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HYDROGEN FUEL INITIATIVE

DOE Has Made Important Progress and Involved Stakeholders but Needs to Update What It Expects to Achieve by Its 2015 Target

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Highlights

Highlights of GAO-08-305, a report to congressional requesters

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DOE Has Made Important Progress and Involved Stakeholders but Needs to Update What It Expects to Achieve by Its 2015 Target

Why GAO Did This Study

The United States consumes more than 20 million barrels of oil each day, two-thirds of which is imported, leaving the nation vulnerable to rising prices. Oil combustion produces emissions linked to health problems and global warming. In January 2003, the administration announced a 5-year, $1.2 billion Hydrogen Fuel Initiative to perform research, development, and demonstration (R&D) for developing hydrogen fuel cells for use as a substitute for gasoline engines. Led by the Department of Energy (DOE), the initiative's goal is to develop the technologies by 2015 that will enable U.S. industry to make hydrogen-powered cars available to consumers by 2020.

GAO examined the extent to which DOE has (1) made progress in meeting the initiative's targets, (2) worked with industry to set and meet targets, and (3) worked with other federal agencies to develop and demonstrate hydrogen technologies. GAO reviewed DOE's hydrogen R&D plans, attended DOE's annual review of each R&D project, and interviewed DOE managers, industry executives, and independent experts.

What GAO Recommends

GAO recommends that DOE update its *Hydrogen Posture Plan*'s assessment of what can reasonably be achieved by 2015 and how this may differ from its prior posture plans. In commenting on a draft of the report, DOE agreed with the recommendation, stating that it will update its posture plan during 2008.

To view the full product, including the scope and methodology, click on GAO-08-305. For more information, contact Mark Gaffigan at (202) 512-3841 or gaffiganm@gao.gov.

What GAO Found

DOE's hydrogen program has made important progress in all R&D areas, including both fundamental and applied science. Specifically, DOE has reduced the cost of producing hydrogen from natural gas, an important source of hydrogen through the next 20 years; developed a sophisticated model to identify and optimize major elements of a projected hydrogen delivery infrastructure; increased by 50 percent the storage capacity of hydrogen, a key element for increasing the driving range of vehicles; and reduced the cost and improved the durability of fuel cells. However, some of the most difficult technical challenges lie ahead, including finding a technology that can store enough hydrogen on board a vehicle to achieve a 300-mile driving range, reducing the cost of delivering hydrogen to consumers, and further reducing the cost and improving the durability of fuel cells. The difficulty of overcoming these technical challenges, as well as hydrogen R&D budget constraints, has led DOE to push back some of its interim target dates. However, DOE has not updated its 2006 *Hydrogen Posture Plan's* overall assessment of what the department reasonably expects to achieve by its technology readiness date in 2015 and how this may differ from previous posture plans. In addition, deploying the support infrastructure needed to commercialize hydrogen fuel-cell vehicles across the nation will require an investment of tens of billions of dollars over several decades after 2015.

DOE has effectively involved industry in designing and reviewing its hydrogen R&D program and has worked to align its priorities with those of industry. Industry continues to review R&D progress through DOE's annual peer review of each project, technical teams co-chaired by DOE and industry, and R&D workshops. Industry representatives are satisfied with DOE's efforts, stating that DOE generally has managed its hydrogen R&D resources well. However, the industry representatives noted that DOE's emphasis on vehicle fuel cell technologies has left little funding for stationary or portable technologies that potentially could be commercialized before vehicles. In response, DOE recently increased its funding for stationary and portable R&D.

DOE has worked effectively with hydrogen R&D managers and scientists in other federal agencies, but it is too early to evaluate collaboration among senior officials at the policy level. Agency managers are generally satisfied with the efforts of several interagency working groups to coordinate activities and facilitate scientific exchanges. At the policy level, in August 2007, DOE convened the inaugural meeting of an interagency task force, composed primarily of deputy assistant secretaries and program directors. The task force is developing plans to demonstrate and promote hydrogen technologies.

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Abbreviations

DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
HTAC	Hydrogen and Fuel Cell Technical Advisory Committee
IWG	Interagency Working Group on Hydrogen and Fuel Cells
IPHE	International Partnership for the Hydrogen Economy
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
R&D	research, development, and demonstration
USCAR	U.S. Council for Automotive Research

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United States Government Accountability Office
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January 11, 2008

The Honorable Bart Gordon
Chairman
Committee on Science and Technology
House of Representatives

The Honorable Nick Lampson
Chairman
The Honorable Bob Inglis
Ranking Member
Subcommittee on Energy and Environment
Committee on Science and Technology
House of Representatives

The Honorable Michael M. Honda
House of Representatives

The United States uses more than 20 million barrels of oil each day, roughly two-thirds of which is imported. Disruptions in supply from natural disasters such as hurricanes in the Gulf of Mexico and political instability in some oil-producing regions have caused prolonged price spikes, at times quadrupling the price of oil. In recent years, reduced domestic production and increased world consumption have contributed to recent records for the price of oil. In 2004, when oil cost refiners about $41 a barrel, the nation spent about $6 billion a week for its oil when adjusted for inflation; by October 2007, oil cost refiners about $80 per barrel and the nation spent more than $11 billion a week. Oil prices are likely to climb even higher as global oil production peaks, which many studies estimate could occur within the next 35 years. Moreover, the nation's transportation sector is 97 percent dependent on oil-derived products that, when burned in conventional internal combustion engines, produce harmful emissions that raise health problems and global warming concerns.

To reduce the nation's dependence on foreign oil and to decrease greenhouse gas emissions, President Bush in January 2003 announced the initial phase of a 5-year, $1.2 billion Hydrogen Fuel Initiative to conduct research, development, and demonstration (R&D) for developing hydrogen-powered fuel cells as an alternative to the internal combustion engine in vehicles. Hydrogen fuel cells emit only water and heat as byproducts—an important factor for limiting carbon emissions. The Hydrogen Fuel Initiative, primarily led by the Department of Energy (DOE), set a target date of 2020 for making hydrogen vehicles commercially available to consumers to achieve its goal of allowing a child born in 2003 to be able to drive a hydrogen vehicle as his or her first car.

