.6 percent, and Ford owned 14 percent of Ballard. DaimlerChrysler last year announced further investment in Ballard, at $1 billion over the next four years.

Others

The **South Korean** Government began its support for fuel cell development in 1985 by focusing on small fuel cell units using South Korean reformers, which produce hydrogen gas from fuels such as natural gas. As part of a program to catapult South Korea into the ranks of the most technologically advanced countries, fuel cell development was designated as a national priority for its R&D program in 1992. However, funding for the national program has been modest. From 1992 to 2000, South Korea spent only about $20.9 million while the government-run Korea Electric Power Corporation (KEPCO) and the private sector together provided $20.4 million, for an average of about $2.6 million annually.

In recent years, the Government of **Australia** has become interested in the fuel cell field, particularly because of the recent successful operation of a 1.5-kW PSOFC unit developed by Ceramic Fuel Cell Limited (CFCL). CFCL was formed in 1992 by a consortium of private (utilities and resource companies) and government organizations. In November 1998, the Ministry of Industry, Science, and Resources, via its Industry Research and Development Board, provided CFCL a $15 million grant for the development of a 100-kW PSOFC system. Outside of CFCL, there are only a few small fuel cell development efforts in Australia:

- A small basic research project is under way on PEMFCs at Monash University in Melbourne.

- The national research organization CSIRO is working on an advanced energy technology demonstration project, linking solar energy with micro turbines and fuel cell.

Appendix C

Technical and Economic Barriers to the Use of Fuel Cells

The technical and economic barriers to the development and commercialization of fuel cell systems are closely related. Therefore, this discussion will simultaneously address all barriers. The discussion presented below generally applies, to varying degrees, to all fuel cell applications: transportation, stationary/distributed generation, and portable applications. Parts of this discussion were excerpted from the National Hydrogen Energy Roadmap.[iii] Specific issues not relevant to all applications or fuel cell types are also identified.

Cost

Cost is a barrier for all types of fuel cells across all applications. Cost reductions must be realized in raw materials, manufacturing of fuel cell stacks and components, and purchased components. The amount of cost reductions required depends on the type of fuel cell and application.

Raw materials costs must be reduced by a combination of alternative (lower cost) materials, quantity pricing, and reduction in required amounts of expensive materials. Manufacturing cost reductions can be partly realized from classical learning curve gains. However, it will likely require introduction of new and innovative manufacturing technologies or designs requiring simpler manufacturing processes. Because of the non-standard size and specialized requirements of components for fuel cell systems, costs are unusually high at low volumes.

The cost issue is particularly severe for transportation fuel cell systems. Ongoing manufacturing cost analyses supported by the Department indicate that implementation of current technology in automotive quantities (500,000 units/year) would result in a cost between $195-325/kW.[iv] This cost represents today's current fuel cell performance scaled to high volume manufacturing; actual cost to achieve parity with the performance, size and weight of a conventional vehicle is higher because current technology does not meet those requirements. The current cost of internal combustion engine power plants is around $25-35/kW.

Stationary and distributed generation systems - phosphoric acid, tubular solid oxide, and molten carbonate fuel cells - also face significant cost challenges. The Solid State Energy Conversion Alliance's ultimate cost goal for 5kW planar solid oxide module (mass produced at 100,000 units per year) is approximately $400/kW. This target also represents about an order of magnitude cost reduction over current systems.[v] Several developers have operated single cells for 40,000 hours and several small stacks (~2kW) have been operated for more than 1000 hours. Technology improvement to achieve 40,000 hours life and $400/kW represent significant challenges.

The cost issues facing portable and standby power applications are less acute than the challenges facing transportation and stationary. Standby power will likely require cost targets similar to those of distributed generation systems but will not require the extended life. Portable power has the potential to garner premium pricing with limited life requirements.

Despite these challenges, manufacturing cost analyses indicate that if technology advances continue and if said economies of scale are achieved, current fuel cell technology pathways will meet the necessary cost targets to allow for commercial introduction.

Durability and Performance

The market places severe demands on reliability and life characteristics for successful competition with existing power generation technologies. For example, most stationary markets require lifetimes of over 40,000 hours for major subsystems and transportation applications require at least 5,000 hours (to achieve >100,000 miles) under severe climatic, on/off, and transient cyclic conditions. The life/reliability characteristics of fuel cell technologies have not been verified satisfactorily, although 200-kW PAFC power plants have demonstrated acceptable reliability and availability in extensive worldwide demonstrations.

