Hydrogen Fuel Cells: Research Progress and Near-Term Opportunities

Christy Cooper
US Department of Energy Hydrogen Program
Washington, DC

INTRODUCTION

The United States faces some energy challenges that if not resolved will negatively affect our security, economy, and environment. The country depends on foreign oil for transportation, and greenhouse gases and other criteria pollutant emissions need to be reduced. There is no single solution to these critical problems; rather they require a multifaceted approach. Hydrogen, together with advanced biofuels, plug-in hybrids, and other energy efficient transportation technologies, can be an important part of a more comprehensive and balanced energy portfolio. Fuel cells are central to establishing this integrated solution. This article describes some of the benefits of hydrogen and fuel cells, as well as some of the obstacles to their implementation on a large scale. In addition, this article highlights achievements and partnerships that are moving the technology out of the lab and into practical, real-world use.

Hydrogen, an energy carrier, can be derived from abundant and diverse energy resources, including natural gas and coal (with carbon sequestration), nuclear energy, and renewable energy resources such as wind, solar, geothermal, and biomass (including waste biogas). Hydrogen production from renewable and nuclear sources and from coal-based systems with carbon sequestration results in near-zero greenhouse gas emissions. Natural gas-derived hydrogen offers a cost-competitive near-term option that results in lower carbon emissions than the production and consumption of gasoline or the operation of hybrid-electric vehicles. Hydrogen also offers a way to "store" energy from variable renewable resources such as wind and solar power.

Fuel cells are energy conversion devices that can efficiently use hydrogen to make electricity. Water and heat are the only byproducts of using a hydrogen fuel cell. In addition to producing zero carbon dioxide and near-zero greenhouse gas emissions at the point of use, fuel cells operate quietly and can be scaled to power a variety of applications including highway vehicles, specialty vehicles (e.g., forklifts and airport baggage tugs), stationary power generation units (for backup and primary power), and portable electronic equipment and auxiliary power units. They offer more than two times the efficiency of traditional combustion technologies. For vehicles, this efficiency results in a more than 50% reduction in fuel consumption when compared to a conventional vehicle that is powered by a gasoline-fueled internal combustion engine.[1] Efficiencies for stationary applications can be even greater in combined heat and power (or co-generation) applications. The expanded use of stationary fuel cells can also help to increase the reliability of the electricity grid by reducing system loads and bottlenecks. Fuel cells are an important enabling technology for the widespread use of hydrogen, and they represent a radically different approach to energy conversion that could replace conventional power generators like internal combustion engines, turbines, and batteries.

CHALLENGES

Despite the inherent benefits, there are several challenges to the widespread use of hydrogen and fuel cells. Among the greatest challenges is reducing the initial or capital equipment cost. Fuel cells and hydrogen produced from multiple energy sources must be cost-competitive with traditional technologies and fuels to succeed in the marketplace. Another technical challenge to fuel cell vehicle commercialization is onboard vehicle fuel storage. Hydrogen has a high energy content by weight but not by volume. This makes it difficult to store sufficient quantities (e.g., enough to enable the 300-mile driving range that US consumers demand) within the size and weight constraints of a passenger light duty vehicle.

Delivery infrastructure is also a challenge. Hydrogen can be delivered by truck, and there are approximately 1200 miles of hydrogen pipeline located in certain parts of the country. Unlike with gasoline, however, there is no extensive network of fueling stations or national fuel delivery infrastructure for hydrogen. For fuel cell vehicles to enter the mainstream market, consumers need a convenient place to fuel them, and there must be a cost-effective way for the fuel to be delivered to hydrogen stations.

Working with partners across the public and private sectors, the US Department of Energy (DOE) Hydrogen Program is working to overcome these challenges. This program supports basic and applied research, technology development and learning demonstrations, safety research, systems analysis, and public outreach and education activities aimed at advancing the development and use of hydrogen and fuel cell technologies for transportation as well as for stationary and portable power generation.