Since the 1970s, the federal government has conducted R&D on hydrogen and fuel cells, which operate similarly to a battery to produce electricity. Hydrogen, like electricity, carries energy in a usable form from one place to another. Moreover, hydrogen can be stored and efficiently converted to energy when needed, making it ideal to power fuel cells to generate energy. In addition to potential use in vehicles, hydrogen fuel cells can be used in stationary applications, such as replacing diesel generators used to provide emergency power in hospitals, and portable applications, such as replacing batteries used in electric wheelchairs and laptop computers. However, while hydrogen is the most plentiful element in the universe, it is not found in its gaseous state on earth because it is lighter than air and rises in the atmosphere. Instead, hydrogen must be extracted from such common compounds as fossil fuels, biomass, and water, a process that requires energy.

To develop the Hydrogen Fuel Initiative, DOE met with stakeholders, including industry executives and university scientists, in a series of meetings and workshops. DOE determined that hydrogen fuel cell technologies must be ready by 2015 to enable industry to begin commercialization by 2020. DOE issued its first *Hydrogen Posture Plan* in February 2004 and updated it in December 2006. The plan established priorities for hydrogen R&D areas and set interim and final targets, focused on developing hydrogen-powered fuel cells that match the performance of gasoline-powered vehicles in terms of driving range, durability, and cost. DOE began to implement the Hydrogen Fuel Initiative in fiscal year 2004. DOE's Office of Energy Efficiency and Renewable Energy, which conducts most of the initiative's R&D work, oversees the Hydrogen Fuel Initiative through the hydrogen program manager. The initiative's R&D is coordinated with other renewable energy programs; DOE's Offices of Fossil Energy, Nuclear Energy, and Science; and the Department of Transportation (DOT), which conducts R&D in such areas as vehicle-related safety codes and standards and medium- and heavy-duty vehicle demonstrations.

Title VIII of the Energy Policy Act of 2005 extended the Hydrogen Fuel Initiative beyond the President's initial 5-year program by authorizing R&D funding through 2020 and directing DOE to conduct R&D to develop, among other things, the necessary supporting infrastructure, including pipelines and fueling stations. The act also directed DOE to work with industry and established the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC)—which includes representatives of industry, academia, professional societies, government agencies, financial organizations, and environmental groups—to review and make recommendations to the Secretary of Energy on DOE's implementation of its hydrogen R&D programs and activities; the safety, economical, and environmental consequences of technologies; and DOE's long-term R&D plans. In addition, the act directed the President to establish the Interagency Task Force, chaired by the Secretary of Energy, to coordinate federal agencies' hydrogen and fuel cell R&D efforts and promote hydrogen technologies. The task force is to include representatives from, at a minimum, DOT, the Department of Defense (DOD), the Department of Commerce, the Department of State, the National Aeronautics and Space Administration (NASA), the Environmental Protection Agency, and the White House's Office of Science and Technology Policy. Subsequently, in November 2006, HTAC recommended that the Interagency Task Force include assistant secretary-level officials with policy-setting authority from each participating agency.

DOE—with input from industry, university, and federal agency stakeholders—identified the following four major technical challenges that must be overcome before hydrogen technologies can be deployed on a large scale:

- *Production*. Current production R&D efforts focus on economically extracting hydrogen from other compounds using fossil, renewable, and nuclear energy. For example, DOE established 2015 as the target date for extracting hydrogen from natural gas at a cost equivalent of $2 to $3 per gallon of gasoline.
- *Storage*. Storing hydrogen requires it to be either compressed under very high pressure as a gas or super-cooled to obtain a liquid; however, these technologies consume significant amounts of energy and are currently too costly. Current hydrogen storage R&D efforts focus on developing less energy-intensive and less expensive methods of storing hydrogen. For example, DOE established 2015 as the target date for developing a hydrogen fuel cell vehicle that can travel at least 300 miles using only the hydrogen stored onboard.
- *Delivery*. Current truck delivery technologies cannot compete with gasoline technologies because of the cost of compressing or liquefying

hydrogen. Although delivery by pipeline is more economical, hydrogen causes pipelines to become brittle, raising safety concerns. Current R&D efforts focus on, among other things, reducing the cost of delivering hydrogen by truck and pipeline, and developing new composite materials for safer delivery by pipeline, targeting a point-to-point delivery cost of less than $1 per gallon of gasoline equivalent.

- *Fuel Cell Cost and Durability*. The type of hydrogen fuel cell considered the most promising for vehicles currently has cost and durability limitations. Specifically, current fuel cell systems (1) cost about $8,000 to produce at high volume, compared to $2,000 to $3,000 to produce a conventional internal combustion engine and (2) operate for less than half the life span of a conventional internal combustion engine. Current hydrogen fuel cell R&D efforts focus on reducing the cost and increasing the durability of fuel cells. For example, DOE set a target date of 2015 to develop a fuel cell with a life span of about 5,000 hours—or about 150,000 miles—making it competitive with internal combustion engines.

Industry representatives have noted that they are spending far more for hydrogen R&D than the federal government's Hydrogen Fuel Initiative. Specifically, while actual R&D figures are proprietary, Chrysler LLC, Ford Motor Company, and General Motors Corporation each has reported spending at least as much as the federal government on R&D for hydrogen fuel cell vehicles, and each plans to spend $6 to $10 billion from 2006 through 2015.

Furthermore, DOE is analyzing infrastructure requirements for deploying hydrogen fuel cell technologies, including hydrogen production facilities and pipelines to deliver hydrogen to major metropolitan markets. To facilitate this effort, DOE is working with DOT, industry groups, and international organizations to develop national and international safety codes and standards, such as fire codes for stationary fuel cells and standards for hydrogen fueling stations. DOE is also validating hydrogen technologies in real-world environments by, for example, collecting information on the performance of 77 hydrogen fuel cell vehicles used as a demonstration in several cities for commuting and other daily driving needs. To stimulate public awareness and acceptance of hydrogen technologies, DOE is disseminating safety-related information for emergency personnel as well as nontechnical information for the general public on hydrogen production, storage, and delivery; fuel cells; and near-term markets.