The low PEMFC and PAFC operating temperatures require platinum catalysts to achieve useful power densities. The use of platinum catalysts at the low temperature makes them susceptible to poisoning by carbon monoxide (CO) in the fuel stream. Sulfur compounds are even more problematic in that the damage they cause is permanent and cumulative. Thus, fuel streams that result from reforming natural gas and other fuels, either on- or off-board vehicles must go through extensive cleanup before being used in a PEMFC. Higher operating temperature alleviates this situation but does not eliminate it. MCFCs and SOFCs are not susceptible to CO poisoning but they are affected by sulfur. When combined with the reactive nature of the MCFC electrolyte, the operating temperature of 650°C (1200°F) leads to corrosion problems with the MCFC cell hardware (typically expensive corrosion-resistant alloys) and the cathode.[vi] For SOFC, operating above 800°C (1475°F), thermal expansion coefficients of the cell components and hardware materials must be carefully matched to prevent severe thermal stresses and cell failure during transient operation.

Successful development of low-cost, high-performance components is critical to achievement of overall system cost and performance goals for all fuel cell types and applications. Furthermore, high performance is required to improve power plant packaging (volume and weight) for a given power output. This issue is particularly important for transportation applications where weight and efficiency affect the achievable driving range and volume constraints are strict.

One of the major technology breakthroughs being pursued for PEMFCs is a membrane material that operates at slightly higher temperatures. Higher temperature operation would allow more extensive use of the waste heat in cogeneration or as process heat in the fuel reformer, would reduce the size of the radiator for automotive applications, and would reduce the requirement for carbon monoxide (CO) management devices.

For building applications, the high temperature membrane is expected to have an operating pressure less than 1.5 atmospheres, an operating life of greater than 20,000 hours, and have a projected manufacturing cost consistent with an overall installed fuel cell system cost of <$1500/kW for initial commercialization and ultimately $400/kW for large markets.

Fuel Infrastructure

Fuel cells operate on hydrogen, a fuel that in the past has been primarily used as an industrial chemical and by NASA for the space program. Hydrogen fuel, however, combined with the use of fuel cell power systems for vehicle propulsion or for stationary power generation, has the potential to significantly reduce the U.S. dependence on petroleum imports and reduce the emissions of pollutants and greenhouse gases. Hydrogen is the most abundant element in the universe; however, it is normally found as a part of a larger molecule such as water or a hydrocarbon. Even though hydrogen has been identified as able to contribute to a long-term solution to the U.S. energy needs, the development of low-cost and efficient production processes, as well as lightweight, compact, and affordable storage devices, are still needed to make hydrogen an attractive energy option. For consumers to consider hydrogen to be an attractive option, a hydrogen delivery infrastructure is also required to provide the same convenient, safe access to hydrogen as consumers currently have to such fuels as gasoline and natural gas.

Hydrogen Production

Multiple challenges must be overcome to achieve the vision of secure, abundant, inexpensive, and clean hydrogen production with low carbon emissions.

<u>Hydrogen production costs from fossil energy resources are high relative to conventional fuels.</u> With most hydrogen currently produced from hydrocarbons (primarily natural gas), the cost per unit of energy delivered through hydrogen is higher than the cost of the same unit of energy from the hydrocarbon itself. As a matter of thermodynamics, this will always be the case, although more efficient use of the energy (i.e., in fuel cells versus internal combustion engines) is expected to allow "well-to-wheels" costs to become comparable.

<u>Methods for producing hydrogen from renewable energy resources need development.</u> While wind, solar, and geothermal resources can produce hydrogen electrolytically, and biomass can produce hydrogen directly, other advanced methods for producing hydrogen from renewable and sustainable energy sources without generating carbon dioxide are still in early research and development phases. Processes such as thermo-chemical water splitting, photoelectrochemical electrolysis, and biological methods require long-term, focused efforts to move toward commercial readiness. Renewable technologies, such as solar, wind, and geothermal, need further development for hydrogen production to be more cost-competitive from these sources.