PROGRESS TOWARD COMMERCIALIZATION

DOE-funded research and development (R&D) has made significant progress in overcoming technical challenges to hydrogen and fuel cell technology commercialization. Accomplishments over the last six years include:

- Reduction in the projected cost of distributed hydrogen production using natural gas (assuming widespread deployment) from $5.00 to $3.00 per gallon gasoline equivalent (gge)* – a 40% reduction.[2]

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The United States faces some energy challenges that if not resolved will negatively affect our security, economy, and environment. The country depends on foreign oil for transportation, and greenhouse gases and other criteria pollutant emissions need to be reduced. There is no single solution to these critical problems; rather they require a multifaceted approach. Hydrogen, together with advanced biofuels, plug-in hybrids, and other energy efficient transportation technologies, can be an important part of a more comprehensive and balanced energy portfolio. Fuel cells are central to establishing this integrated solution. This article describes some of the benefits of hydrogen and fuel cells, as well as some of the obstacles to their implementation on a large scale. In addition, this article highlights achievements and partnerships that are moving the technology out of the lab and into practical, real-world us.</td></tr>
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- Reduction in the projected cost of hydrogen production using renewable-based technologies (assuming widespread deployment) from $5.15 to $4.80 per gge (e.g., electrolysis and distributed reforming† of bio-derived liquids – ethanol, sugars).[3]
- Development of technologies for the production of hydrogen from coal that will enable increased efficiency, reduced cost, and improvements in hydrogen purity.
- Reduction in the projected, high-volume manufacturing cost of automotive fuel cell systems from $275/kilowatt (kW) in 2002 to $73/kW in 2008[4]‡ and improvement in the projected durability of fuel cell systems in vehicles from 950 hours in 2006 to 1900 hours in 2008.[5] (The program's targets are $30/kW and 5000-hour durability – approximately 150,000 miles of driving – which will enable fuel cells to be competitive with current gasoline internal combustion engine systems.)
- Identification of new materials that have the potential to increase hydrogen storage capacity by more than 50%,[6] and the development and demonstration of a novel "cryo-compressed" tank concept.
- Improvement in the efficiency and durability of fuel cells for distributed energy generation.

Technology Validation

Complementing the program's robust R&D effort is a technology validation component, the focal point of which is the National Hydrogen Learning Demonstration. This 50/50 government/industry cost-shared effort brings together automobile and energy companies, as well as their suppliers and other stakeholders, to evaluate light-duty fuel cell vehicles and hydrogen infrastructure in real-world operating conditions. Data collected on fuel cell durability and efficiency, vehicle range, and hydrogen cost, among other performance parameters, feeds back to the R&D program and is measured against established technical targets. The data is published as "composite data products" that provide the public, R&D community, and other stakeholders a means for understanding progress and technology readiness.

The demonstration includes 140 vehicles and 20 fueling stations to date; vehicle data has been analyzed over the course of approximately 346,000 trips, traveling nearly 2 million miles, with more than 88,000 kg of hydrogen produced or dispensed. Results have shown a vehicular fuel cell efficiency of 53-58%, vehicle range of up to 254 miles, and a projected system durability of 1977 hours (equivalent to about 59,000 miles).[7]

In addition to the National Hydrogen Learning Demonstration, other technology validation projects are demonstrating fuel cells in distributed energy applications and examining the operation of integrated, renewable-based power generation and hydrogen production technologies. These efforts involve hydrogen generation from solar, wind, and geothermal energy and include techno-economic analysis of hydrogen as an energy storage medium for variable renewables and "peak shaving."

The DOE Hydrogen Program also seeks to address non-technical barriers to hydrogen and fuel cell commercialization, including critical needs in the areas of safety, codes and standards, and education. Activities include:

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

PRACTICAL OPERATION IN EARLY MARKETS

R&D progress has paved the way for fuel cells to enter the commercial market in applications with less stringent technical requirements than vehicles, such as portable and stationary applications and specialty vehicles. There are more than 50 commercially available fuel cell products to support these markets.[8] Accelerating their use will preserve jobs in an industry that needs high volume purchases to ramp up production, support commercialization, and enable a domestic supplier base. It will also greatly expand the growth of the green job market with new opportunities associated with manufacturing fuel cells and related hydrogen technologies, fuel cell maintenance and support systems, and hydrogen production.[9] In addition, the success of these early markets will help overcome a number of non-technical barriers that also face the broader vehicular marketplace, including the lack of reliability data in the field, the lack of user confidence, and the inherent resistance to new technologies.