You asked that we assess DOE's Hydrogen Fuel Initiative as DOE enters the last year of its initial 5-year, $1.2 billion program. Specifically, you asked that we examine the extent to which DOE's hydrogen R&D program has (1) made progress in meeting the initiative's R&D targets, (2) worked with industry to set and meet R&D targets, and (3) worked with other federal agencies to develop and demonstrate hydrogen technologies.

To ensure that we obtained a thorough understanding of DOE's hydrogen R&D program, we reviewed documents and interviewed DOE program managers and national laboratory scientists, company and industry association executives, independent experts, and state government officials. More specifically, to assess DOE's progress in meeting its R&D targets, we (1) reviewed DOE's *Hydrogen Posture Plans* and R&D project reports; (2) attended DOE's annual review of its projects in May 2007; (3) interviewed DOE hydrogen program managers and scientists at DOE's National Renewable Energy Laboratory and Los Alamos National Laboratory; (4) spoke with HTAC members and attended HTAC meetings; (5) interviewed industry representatives and reviewed industry assessments of DOE's progress in developing and demonstrating vehicle, stationary, and portable technologies; and (6) reviewed reports of the National Academies of Science and Engineering on the hydrogen program and spoke with cognizant officials. To determine the extent to which DOE has worked with industry to set and meet R&D targets, we reviewed pertinent documents and assessed DOE's processes for soliciting industry input, including attending a meeting of the fuel cell technical team at Los Alamos National Laboratory. We also interviewed cognizant DOE managers and scientists and executives of car manufacturers, energy companies, utilities, hydrogen producers, fuel cell manufacturers, and suppliers of hydrogen-related components. To determine the extent to which DOE has worked with other federal agencies to develop and demonstrate hydrogen technologies, we reviewed pertinent documents and spoke with officials at DOE, DOT, DOD, the Department of Commerce, NASA, and the U.S. Postal Service. We also attended the Interagency Task Force's first meeting in August 2007. We conducted our work from March through December 2007 in accordance with generally accepted government auditing standards. Appendix I provides additional information about our scope and methodology.

Results in Brief

DOE's hydrogen R&D program has made important progress, but some of the most difficult technical challenges—those that require significant scientific advances—lie ahead, and many years of hydrogen R&D and infrastructure development beyond the 2015 target date will be needed before hydrogen can compete with current technologies. Specifically, DOE has reduced the cost of producing hydrogen from natural gas—an important source of hydrogen through the next 20 years; increased the storage capacity of hydrogen by 50 percent—a key element for increasing the driving range of vehicles; developed a sophisticated model to identify and optimize major elements of a projected hydrogen delivery infrastructure, and reduced the cost and improved the durability of fuel cells. However, DOE and industry officials stated that meeting some longer-term targets will require major scientific advances. For example, current fuel cell technology relies on platinum to separate electrons from protons to generate electricity. Because of the high cost of platinum, DOE's targets for reducing fuel cell costs include reducing the amount of platinum in fuel cells by more than 80 percent from its 2005 levels or finding a substitute. Some industry representatives noted that DOE's target dates were very ambitious, given the technical challenges and budget constraints. Relatedly, nearly 25 percent of the Hydrogen Fuel Initiative's funding for fiscal years 2004 through 2006 was spent on congressionally directed projects that were largely outside the initiative's R&D scope. In response, DOE has pushed back target dates for certain key technologies—the target date for using wind energy to produce hydrogen was pushed back from 2015 to 2017—and reduced funding for stationary and portable applications. Although DOE has pushed back interim target dates, it has not updated its 2006 *Hydrogen Posture Plan's* overall assessment of what the department reasonably expects to achieve by its technology readiness date in 2015, including how this may differ from previous posture plans. DOE also has not identified the R&D funding needed to achieve its 2015 target. Moreover, deploying the production facilities, fueling stations, and other support infrastructure needed to commercialize hydrogen fuel cell vehicles across the nation will require sustained industry and federal investment of tens of billions of dollars over several decades after 2015, according to DOE officials and industry representatives.

DOE has effectively solicited industry input and has worked to align its R&D priorities with those of industry, and industry representatives stated that DOE generally has managed its hydrogen R&D resources well. Specifically, DOE involved industry and university experts at the earliest planning stages and has continually focused on the highest R&D priorities. DOE has hosted annual peer reviews of each R&D project and has sponsored periodic workshops to solicit industry feedback on the progress, priorities, and direction of the hydrogen R&D program. DOE has also established 11 technical teams with DOE, industry, and national laboratory representation to assess progress in specific areas and bring technical and other issues to management attention. In addition, both the National Academies of Science and Engineering and HTAC provide input. One area of criticism that industry representatives identified is that DOE has focused its limited resources on developing vehicle technologies and given low priority to stationary and portable technologies. These industry representatives note that stationary and portable technologies may have more near-term market potential than vehicle technologies and, therefore, may be integral to resolving technical or infrastructure challenges and developing the public acceptance necessary to deploy hydrogen nationally. DOE recently has begun to emphasize near-term stationary and portable market applications by soliciting industry, non-profit, and federal organizations for ideas on early adoption of technologies and providing R&D grants.

