Hydrogen and fuel cell technologies – status, challenges and future opportunities

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Hydrogen and fuel cells are key elements in a portfolio of advanced energy technologies that the U.S. Department of Energy (DOE) is developing to address energy challenges today and in the future. The use of hydrogen as an energy carrier has the potential to reduce dependence on petroleum and decrease pollution and greenhouse gas emissions. Therefore, hydrogen and fuel cell technologies are being developed and validated in parallel with complementary near-term energy efficiency and renewable energy solutions, such as ethanol and hybrid electric vehicles.

The DOE Hydrogen Program continues to make progress toward achieving its cost and performance goals by researching, developing, and validating hydrogen production, storage, and fuel cell technologies. The Program works in partnership with a diverse array of organizations, including: automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, code and standards development organizations, federal and state agencies, universities, national laboratories, and other national and international stakeholders.

Program Overview

The Program's research, development, and demonstration (RD&D) efforts focus on hydrogen and fuel cell technologies for light-duty vehicles, distributed power generation, auxiliary power, and portable power applications. Due to the large consumption of energy and relative inefficiency of our nation's light-duty vehicle fleet, it is clear that the Program will achieve the most progress toward its goals of reducing oil use and CO_2 emissions by developing economically viable technologies for light-duty passenger vehicles. However, technologies for stationary power applications can also be of significant value in contributing to a more efficient, secure, and diversified energy infrastructure. In addition, the deployment of stationary and portable power technologies will help to grow early markets for fuel cells, which will further help to achieve the economies of scale needed for cost reduction and will establish a supply base for many of the same technologies that will be used in vehicles.

Due to these considerations, the Program has placed a high priority on establishing "technology readiness" for fuel cell-powered passenger vehicles by 2015. To accomplish this, the Program has identified key barriers that need to be overcome to enable the successful market introduction of fuel cell vehicles. We refer to these as "critical path" barriers, and they include: reducing the cost of hydrogen to less than $3 per gallon gasoline equivalent; improving onboard hydrogen storage technologies to enable vehicle range of more than 300 miles, within the weight, volume and cost constraints of today's vehicle market; improving the durability of vehicular fuel cells to 5000 hours (~150,000 miles) of driving; and reducing the cost of vehicular fuel cells to $30/kW (at high-volume).

The key objective of our efforts in hydrogen production and delivery is to reduce the cost of hydrogen to $2−3/gge (gallon gasoline equivalent), delivered and untaxed. Research funded jointly by DOE and our partners in industry has reduced the cost of hydrogen produced from the distributed reforming of natural gas to meet this target. With this accomplishment, we have provided a cost-effective pathway for producing hydrogen when fuel cell vehicles are introduced into the market. Hydrogen production, therefore, no longer presents a "critical path" barrier. The benefits of fuel cell vehicles using hydrogen produced from natural gas will be substantial: our well-to-wheels analysis indicates that they would emit 46% less CO_2 than gasoline internal combustion vehicles and 33% less CO_2 than gasoline hybrids (based on technology expected in 2015). However, using hydrogen from natural gas remains a strategy for the near term only, for two key reasons: first, in order to fully realize the CO_2-reduction potential of fuel cell vehicles, they will have to be fueled with hydrogen from renewable, carbon-neutral sources; second, natural gas is expected to remain a critical resource for our nation's power generation needs, and its use for powering our light-duty vehicle fleet beyond the early stages of market penetration will place excessive demand on natural gas supplies. Therefore, we continue to see a vital role for government R&D in hydrogen production, including near-term research to reduce the costs involved in renewable production pathways, such as distributed electrolysis and reforming of bio-derived liquids, and in longer-term research to advance technologies that will be needed for the higher-volume centralized production pathways.

Centralized production technologies will provide the hydrogen needed for the full market-penetration of fuel cell vehicles, and will allow fuel cell vehicles to achieve their potential in terms of emissions reductions. These pathways include: coal and biomass gasification with carbon sequestration; wind- and solar-driven electrolysis; photoelectrochemical and biological production; solar and nuclear high-temperature thermochemical water splitting; and high-temperature electrolysis. All of these will require substantial, long-term investment in a delivery infrastructure. Cost effective technologies to deliver hydrogen are also being investigated through infrastructure analysis and R&D on: compression technology; systems for stationary storage and tube trailers; liquefaction technologies; improved pipeline materials; and new liquid or solid hydrogen carriers.