Fuel Cells for Forklift Trucks and Backup Power

For specialty vehicles, such as forklift trucks, fuel cells can be a cost-competitive alternative to traditional lead-acid batteries. Batteries have a limited range, take substantial time to recharge and cool before reuse, are prone to voltage drops as power discharges, and create downtime during battery change-outs (which can take from 15 to 30 minutes in many operations). For these reasons, on a lifecycle basis, fuel cells can be cost-competitive with batteries, particularly for continuously-used forklift trucks running two or three shifts per day when multiple battery change-outs may be required. Fuel cells are eligible for a federal tax credit up to $3,000/kW,§ which reduces the initial capital requirements, and in some situations, the operations and maintenance savings associated with fuel cells can provide a financially-attractive payback. The higher cost of hydrogen, compared with conventional fuels or electricity (which also directly affects the lifecycle economics), may be mitigated by generating hydrogen on site. Like batteries, fuel cells produce no harmful emissions at the point of use, but unlike batteries, fuel cells can be rapidly refueled, thus eliminating the time and cost associated with swapping batteries. The voltage delivered by the fuel cell is constant as long as hydrogen fuel is supplied. Using fuel cell-powered forklifts can boost productivity by eliminating trips to the battery changing station; also with no chargers, battery storage, or changing areas or equipment needed, more warehouse space is available. Table 1 compares the cost of material handling equipment powered by batteries versus fuel cells over the life of the equipment.

Fuel cells have also emerged as a potentially viable option for backup power, particularly in the telecommunications sector. Traditional backup power technologies include batteries and

Table1. **Lifecycle cost estimates of battery-powered and fuel cell-powered material handling equipment.**

	Pallet Trucks (3 kW Power System)		
	Battery-Powered (2 batteries per truck)	PEM Fuel Cell-Powered, Without $3K/kW Incentive	PEM Fuel Cell-Powered, With $3K/kW Incentive
Net Present Value of Capital Costs	$ 17,654	$23,835	$16,684
Net Present Value of Operations and Maintenance Costs (including fuel costs)	$127,539	$52,241	$52,241
Net Present Value of Total Costs of System	**$145,193**	**$76,075**	**$68,925**

Notes:

1. Based on: Battelle Memorial Institute, *Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane (PEM) Fuel Cell Markets*, April 2007.
2. Assumptions: Operate 7 hours/shift, 3 shifts/day, 7 days/week; batteries changed out every shift, taking about 30 minutes; operator cost $15/hour; PEM fuel cell forklift uses 3 kW stacks with NiMH batteries; stack replaced every 5 years at $3,000/kW; batteries replaced every 5 years at $1,800/kW; PEM fuel cell forklift refueled once every shift, refueling time 1 minute; no disposal costs were assumed for any of the technologies.
3. The Emergency Economic Stabilization Act of 2008 includes a fuel cell investment tax credit that is equal to 30% of the qualified fuel cell property, not to exceed an amount equal to $1,500 for each 0.5 kW of capacity of such property.

Table 2. **Estimated lifecycle cost comparison of battery and PEM fuel cell backup power systems.**

	5kW Outdoor Installations		
	Battery/Generator	PEM Fuel Cell Without Incentive	PEM Fuel Cell With $3K/kW Incentive
52-hour run time	$61,082	$61,326	$46,326

Notes:

1. Based on: Battelle Memorial Institute, *Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets* (April 2007).
2. Total cost includes capital costs and operations and maintenance costs.
3. Assumes 5-year battery replacement schedule. Analysis of 3-year replacement schedules (for cold or harsh environments) indicates PEM fuel cells compare more favorably to traditional technologies.
4. The Emergency Economic Stabilization Act of 2008 provides for an investment tax credit for fuel cells of $3,000/kW or 30%.

generators operating on diesel, propane, or gasoline; most backup power communication and control systems use a combination of generators and batteries to provide redundancy in order to avoid service disruptions. Although these systems are reliable and well-established, concerns with batteries and generators are encouraging customers to seek out alternatives that provide high reliability and durability at a reasonable cost. Compared to batteries, fuel cells offer longer continuous run-time and greater durability in outdoor environments under a wide range of temperature conditions. With fewer moving parts, they require less maintenance than both generators and batteries. They can also be monitored remotely, reducing actual maintenance time. Compared to generators, fuel cells are quieter and have no emissions. As Table 2 indicates, fuel cells can also offer significant cost advantages over both battery-generator systems and battery-only systems when shorter run-time capability of up to three days is sufficient.