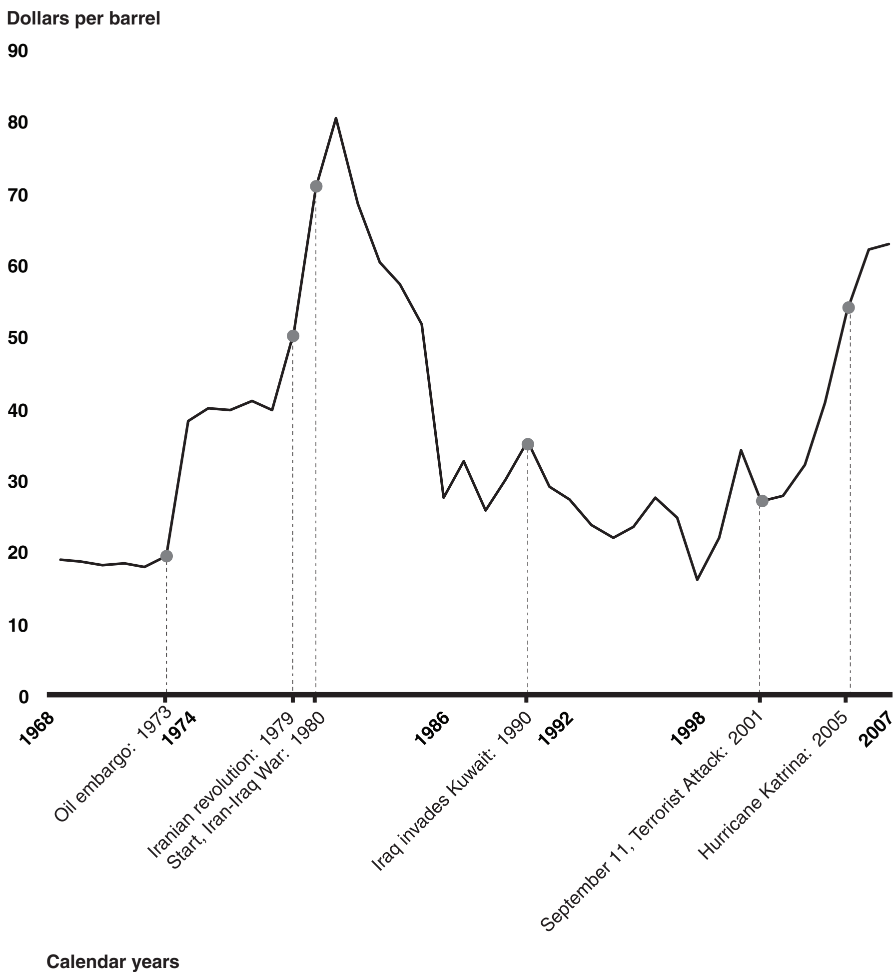
DOE's interagency coordination efforts among working level managers and scientists have been productive and useful, but it is too early to evaluate collaboration among senior officials at the policy level because a body created to do so, the Interagency Task Force, just held its first meeting in August 2007. At the working level, DOE has established several interagency coordination bodies to facilitate cooperation and share knowledge. For example, one working group has created Web-based tools and joint workshops to coordinate R&D activities and facilitate interagency technology partnerships by bringing the Defense Logistics Agency together with DOE in an initiative for deploying hydrogen-fuel-cell-powered forklifts. Working level managers at federal agencies involved in hydrogen-related activities generally were satisfied with the level of coordination. However, the Interagency Task Force—composed of deputy assistant secretaries, program directors, and other senior officials—has just begun to plan actions to demonstrate and promote hydrogen technologies. In its inaugural meeting in August 2007, the task force did not clearly define its role or strategy, but member agencies plan to develop a path forward and an action plan by May 2008. HTAC criticized DOE for taking too long to initiate the effort and for not securing participation of departmental assistant secretaries to ensure appropriate authority inside each agency for making hydrogen-related budget and policy decisions. In addition, some Interagency Task Force members observed that lack of a common vision may hinder decision making.

To accurately reflect the progress made by the Hydrogen Fuel Initiative and the challenges it faces, we recommend that the Secretary of Energy update the *Hydrogen Posture Plan's* overall assessment of what DOE reasonably expects to achieve by its technology readiness date in 2015, including how this updated assessment may differ from prior posture plans and a projection of anticipated R&D funding needs. DOE agreed with our recommendation, stating that it plans to update the *Hydrogen Posture Plan* during 2008.

Background

For decades, oil has been relatively inexpensive and plentiful, helping to spur the United States' economic growth. Despite price spikes primarily caused by instability in the Middle East and other oil-producing regions or by natural disasters, the price of oil has historically returned to low levels. However, in recent years, increasing world consumption of oil has put more upward pressure on the price of oil, making the price less likely to return to low levels. Figure 1 shows the volatility of the oil market because of political instability and natural disasters, but also illustrates an upward trend in price in recent years.

Figure 1: U.S. Refineries' Oil Prices, 1968 to 2007



Source: GAO analysis of DOE data.

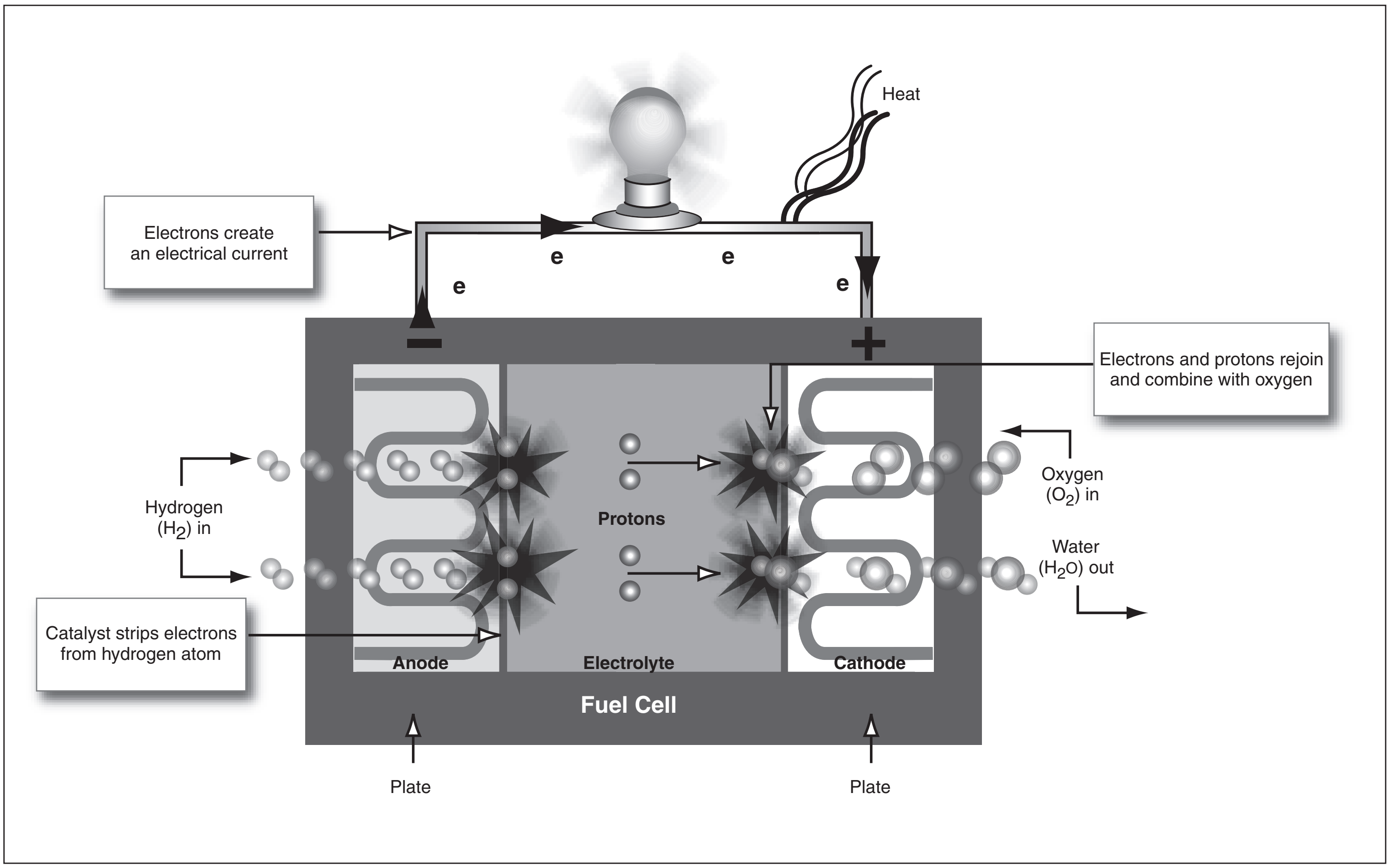
Note: Oil prices are in real terms, adjusted to fiscal year 2007 dollars to account for inflation. For 2007, oil prices for January through September were averaged. Refiners' oil prices better reflect the cost of oil than spot market prices because refiners typically purchase oil through long-term contracts that generally are not affected by short-term price changes.