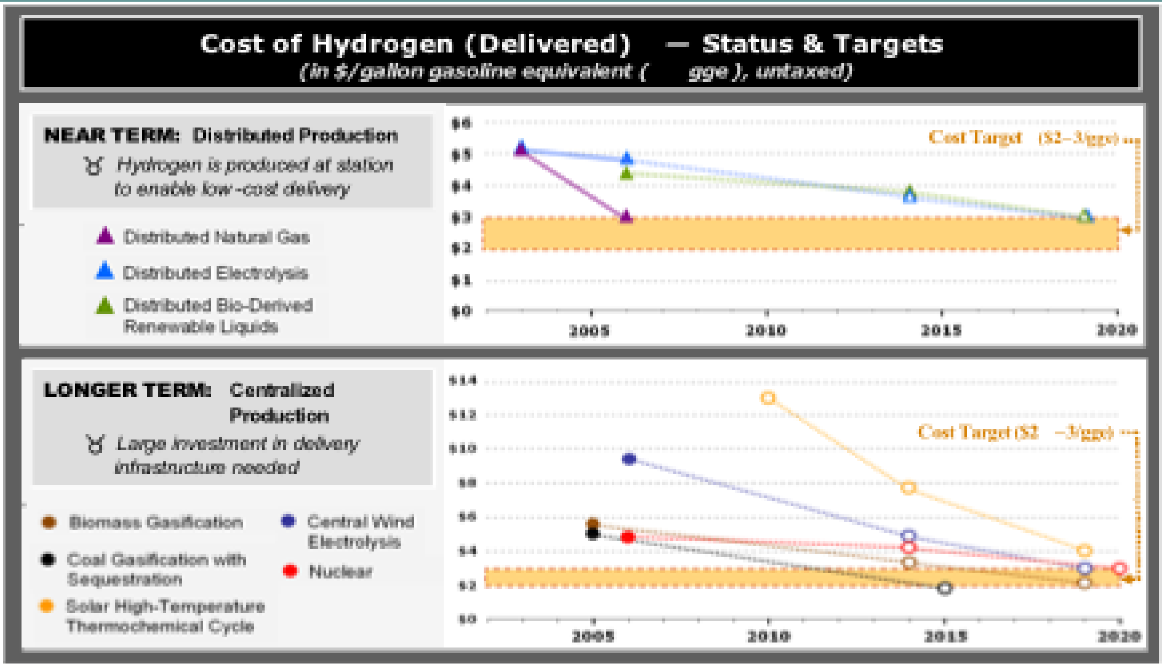


Figure 1. The DOE Hydrogen Program is reducing the cost of producing hydrogen

Onboard storage of hydrogen remains a "critical path" barrier, and it is one of the primary focus areas for our near-term R&D efforts. While compressed hydrogen storage systems provide a valuable pathway for the early market introduction of fuel cell vehicles, this technology will not be able to provide a 300-mile driving range within the current weight, volume, and cost constraints of the vehicle market. Therefore, we are exploring and developing materials-based storage technologies in three promising areas: metal hydrides, chemical hydrogen storage, and hydrogen sorption. Our applied R&D in this area is closely coordinated with basic research (conducted by the DOE Office of Science), which seeks to develop the understanding of the chemical and physical processes governing the interactions between hydrogen and various materials. Our R&D efforts in this area continue to identify promising materials with high storage capacities and to pursue technologies to enable these materials to store and release hydrogen at practical operating temperatures and pressures.