Public and Private Adoption of Fuel Cells

Other types of fuel cells, including molten carbonate fuel cells (MCFCs) and phosphoric acid fuel cells (PAFCs), suitable for combined heat and power applications are also commercially available to provide electricity at critical load facilities including hospitals, data centers, and banks. In these applications, fuel cells can provide high-quality, reliable, grid-independent, on-site electric power, with reduced emissions compared to conventional power technologies.

Grocers, banks, tire and hardware companies, logistics providers, and others in the private sector have begun to recognize the value of using fuel cells to support their operations. The DOE is working in partnership with other federal agencies to identify opportunities for incorporating fuel cells into government operations as well. Early federal adoption not only shows the public that hydrogen and fuel cells are real and no longer confined to the laboratory, but it also proves the government takes its leadership role seriously – that agencies are incorporating into their own operations clean, energy-efficient, advanced technologies (including fuel cells) that will reduce our nation's dependence on oil as well as greenhouse gas emissions and criteria pollutants.

In addition to achieving societal benefits, early federal adoption can support commercialization and industry growth by affecting fuel cell cost reduction. A recent study released by Oak Ridge National Laboratory found that implementing a government acquisition program focused on fuel cells for backup power and specialty vehicles/lift trucks would result in manufacturing

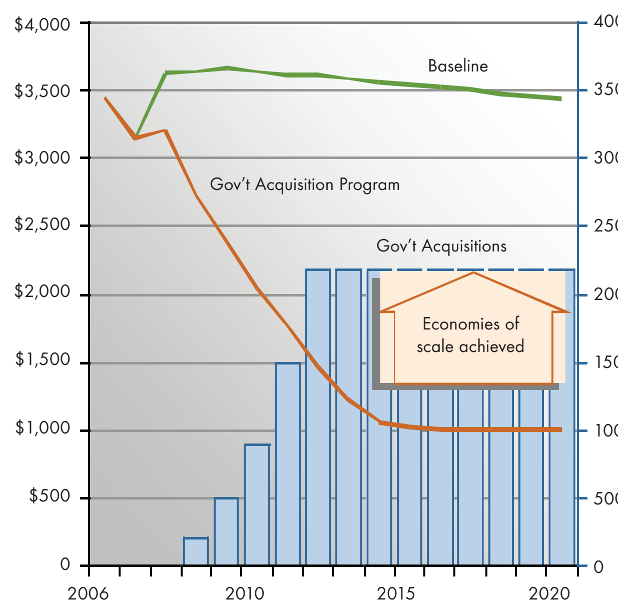

Figure 1. **Estimated impact of government acquisitions on fuel cell stack costs.[11]**

http://wstiac.alionscience.com/quarterly

economies of scale that could enable fuel cells to be cost competitive with conventional technologies, such as batteries and small combustion engines.[10]

Unlike other alternative fuels and advanced technologies that benefit from a history of deployment activity, however, hydrogen and fuel cells are new to federal energy managers. Enabling early adoption, therefore, requires a combination of technical and financial assistance, data collection, and communications and outreach. In addition to identifying ways in which the DOE can incorporate fuel cells into its facilities – potentially to support data center operation and national laboratory critical load needs – the program seeks to facilitate early adoption of hydrogen and fuel cell technologies among other federal agencies. Working through an interagency task force and working group, the program has facilitated partnerships with other agencies. These partnerships help identify deployment opportunities in key early markets, provide financial assistance through cost-shared agreements, and offer technical expertise to support competitive procurements as well as use third-party financing to take advantage of the fuel cell investment tax credit and other policy incentives that can minimize the government outlay for fuel cell projects.**

These partnerships have resulted in projects that will provide valuable data on the status of the technologies in real-world operation and information that will be used to validate the benefits of the technologies. Notable efforts include the following:

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

Similar to the vehicle demonstrations, data collected through these efforts will be made available as composite data products, giving other potential users important information about the technology's performance in practical, real-world operation.