Low demand inhibits development of production capacity. Although there is a healthy, growing market for hydrogen in refineries and chemical plants, there is little demand for hydrogen as an energy carrier. Long-term demand growth will depend on the development and implementation of hydrogen storage and conversion devices, so that products such as hydrogen-powered cars and generators meet market requirements. Without the increased demand coming from widespread transportation applications, there is little incentive for industry to invest in new production infrastructure technologies.

Current hydrogen production technologies need improvement. Existing technologies can produce hydrogen from hydrocarbons using processes such as steam methane reformation and gasification. Improvements are required to increase the cost effectiveness and efficiency of these technologies. Continued research and development is necessary to improve carbon capture and sequestration feasibility, which would be required in the long term for hydrogen produced from fossil fuels.

Hydrogen Distribution

A comprehensive delivery infrastructure for hydrogen faces numerous scientific, engineering, environmental, institutional, and market challenges.

An economic strategy is required for the transition to a hydrogen delivery system. Since fueling economics depend on volume, the chicken and egg dilemma (which comes first: fuel or end use applications?) impedes the installation of an effective infrastructure. There is no simple reconciliation between the level of investments required to achieve low costs and the gradual development of the market. Returns on investments in delivery systems will only be realized if there is long-term public acceptance and use of hydrogen and hydrogen-powered products.

Full life-cycle costing has not been applied to delivery alternatives. Any strategy to select appropriate delivery systems should involve full life-cycle costing of the options. Life-cycle cost analyses should compare gaseous and liquid hydrogen delivery, and hydrogen carrier media such as metal and chemical hydrides, methanol, and ammonia. Multiple delivery infrastructures may be necessary, which could add to the cost of transitioning to a hydrogen economy.

Hydrogen delivery technologies cost more than conventional fuel delivery. The high cost of hydrogen delivery methods could lead to the use of conventional fuels and associated delivery infrastructure up to the point of use, and small-scale conversion systems to make hydrogen onsite. However, cost effective means do not currently exist to generate hydrogen in small-scale systems.

Current dispensing systems are inconvenient and expensive. Customers expect the same degree of convenience, cost performance, and safety when dispensing hydrogen fuel as when dispensing conventional fuels. Current hydrogen fueling solutions and designs are not sufficiently mature.

Hydrogen Storage

Hydrogen storage must meet a number of challenges before hydrogen can become an acceptable energy option for the consumer. The technology must be made transparent to the end user—similar to today's experience with internal combustion gasoline-powered vehicles. Specific challenges include the following:

Hydrogen Storage Capacity. Hydrogen storage is a critical enabling element in the hydrogen cycle, from production and delivery to energy conversion and applications. Improved storage technologies are needed to satisfy end-user expectations and foster consumer confidence in hydrogen-powered alternatives. A substantial research and development investment in hydrogen storage technologies will be required to achieve the performance and cost targets for an acceptable storage solution.

New media development is needed to provide reversible, low-temperature, high-density storage of hydrogen. These storage characteristics generally describe the technical goals for some of the solid-state materials, including hydrides and carbon adsorption materials. The ultimate hydrogen storage system for meeting manufacturer, consumer, and end-user expectations would be low in cost and energy efficient, provide fast-fill capability, and offer inherent safety. Hydrogen storage systems need to enable a vehicle to travel 300 to 400 miles and fit in an envelope that does not compromise either passenger space or storage space. Current energy storage technologies are insufficient to gain market acceptance because they do not meet these criteria.

Low demand means high costs. As there are few hydrogen-fueled vehicles on the road today, the more mature compressed and liquid hydrogen storage technologies are quite expensive. High-pressure cylinders will be amenable to high-volume production, once demand warrants it. Raw material costs could also be reduced substantially if there were sufficient demand. For emerging technologies, manufacturing feasibility and cost reduction measures will play integral roles in the technology development process. The initially low rates at which automakers expect to introduce fuel cell vehicles will present a challenge to the commercialization and cost reduction of hydrogen storage technologies.