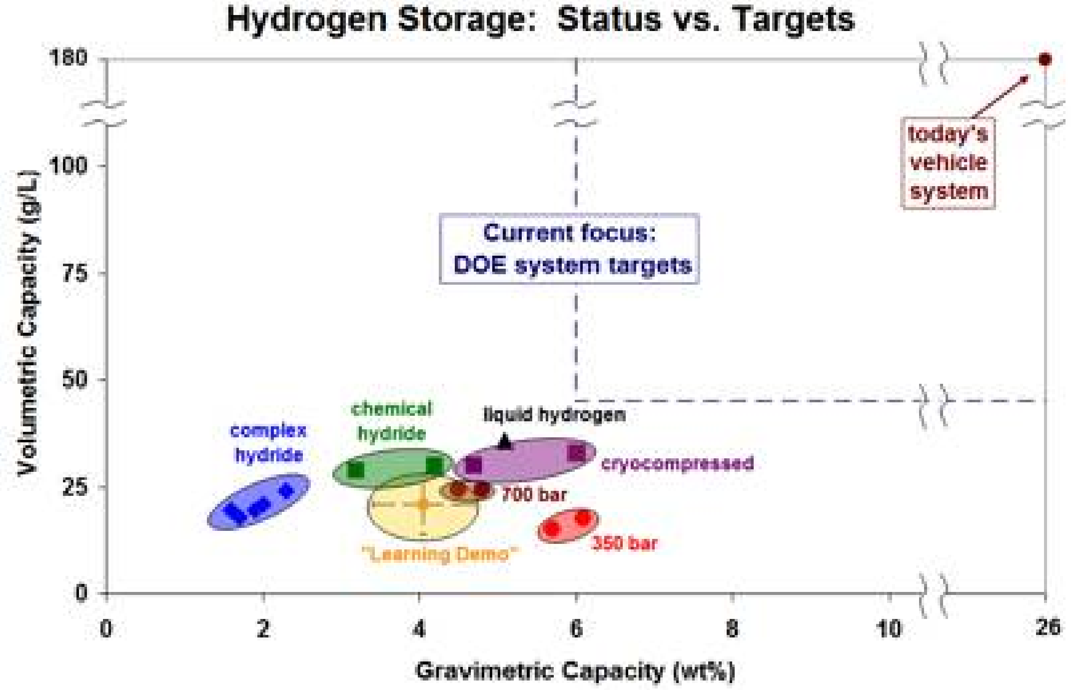
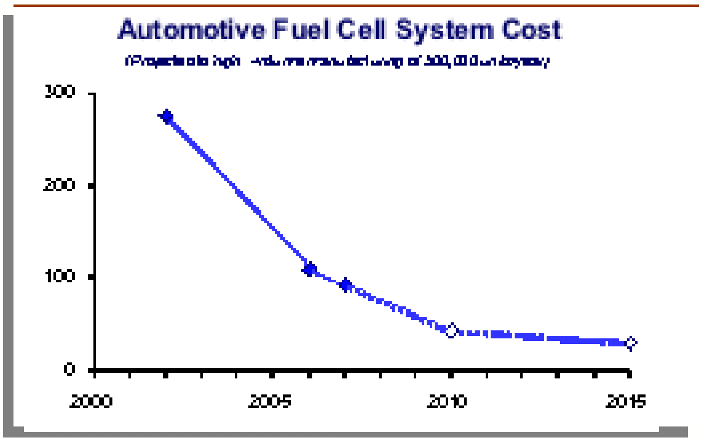


Figure 2. The Program's goal for onboard storage is to enable a 300-mile driving range while meeting all requirements for safety, cost, and performance. This chart represents "system capacity," which includes estimates for materials, tanks, and balance of plant

While much progress has been made in polymer electrolyte membrane (PEM) fuel cell technology, the cost and durability of fuel cells also remain "critical path" barriers. Current R&D activities focus on improving electrocatalysts, membranes, water transport in the stack, and bipolar plate materials. In the development of automotive fuel cell power systems, the cost per kilowatt has been reduced from $275/kW in 2002 to $94/kW in 2007 (based on projections for high-volume manufacturing). These projected costs are showing substantial progress toward our cost targets of $45/kW by 2010 and $30/kW by 2015. Fuel cell stack durability in the laboratory (with automotive cycling) has doubled from 1,000 to 2,000 hours between 2003 and 2006, and continues to move closer to the 2015 target of 5,000 hours for light-duty vehicle operations.

In addition to our work in PEM fuel cells for light-duty vehicles, we are also actively pursuing improvements in technologies for stationary, portable power, and auxiliary power applications. For distributed generation fuel cell applications, the Program focuses on near-term fuel cell systems running on natural gas or liquid petroleum gas, while also exploring the longer-term potential for systems running on renewable fuels.