In 2005, the world consumed about 84 million barrels of oil per day, and world oil production has been running at near capacity to meet the growing demand. DOE's Energy Information Administration projects that world oil consumption will continue to grow, reaching about 118 million barrels per day in 2030. In February 2007, we reported that most studies, amidst much uncertainty, estimate that oil production will peak sometime between now and 2040, which could lead to rapid increases in oil prices.[1] We concluded that the United States—which consumes about one-quarter of the world's oil and is about 97 percent dependent on oil for transportation—would be particularly vulnerable to the projected price increases.

Fuel cells convert the chemical energy in hydrogen—or a hydrogen-rich fuel—and oxygen to create electricity with low environmental impact. Although fuel cells can use a variety of fuels, hydrogen is preferred because of the ease with which it can be converted to electricity and its ability to combine with oxygen to emit only water and heat. Fuel cells look and function very similar to batteries. However, for a battery, all the energy available is stored within the battery and its performance will decline as its fuel is depleted. A fuel cell, on the other hand, continues to convert chemical energy to electricity as long as fuel is fed into the fuel cell. Like a battery, a typical fuel cell consists of an electrolyte—a conductive medium—and an anode and a cathode sandwiched between plates to generate an electrochemical reaction. (See fig. 2.) Like the respective negative and positive sides of a battery, the current flows into the anode and out of the cathode.

[1]GAO, *Crude Oil: Uncertainty about Future Oil Supply Makes It Important to Develop a Strategy for Addressing a Peak and Decline in Oil Production*, GAO-07-283 (Washington, D.C.: Feb. 28, 2007).

Figure 2: Schematic of a Typical Fuel Cell



Source: DOE.

Fuel cells typically are classified according to their type of electrolyte and fuel. Table 1 identifies the various types of fuel cells and their uses.

Table 1: Fuel Cell Types and Examples of Their Applications

Fuel cell type	Examples of applications	Operating temperature	Electric output (kilowatts)
Alkaline	Space exploration	194-212° F	10 - 100
Phosphoric acid	Stationary and combined heat and power	302-392° F	50 – 1,000
Proton exchange membrane	Vehicles, backup generators for emergency service, mobile phones, and electronics	122-212° F	Less than 250
Molten carbonate	Electric utilities and other industrial applications	1,112-1,292° F	Less than 1,000
Solid oxide	Electric utilities and other industrial applications	1,202-1,832° F	5 - 3,000

Source: DOE.

NASA began conducting R&D on hydrogen and fuel cells in the 1960s to develop a simple alkaline fuel cell for the space program. However, alkaline fuel cells do not work well for cars, in part because of their propensity to be damaged by carbon dioxide. In response to the 1973 oil embargo, the federal government began conducting R&D to improve automobile efficiency and reduce the U.S. transportation sector's dependence on oil by developing technologies for using alternative fuels, including (1) ethanol from corn and other biomass, (2) synthetic liquids from shale oil and liquefied coal, and (3) hydrogen directly used in internal combustion engines. In 1977, DOE's Los Alamos National Laboratory began R&D on fuel cells called polymer electrolyte membrane or proton exchange membrane, which have a low operating temperature, need only hydrogen and oxygen from the air, and are very efficient. However, DOE and industry reduced R&D funding for alternative fuels during the 1980s, when crude oil prices returned to historic levels.

DOE formed (1) an R&D partnership with the U.S. Council for Automotive Research (USCAR)[2] in 1993 and (2) the FreedomCAR Partnership in 2002 to develop advanced technologies for cars, including hydrogen fuel cells for vehicles. The hydrogen-related R&D elements of the FreedomCAR became part of the Hydrogen Fuel Initiative. While DOE conducts most of the initiative's R&D, which generally has focused on developing fuel cells for vehicles, DOT also is a member of the initiative, primarily focusing on regulatory issues related to the safety of vehicles, pipelines, and transport of hydrogen. The Hydrogen Fuel Initiative is also working with industry to

[2]In 1993, DOE and USCAR formed the Partnership for a New Generation of Vehicles to (1) improve competitiveness in vehicle manufacturing, (2) implement commercially viable innovations, and (3) develop vehicles with up to three times the fuel efficiency of comparable 1994 family sedans.

demonstrate and deploy other types of fuel cells for stationary and portable applications.