CONCLUSION

Together with its partners, the DOE plans to continue building on recent progress. For more information about hydrogen and fuel cells, DOE Hydrogen Program activities, and upcoming events, please visit www.hydrogen.energy.gov.

NOTES & REFERENCES

* Transportation fuels are often compared on their equivalency to gasoline. The amount of fuel with the energy content of one gallon of gasoline is referred to as a gallon gasoline equivalent, or gge.

† Distributed reforming refers to the generation of hydrogen on a small scale at or near the point of use. For instance, rather than generating hydrogen on a large scale and transporting it from a centralized location, the hydrogen required for fuel cells can be generated on-site.

‡ The costs of $275/kW and $73/kW are based on 2002 and 2008 dollars, respectively. The 2015 target of $30/kW is based on 2002 dollars.

§ The Emergency Economic Stabilization Act of 2008 includes a fuel cell investment tax credit (ITC) of $3,000/kW or 30%; for more information, see www.usfcc.com/ITC-TaxQA10-2008%20_2_.pdf.

** The Hydrogen and Fuel Cell Interagency Task Force, established by Section 806 of the Energy Policy Act of 2005, includes senior-management level representatives of federal agencies and is focused on demonstration and deployment; the staff-level Hydrogen and Fuel Cell Interagency Working Group coordinates hydrogen and fuel cell research and development activities across the federal government.

[1] US Department of Energy Hydrogen Program, Record #5018: "Reduction in Fuel Consumption with FCVs," http://www.hydrogen.energy.gov/program_records.html.

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

[3] US Department of Energy Hydrogen Program, Record #6002: "Electrolysis Analysis to Support Technical Targets," www.hydrogen.energy.gov/program_records.html.

[4] US Department of Energy Hydrogen Program, Record #5005, "Fuel Cell System Cost," and Record #8019, "Fuel Cell System Cost – 2008," www.hydrogen.energy.gov/program_records.html.

[5] US Department of Energy Hydrogen Program, Record #9001, www.hydrogen.energy.gov/program_records.html.

[6] US Department of Energy Hydrogen Program Record #5037, "Hydrogen Storage Materials–2004 vs. 2006," www.hydrogen.energy.gov/program_records.html.

[7] Composite data products are available at www.eere.energy.gov/hydrogenandfuelcells/tech_validation/fleet_demonstration.html

[8] See product listings available at www.usfcc.com/resources/outreachproducts.html and www.hydrogenassociation.org/general/productsSearch.asp

[9] US Department of Energy, "Effects of a Transition to a Hydrogen Economy on Employment in the United States," Report to Congress, July 2008, http://www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf.

[10] Greene, D.L. and K.G. Duleep, "Bootstrapping a Sustainable North American PEM Fuel Cell Industry: Could a Federal Acquisition Program Make a Difference?" October 2008.

[11] Greene, D.L. and K.G. Duleep, "Bootstrapping a Sustainable North American PEM Fuel Cell Industry: Could a Federal Acquisition Program Make a Difference?" October 2008.

Ms. Christy Cooper is responsible for communications activities and supports market transformation activities for the Hydrogen, Fuel Cells and Infrastructure Technologies Program in the Department of Energy's Office of Energy Efficiency and Renewable Energy. In this capacity, she is part of a new and growing Program effort to advance the use of hydrogen fuel cells in key early markets including material handling equipment, backup power, and primary power, as well as integrated renewable hydrogen energy systems. Ms. Cooper previously served as the Program's Education team lead and was responsible for a broad range of education and training activities for safety and code officials, state and local government representatives, local communities, and potential end-users, as well as university and other student programs. She currently serves as a co-chair of the International Partnership for the Hydrogen Economy Education Work Group and manages DOE's activities in its capacity as co-chair of the Interagency Hydrogen and Fuel Cell Working Group. Ms. Cooper began her career at DOE's Office of Energy Efficiency and Renewable Energy in 1995 with the Clean Cities Program, a market development program for alternative fuel vehicles. There she was responsible for new coalition development and communications and outreach activities. She also managed the Fuel Economy Information Program and fueleconomy.gov.