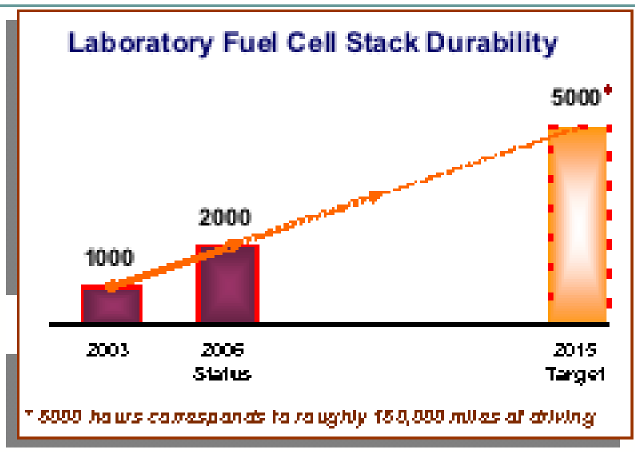


Figure 3. The Program is reducing the high-volume manufacturing cost of automotive fuel cell systems.
Figure 4. The Program is increasing the durability of laboratory fuel cell stacks (figures shown reflect automotive cycling in the lab).

To provide valuable data on fuel cell performance under real-world conditions, the Program is validating integrated hydrogen and fuel cell systems for transportation and electricity generation. The controlled vehicle fleet test and evaluation effort involves four teams of automobile and energy companies working collaboratively in 50/50 cost shared projects. Currently, 92 fuel cell vehicles and 14 hydrogen stations are being evaluated under this effort. Critical fuel cell system parameters have been validated in first-generation vehicles, including: 53–58% efficiency; durability of 1,900 hours (~57,000 miles); and a vehicle range of 103–190 miles. Additionally, projects that integrate renewable power-generation and hydrogen production have demonstrated the use of water electrolysis via solar and wind energy to generate electricity and to fuel hydrogen buses.

The Program's vehicle and infrastructure learning demonstration involves four teams of automobile and energy companies working in 50/50 cost-shared projects

In addition to the need for the technological advances discussed above, the program has identified and begun to address many of the economic and institutional barriers that may impede the progress of hydrogen and fuel cell technologies as they move from the technology-readiness phase into consumer markets and widespread commercialization. We recognize that technology that meets consumer requirements is necessary, but not sufficient, for industry to move forward with commercialization. Among these non-technological barriers, the need for technically sound codes and standards represents a "critical path" barrier, as the widespread market introduction of fuel cell vehicles will not be possible without sufficient codes and standards and permitting practices in place. We are addressing this challenge by working with domestic and international organizations to identify gaps in the codes and standards development process; to facilitate the creation and adoption of building codes and equipment standards for hydrogen systems in commercial, residential, and transportation applications; and to help harmonize the development of international standards.

Additional work in non-technological areas is being done through our efforts in education and market transformation. Our education activities are aimed at increasing knowledge and understanding of hydrogen and fuel cells among emergency responders, safety and code officials, and other key audiences. To advance the commercialization of hydrogen and fuel cell technologies, our market transformation activities aim to promote early adoption of fuel cells in stationary, portable, and specialty vehicle applications, such as forklifts and emergency backup power. In addition to lowering costs and establishing a domestic supplier base, these early markets will help to build user confidence and overcome other societal barriers that are faced by a new, unfamiliar technology.

Involving Industry

A key element of DOE's strategy for the Hydrogen Program has been to closely involve industry in both the planning and the implementation of R&D activities, and to ensure that the Program's priorities are closely aligned with those of industry. The Program's strategic partnership with the automobile manufacturers and energy companies—the "FreecomCAR and Fuel Partnership" (the Partnership)—has been key to the significant progress made.

DOE established the Partnership in 2002 to examine the pre-competitive, high-risk research needed to reduce the dependence of the nation's personal transportation system on imported oil and minimize harmful vehicle emissions. The Partnership plays an important role in guiding the research efforts of its members, which include DOE, the U.S. Council for Automotive Research (whose members are Ford Motor Company, General Motors Corporation, and Chrysler Corporation) and five major energy companies (BP, Chevron, ConocoPhillips, ExxonMobil, and Shell). In addition to the extensive role the Partnership has in helping to shape the strategic priorities of the Program, regular meetings of the Partnership's technical teams, which are co-chaired by DOE and industry, provide a valuable channel for industry input.

Communication and coordination between DOE and industry also takes place through frequent R&D workshops and the constant, informal interaction between the Program's managers and the industry-led projects they oversee. Approximately 35% of the Program's funding goes to industry, which includes large hydrogen and fuel cell industry players, small businesses, as well as automobile and energy companies. The majority of our funding involves significant cost-sharing, which has had a substantial impact: our partners in industry and academia have added nearly $300 million to the $1.2 billion in federal funding for the hydrogen fuel initiative. DOE is also involved in the California Fuel Cell Partnership, a group of automobile, fuel, and fuel cell technology companies and government agencies working to deploy fuel cell vehicles on California's roads.