DOE further focused its hydrogen R&D in response to the National Energy Policy issued in 2001, which highlighted hydrogen as one of several R&D priorities. DOE hosted several meetings and workshops, including two major workshops in 2001 and 2002 that were designed to develop an R&D agenda and involved stakeholders from industry, universities, environmental organizations, federal and state agencies, and national laboratories.[3] These meetings and workshops laid the groundwork for identifying a common R&D vision and challenges, and each DOE program has used meetings and workshops to develop separate detailed R&D plans that set near-term and long-term targets to enable commercialization decisions by 2015.

In February 2004, DOE integrated these plans into its first *Hydrogen Posture Plan*, a single high-level agenda. The *Hydrogen Posture Plan's* approach is to conduct R&D in multiple pathways within key technology areas with the intent of providing several promising options for industry to consider commercializing. For example, DOE is using a mix of fossil, renewable, and nuclear energy to develop and demonstrate technologies that can extract hydrogen from a variety of sources, including natural gas, coal, biomass, water, algae, and microbes. DOE officials state that they prioritize the most promising technologies and terminate specific efforts that show little potential. Based on its review of the posture plan, the National Academy of Engineering made 48 recommendations, most of which were incorporated by DOE, including focusing on both applied and fundamental science R&D.[4]

In addition to the R&D funded through the Hydrogen Fuel Initiative, DOE conducts R&D on various other hydrogen-related technologies. For example, the Office of Fossil Energy is working on a hydrogen-based solid oxide fuel cell, with funding provided through the Solid State Energy Conversion Alliance, for stationary applications of electricity generation. Fossil Energy's R&D plan for extracting hydrogen from coal complements

[3]DOE, *A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond*, (Washington, D.C.: February 2002) and DOE, *National Hydrogen Energy Roadmap*, (Washington, D.C.: November 2002).

[4]National Research Council of the National Academies, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, (Washington, D.C.: 2004).

a separately funded demonstration program called FutureGen. The effort is designed to construct a prototype integrated gasification combined-cycle coal power plant to be operational by 2015 that will demonstrate production of hydrogen as well as reduced emissions. Fossil Energy also funds R&D on the capture and sequestration of carbon dioxide, considered an important area of R&D if coal is to be used as a long-term source of hydrogen. The Office of Nuclear Energy's R&D plan for producing hydrogen-using nuclear energy—called the Nuclear Hydrogen Initiative—complements the separately funded Next Generation Nuclear Plant program. The effort focuses on conducting R&D on a new generation of nuclear power plants capable of producing large amounts of hydrogen efficiently and economically. The first prototype is scheduled to be operational between 2018 and 2021.

The Hydrogen Fuel Initiative Has Made Important Progress but Will Require Significant Scientific Advances and Continued R&D beyond 2015 and Investment in Developing the Physical Infrastructure

DOE's hydrogen R&D program has made important progress, but some target dates have been pushed back, and further progress in certain areas will require significant scientific advances and continued R&D beyond 2015. Specifically, during its first 4 years, the Hydrogen Fuel Initiative has achieved such targets as reducing the cost of extracting hydrogen from natural gas, but other target dates have slipped as a result of technical challenges and budget constraints. For example, DOE officials and industry representatives stated that achieving targets for hydrogen storage will require fundamental breakthroughs, while achieving targets for other technologies will require significant scientific advances and cost reductions. However, DOE has not updated its 2006 *Hydrogen Posture Plan's* overall assessment of what the department reasonably expects to achieve by its technology readiness date in 2015 and its anticipated R&D funding needs to meet the 2015 target. Furthermore, full-scale deployment of hydrogen technologies will require sustained industry and federal investment, possibly for decades beyond 2015, to develop supporting infrastructure.

The Hydrogen Fuel Initiative Has Made Important Progress, but Some Target Dates Have Slipped, and Some Targets Require Significant Scientific Advances

According to DOE, key R&D targets to achieve technology readiness in 2015 focus primarily on (1) extracting hydrogen from diverse, domestic resources at a cost equivalent to about $2 to $3 per gallon of gasoline, (2) storing hydrogen on-board vehicles to enable a driving range of at least 300 miles for most light duty vehicles, (3) delivering hydrogen between two points for less than $1 per kilogram, and (4) developing proton exchange membrane fuel cells that cost about $30 per kilowatt and deliver at least 5,000 hours of service for vehicles—which compares to about 150,000 miles in conventional gasoline-powered vehicles—and at least

40,000 hours for stationary applications. As shown in table 2, DOE has made progress on meeting some of its near-term targets, in both applied and fundamental science, important stepping stones for meeting DOE's 2015 targets.

Table 2: Status of Key Hydrogen Fuel Initiative Technologies and Target Dates

Technology	Target area	Status	Target (2010)	Target (2015)
Fuel cell	Cost[a]	$107/kW	$45/kW	$30/kW
	Durability	2,000 hours	5,000 hours (80°C)	5,000 hours (80°C)
Storage	System gravimetric capacity (net)[b]	2.3 wt%	6 wt%	9 wt%
	System volumetric capacity (net)[c]	0.8 kWh/L	1.5 kWh/L	2.7 kWh/L
	Cost[d]	$15-$18/kW	$4/kW	$2/kW
Production	Cost, distributed natural gas[e]	$3.00/gge	$2.00-$3.00/gge	$2.00-$3.00/gge
	Cost, distributed bio-derived renewable liquids	$4.40/gge	$3.80/gge (2012 target)	<$3.00/gge (2017 target)
	Cost, distributed water electrolysis	$4.80/gge	$3.80/gge (2012 target)	<$3.00/gge (2017 target)
	Cost, central wind-water electrolysis	$5.90/gge	$3.10/gge (2012 target)	<$2.00/gge (2017 target)
Technology validation (demonstrated in vehicles)	Driving range	200 miles	250 miles (2008 target)	300 miles
	Efficiency	53-58 percent	(see 2015)	60 percent
	Durability	1,600 hours	2,000 hours (2009 target)	5,000 hours

Source: DOE.