System Integration

The successful integration and operation of fuel processors, cell stacks, and balance of plant components (compressors, pumps, humidifiers, heat exchangers, sensors, controls, etc.) in fuel cell systems operating under real world conditions have yet to be adequately demonstrated. The one exception is the phosphoric acid fuel cell system that is marketed commercially worldwide (the United Technologies Fuel Cell PC25), but in relatively low volume to niche markets with government subsidies that help offset the high system price. Limited field experiments, however, of solid oxide, molten carbonate, and polymer electrolyte systems for stationary and transportation applications have met with varying levels of success. As a result, projected market entry dates for commercial applications of these fuel cell technologies have not met developer or market expectations. System durability issues (in addition to those mentioned above) that will require focused R&D to resolve include:

- Balance of Plant Components: All fuel cell systems, regardless of the fuel cell type, require the successful development and integration of balance of plant components such as heat exchangers, compressors, sensors and controllers. Premature failure of these components is not uncommon, which limits system durability and reliability.

- Thermal and Water Management: Thermal and water management are important for PEM fuel cells, which operate at relatively low temperature and require humidification of the air and fuel supplies to prevent performance degradation. A complicating factor is thermally integrating the low-operating temperature PEM fuel cell with the high-temperature fuel processor, particularly on board a vehicle where issues of waste heat rejection from the system and maintaining a positive water balance onboard the vehicle become critical design and operating issues.

- Miniaturization: To compete with current battery technology, portable power fuel cell applications for consumer electronics require operating characteristics, which are not required by larger power plants such as miniaturization, shock and vibration resistance, orientation insensitivity, and passive operation. Components and subsystems are required.

Codes and Standards

The economics of fuel cell applications will require that the "transaction costs" associated with such factors as siting hydrogen fueling stations, installing fuel cell systems in buildings, and allowing fuel cell vehicles in public garages be minimized. Absent nationwide codes and standards, the legal, permitting, and marketing costs of implementing fuel cell technology will be very high and make it unlikely that cost targets on an installed basis could be met, i.e. a lack of codes and standards directly transform into a serious economic barrier.

The codes and standards issues vary greatly by application category and technology characteristics. Codes and standards are developed by different trade and regulatory organizations at both the national and local level. The process is highly interactive and is very time consuming. As a result, focused codes and standards development must take place years before large-scale commercialization.

Education

Common consumer misconceptions about hydrogen as a fuel can impede widespread acceptance of hydrogen. The following are identified as the most pressing issues to be addressed through education.

The public lacks awareness. Consumers are generally unaware of hydrogen as an energy alternative. Since there is little consensus about the severity of today's environmental problems there is little impetus for change. Hydrogen needs to be "personalized" for consumers so that they understand the value of switching from fossil fuel-based energy systems to hydrogen systems.

Hydrogen education programs are not widespread. A lack of structured education programs on hydrogen exists at all levels. Automotive technicians need to be trained. Teacher training on the costs and benefits of hydrogen has not been a priority, and students at all educational levels are not being introduced to hydrogen. As a result, students are not stimulated to pursue science and technology careers that support growing business interests, and do not share information about hydrogen and its costs and benefits with their parents and peers. Also, policy makers often are not knowledgeable about hydrogen as a fuel, nor do they understand how it works

Consumers harbor safety concerns. Consumers may unnecessarily fear hydrogen if they are misinformed about its safety, and may hold misconceptions about the risk of using it in homes, businesses, and automobiles. Fear may also stem from a lack of understanding about the dangers associated with fuels that consumers use today. A message needs to be communicated that hydrogen can be handled and used safely with appropriate sensing, handling, and engineering measures.

Reference List

[i] United Technologies marketing information, Joe Staniunas, 1994, based on US Department of Commerce Statistical Abstracts of the United States, 1993.

[ii] Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2000, published by Environmental Protection Agency, April 2002.

[iii] National Hydrogen Energy Roadmap document, based on proceedings from National Hydrogen Energy Roadmap Workshop on April 2-3, 2002 in Washington DC, published by the US Department of Energy, November 2002.

[iv] "Cost Modeling of PEM Fuel Cell Systems for Automobiles," Carlson, Thijssen, Lasher, Sriramulu, Stevens, and Garland, SAE 002-01-1930, June 2002.

[v] "Solid State Energy Conversion Alliance – A U.S. Department of Energy Initiative to Promote the Development of Mass, Customized Solid Oxide Fuel Cells for Low Cost Power," Wayne Surdoval, proceedings of the Solid Oxide Fuel Cell 7th International Symposium, 2001.

[vi] Appleby and Foulkes, Fuel Cell Handbook, New York, 1989, Chapter 14.

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