A recent independent review of the Program by the U.S. Government Accountability Office recognized the value of our ongoing involvement with stakeholders: "DOE has effectively solicited industry input and has worked to align its R&D priorities with those of industry," and "DOE's efforts to involve industry early in the planning stages and its ongoing efforts to solicit industry feedback on priorities have been effective in keeping the R&D agenda focused and headed in the right direction."

Working directly with industry also helps to ensure that the successes achieved in the laboratory find their way into the marketplace. And we are seeing the results of this today—out of 34 companies with commercially available products in the United States, 26 of these companies were involved in R&D projects with DOE.

Channels for Feedback: External Review and Evaluation

The Program also employs a number of mechanisms for external review and evaluation. In February 2004, the National Academies of Science and Engineering (NAS) published their review of the Hydrogen Program's RD&D plan and provided recommendations. DOE has implemented most of these recommendations, and has been commended by the NAS for doing so. The NAS also conducts biannual reviews of DOE's R&D progress under the FreedomCAR and Fuel Partnership. The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) provides technical and programmatic advice to DOE on hydrogen research, development, and demonstration efforts. The Government Accountability Office (GAO) has also reviewed the Program, and released its report in February 2008. In addition to these reviews, the Program receives feedback through its Annual Merit Review and Peer Evaluation Meeting, which involves the participation of more than 150 technical experts reviewing individual RD&D projects.

Based on the input from these diverse channels, the Program periodically revises its strategic roadmap and RD&D plans. These revisions also reflect technological progress, programmatic changes, and policy decisions. We believe that incorporating this feedback into a flexible, adaptive strategy, while maintaining focus on the key long-term goals of the Program has been key to our success to date.

International Activities

Many of the Program's activities are pursued internationally through collaborations with the International Partnership for the Hydrogen Economy (IPHE) and the International Energy Agency (IEA). The U. S. is a founding IPHE member and served as the IPHE Secretariat for its first three years until 2007. Through this international partnership, the U.S. has conducted joint hydrogen research with partners in Europe, Asia, and South America. Additionally, the U.S. holds a central role in every one of the IEA Hydrogen Implementing Agreement's seven current tasks, partnering with 21 countries and the European Commission on projects such as integrated systems evaluation, hydrogen storage materials development, biological and photoelectrochemical hydrogen production, high-temperature and small-scale reforming production of hydrogen, wind-hydrogen integration, and hydrogen safety research. Furthermore, the United States holds a central role in each of the IEA's Advanced Fuel Cells Implementing Agreement annexes, partnering with 17 nations on projects in the areas of PEM fuel cells, molten carbonate fuel cells, solid oxide fuel cells, fuel cells for stationary applications, fuel cells for transportation, and fuel cells for portable applications.

To explore the expected impact of policies in different global regions and identify bottleneck issues, the IEA aims to run established regional models in concert, including two U. S. models—the Hydrogen Analysis (H_2A) and Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) models—and the European HyWays model. The international focus on global infrastructure analysis shapes research priorities and informs other important decisions involved in the development of a global hydrogen economy. This international "soft-linking" of hydrogen infrastructure models was agreed upon at the 2007 IEA meeting in Paris.

DOE has also been involved, through the Hydrogen Program and the national labs, in a joint project of the IEA and IPHE, "Building the Hydrogen Economy: An Infrastructure Strategy," which held three international workshops last year. The overall goal of this project is to: (1) summarize lessons learned and analysis from early public and private sector investments in hydrogen economy infrastructure, and

(2) develop a viable vision and pathway (s) forward for future infrastructure investments and development activities.

Hydrogen codes and standards development is another area of particular international interest, and DOE has worked with its foreign partners to develop stationary hydrogen and fuel cell systems installation processes, a handbook on permitting hydrogen fueling stations, and an international standard for hydrogen fuel quality in PEM fuel cells for road vehicles. In the area of hydrogen safety, the United States, along with 11 other countries, is participating in HySafe (the European Commission's Network of Excellence for Hydrogen Safety) to coordinate hydrogen safety RD&D. DOE additionally plays a key role in sponsoring the biennial International Conference on Hydrogen Safety (ICHS), and the Program collaborates with the European Union on a database of hydrogen incidents and lessons learned as well as a bibliography on hydrogen safety.