[a]Cost projections are for 500,000 units per year.

[b]Measures usable hydrogen energy based on weight. Storage system projections are based on complex metal hydride and include material, tank, and balance of plant. Note that compressed tanks have capacities of 3.5 to 4.7 weight percent and can enable partial market penetration.

[c]Measures usable hydrogen energy based on volume.

[d]Projection for 5,000 to 10,000 pounds-per-square-inch tanks; assumes high volume manufacturing for 500,000 units.

[e]Modeled cost, delivered at the pump for dispensing at 5,000 pounds per square inch; assumes large equipment volumes (e.g., 500 units).

Hydrogen Production

For hydrogen to compete with gasoline, DOE must be able to produce hydrogen at prices that approximate the cost of gasoline. Specifically, in the near term, DOE must extract hydrogen from natural gas at a cost of $2 to $3 per gallon of gasoline equivalent and, in the longer term, develop biomass and biomass-derived liquids at similar costs or, for large centralized production facilities, at costs less than $2 per gallon of gasoline equivalent. DOE has established targets of less than $2 per gallon of gasoline equivalent for extracting hydrogen from water using wind energy and from coal using coal energy. The latter technology must also demonstrate carbon capture and sequestration. Other technologies being explored include producing hydrogen from biological, photoelectrochemical, and nuclear processes, but are long-term efforts.

Technologies for extracting hydrogen from diverse sources generally are known and usually involve heat or chemical processes to separate hydrogen from various compounds. DOE reported that it has met its target of extracting hydrogen from natural gas through a process called steam reformation, reducing cost to less than $3 per gallon of gasoline equivalent, nearly one-half of the $5 per gallon of gasoline equivalent that industry had achieved in 2003.[5] As a result, DOE has begun to phase out R&D in steam reformation of natural gas and plans to focus its resources in higher priority areas, leaving industry to continue to refine the steam reformation process and reduce its cost. DOE, however, has pushed back its target dates for extracting hydrogen from biomass and water using wind energy from 2015 to 2017. Specifically, DOE is conducting research on reducing the cost of extracting hydrogen from biomass-derived liquids such as ethanol, but the cost of producing ethanol is still too high to make the technologies competitive. DOE also is developing technologies to cost efficiently extract hydrogen from biomass using a gasification process. Gasification involves heating the biomass to a temperature high enough to separate the hydrogen, but the gasification technologies do not yet meet cost targets. DOE's Office of Fossil Energy leads the effort for extracting hydrogen from coal—also using a gasification technology—and has made progress in developing membranes that can separate hydrogen in the 500 to 900 degrees Fahrenheit gasification process. The R&D effort complements Fossil Energy's FutureGen program, which is scheduled to have a 275-megawatt demonstration plant operational by 2015. DOE's Office of Nuclear Energy leads the effort to use nuclear energy to produce hydrogen, primarily from water. These R&D efforts involve development of a new generation of nuclear reactors that are more efficient and operate at very high temperatures. The Office of Nuclear Energy reports that an engineering-scale demonstration effort for hydrogen production has been pushed back from 2017 to between 2018 and 2021.

[5]DOE assumes that a typical refueling station of 1,500 kilograms per day of hydrogen servicing hydrogen fuel cell vehicles would service the same number of vehicles as typical gasoline stations serve today.

Because steam reformation of natural gas reflects the most mature technology, natural gas is expected to be the primary source of hydrogen through the next 20 years. However, extracting hydrogen from natural gas will simply substitute one fossil fuel for another with similar vulnerabilities to supply disruptions and adverse environmental effects. In the long term, DOE is developing technologies that rely on renewable or nuclear energy from non-carbon-producing sources. DOE officials noted that although the R&D efforts do not require fundamental advances in science, they generally acknowledge that developing the technologies will take years of applied scientific effort before costs can be reduced enough to be competitive with gasoline. One challenge, for example, is minimizing carbon or sulfur impurities when extracting hydrogen from coal. Impurities can shorten the life-span of the separation membranes used in the gasification process and can also impact the life span and performance of fuel cells. Although higher-temperature stationary fuel cells—such as solid oxide fuel cells operating at temperatures exceeding 1,200 degrees Fahrenheit—are more tolerant of impurities, lower temperature proton exchange membrane vehicle fuel cells begin to fail when impurities are present.

Hydrogen Storage

For hydrogen fuel cell vehicles to compete with conventional gasoline vehicles, DOE must develop technologies to store enough hydrogen on board the vehicle to achieve a driving range of at least 300 miles without compromising passenger or cargo space and while meeting all consumer expectations for performance, safety, refueling ease, and cost. In addition, DOE must develop technologies to store and dispense enough hydrogen at fueling stations to meet consumer needs. None of the current technologies have attained these requirements, and none is likely to do so without fundamental scientific breakthroughs, according to DOE officials and industry representatives. Although on a weight basis, hydrogen has almost three times the energy content of gasoline, it has almost four times less energy than gasoline on a volume basis. This means DOE must store a much larger amount of hydrogen within specified space constraints than gasoline to obtain equivalent amounts of energy, raising the technical challenges and the cost.

Currently, hydrogen is most commonly stored as a gas, compressed under high pressure, or is super-cooled to a liquid, but neither technology is likely to meet DOE's 2015 performance and cost targets. For example, hydrogen can currently be compressed to 10,000 pounds per square inch,[6] which is about the highest level of compression being considered because of safety and cost concerns, yet this method stores less than half the hydrogen necessary and is more than nine times the cost needed to meet DOE's 2015 performance and cost targets. Similarly, liquid hydrogen, which must be cryogenically maintained at negative 423 degrees Fahrenheit, typically requires about one-third of its energy content to liquefy the hydrogen. Storing hydrogen in its denser liquid form has a higher storage capacity than compressed hydrogen, but there are challenges related to keeping the hydrogen insulated and losing some hydrogen due to evaporation.