Involving Developing Nations

While the DOE Hydrogen Program's mission centers on domestic energy issues, some of DOE's work has involved hydrogen in developing nations, including the following examples:

- In 2004, the DOE Hydrogen Program worked with the Brazilian Ministry of Mines and Energy to develop a hydrogen energy technology roadmap for Brazil. This roadmap, which was published in March 2005, incorporated possible pathways for future efforts in hydrogen production, storage, transfer, and end-use technologies; safety, codes and standards; and outreach/ communication.
- DOE's National Energy Technology Laboratory (NETL) collaborated with the U. S. Agency for International Development (USAID), Nuvera Fuel Cells, and Indian private sector partners to install a commercial demonstration of a PEM fuel cell for power generation. This megawatt-size proton-exchange membrane (PEM) fuel cell product captures hydrogen produced in the chlor-alkali industry to create on-site electricity and provide power plant operators up to 20% electricity savings.
- NETL & USAID assisted India's National Hydrogen Energy Board (NHEB) Steering Group to develop a national hydrogen roadmap in 2005.

In addition, DOE's national labs continue to support energy efficiency and renewable energy research for government and non-governmental organizations in developing countries. For example, DOE provides guidance on fuel cell research for developing nations, and vehicle manufacturers in such countries partner with the U.S. on fuel cell vehicle demonstration projects. Furthermore, the U.S. has been involved in international research partnerships with developing nations in the areas of hydrogen storage, hydrogen markets and infrastructure modeling, and fuel cell safety and quality assurance testing. Such collaborations aim to overcome critical barriers to achieving commercial readiness for hydrogen fuel cell technologies.

While our RD&D plan has guided the Hydrogen Program to substantial technological progress, it should be kept in mind that its strategy is based on the particular energy consumption and production patterns of the United States. Therefore, as more countries begin to develop hydrogen technology roadmaps, these programs will need to be tailored to address the specific energy resources and challenges of each nation and region. For example, when we worked with Brazil on their roadmap, it became clear that distributed reforming of ethanol would have a higher R&D priority there than in the US, due to their country's large capacity for efficient ethanol production.

Furthermore, there may exist other opportunities for hydrogen technologies in developing nations that would not necessarily apply to the United States. For instance, the higher prices paid for gasoline around the world may make it easier for many countries to produce hydrogen from domestic resources on a cost-competitive basis. Our target for the cost of hydrogen is based roughly on the price we pay domestically for gasoline, and in 2007, we paid an average of $2.38 per gallon, while the worldwide average was over $3.70. Consumers in 143 nations paid more for gasoline than we did, including 40 nations where the price was over $4.50/gallon, and the majority of these are developing countries. If hydrogen were available for a significantly lower price per gallon gasoline equivalent, there may be a case to be made for the early-market introduction of hydrogen vehicles powered by internal combustion engines (ICEs) in some areas. Furthermore, taking into account the differences between driving patterns of Americans and other nations (specifically, the fact that we drive more than most), the requirements for onboard fuel storage in foreign automobile markets may not be as stringent as they are in the United States. Taken together, these differences may mean that the "critical path" barriers faced by some developing nations may be substantially different than those in the United States.

Different opportunities for hydrogen and fuel cells for distributed power generation may also exist in developing nations, especially in the case of regions that have limited or no access to the electrical grid. In such areas, fuel cells may have advantages in cost for power generation, as they would be competing with other, less-efficient distributed power generation sources, rather than with the low-cost (and often government-subsidized) power from the grid. Agricultural areas with plentiful sources of feedstock for biogas production may present a particularly good market for fuel cells. Several fuel cell systems using biogas are running successfully (and economically) in the United States in a variety of applications, including food and beverage processors and waste water treatment facilities. As many developing nations are already seeking ways to take advantage of indigenous biogas resources, the extremely high efficiencies of fuel cell systems, when used in combined heat and power applications (80 to 90% efficiencies have been demonstrated), may make them a particularly appealing option.

While our particular roadmap may not be applicable to many developing nations, there are lessons that can be learned from the experience of the DOE hydrogen program. As discussed earlier, we believe that much of the success of the program can be attributed to our close involvement and coordination with a broad group of stakeholders (including key industry players), and the mechanisms we have in place for external review and evaluation. All of these approaches can be applied to any nation’s hydrogen and fuel cell program, regardless of the technologies or the specific goals identified in its roadmap.