Scientists at Los Alamos National Laboratory succeeded in developing materials that have the potential to meet DOE's 2010 technical targets for chemically storing hydrogen, although it is not clear if the materials will meet cost targets. The scientists used a liquid boron-based compound to bind the hydrogen. Boron, from which the household cleaner borax is derived, readily forms compounds with other chemicals and can be recycled for reuse. The compound binds and releases hydrogen and, in liquid form, can also be used to transport hydrogen through pipelines or in trucks. The National Renewable Energy Laboratory has also made significant progress in developing new nanostructure materials. Scientists have designed these materials with pores at the nanometer scale to resemble globes with many branches or foam structures pocked with holes to significantly increase the surface area on which to bind hydrogen. Recent efforts include manufacturing the nanostructures with boron or calcium compounds, both of which bind and release hydrogen. Likewise, scientists at Sandia National Laboratories have also made progress, improving storage of hydrogen by 50 percent between 2004 and 2006 by developing new materials that absorb hydrogen.

DOE is continuing R&D in compression and liquefaction of hydrogen, in particular, because DOE contends that these technologies will be important for early market penetration. However, for commercial scale deployment of hydrogen technologies, DOE officials and industry representatives agree that an alternative storage method must be found. DOE's R&D focus is on developing new materials that can store hydrogen without requiring high pressures or cryogenic temperatures. These areas

[6] In comparison, tire pressure for passenger cars typically is 30 to 45 pounds per square inch.

focus on developing new materials that can store hydrogen on the surface of a material—called "adsorption;" absorb the hydrogen into a material; or bind the hydrogen within a chemical compound. Adsorption and absorption R&D typically involve nanotechnology to develop new materials structured to increase surface area. Chemical storage of hydrogen has additional challenges, including processing centers that would be needed to bind and release hydrogen from the chemical carrier before the hydrogen can be used by consumers, raising the overall costs. In the last few years, a number of materials have been developed, but not within the energy, temperature, or cost required for commercial scale deployment.

Hydrogen Delivery

Successful commercialization of hydrogen fuel cell technologies—particularly hydrogen fuel cell vehicles—will depend upon a hydrogen delivery infrastructure that provides the same level of safety, convenience, and functionality as the existing gasoline delivery infrastructure. The delivery infrastructure will initially need to support hydrogen production at small facilities distributed throughout the country and, eventually, larger centralized facilities. The delivery infrastructure includes operations at the refueling site itself, such as compression, storage, and dispensing, as well as the actual delivery of hydrogen. DOE developed its 2015 targets with significant input from industry. Specifically, DOE used a sophisticated model for estimating hydrogen delivery costs for a city the size of Indianapolis with 50 percent of the vehicles being hydrogen fuel cell vehicles and with central production of hydrogen located 60 miles from the city's edge. DOE determined that the cost of delivering hydrogen to fueling stations must be less than $1 per gallon of gasoline equivalent. This cost includes operations at the delivery site, such as transferring the hydrogen to storage or dispensing equipment. To put DOE's R&D requirements in perspective, the cost of delivering gasoline from a Gulf Coast refinery to a fuel pump in Dallas, Texas, has been estimated at about $0.18 per gallon.

Currently, hydrogen is delivered by truck as a liquid or gas or by a modest pipeline infrastructure, but at delivery costs mostly ranging from $4 to $9 per gallon of gasoline equivalent, significant advances must be made to reduce costs to meet DOE's targets. Hydrogen is difficult to deliver economically using conventional methods because the hydrogen atom is small and diffuses rapidly, making it difficult to design equipment to prevent leakage. Hydrogen can also corrode the steel used in pipes and trucks, which make up the bulk of current conventional delivery systems. Trucks can carry about 10 times more liquid hydrogen than gaseous hydrogen, but since liquefying hydrogen requires so much energy, hydrogen generally is delivered in gaseous form by truck for distances less than 200 miles and in liquid form for greater distances. In addition, about 630 miles of pipelines currently deliver hydrogen, primarily located near oil refineries mostly along the Gulf Coast where hydrogen predominantly is used. This infrastructure is modest compared to the over 1.5 million miles of pipelines that already deliver natural gas, oil, and other petroleum-related products in the country. Although these pipelines meet the specific hydrogen needs of industry, they must be operated at a constant pressure and they cost on the order of $1 million per mile. Moreover, hydrogen causes brittleness in pipelines, raising concerns about using current materials to build a larger hydrogen pipeline infrastructure, particularly where line pressures may vary.

DOE's priorities in R&D focus on reducing costs for delivering hydrogen in liquid form by truck, in gas form by pipeline, and by binding the hydrogen to a chemical carrier. Specifically, DOE is continuing its R&D on cryogenic liquefaction of hydrogen to decrease costs and encourage near-term deployment of hydrogen technologies. DOE is also conducting R&D to develop new composite materials for pipes or to develop pipe liners to prevent leaks and pipe failures due to embrittlement. Brittleness in pipes carrying hydrogen is not well understood, and some R&D efforts focus on understanding hydrogen's reaction with pipe materials. Once hydrogen technology deployment reaches commercial scale, pipelines provide the lowest cost delivery option. DOE is also researching the potential for delivering hydrogen in chemical form by binding hydrogen to various chemical compounds, alleviating the need for cryogenic liquefaction of hydrogen and improving delivery through pipelines. The chemical compounds include liquids and solids, as well as powders that could flow through pipelines. DOE's R&D focuses on a carrier that could substantially increase carrying capacity of hydrogen for more economic delivery through conventional delivery systems, such as pipelines and trucks. However, no chemical carrier has yet been identified that has the optimal combination of high carrying capacity and low energy requirements for binding and releasing hydrogen. Additional R&D focuses on purifying hydrogen that has been transported, since impurities may reduce the life span and operating efficiency of fuel cells.

Fuel Cells

To be competitive, vehicle fuel cells must have a similar life-span and similar vehicle packaging requirements and be able to operate in the same conditions as gasoline-powered engines. Specifically, vehicle fuel cells must have a life span of about 5,000 hours—equivalent to about 150,000 miles of vehicle travel. Furthermore, fuel cells must be able to operate in environments with temperatures ranging from minus 40 degrees to 104 degrees Fahrenheit and must be able to start up quickly at low temperatures with minimal energy consumption. In addition, the cost of commercial scale production of vehicle fuel cells must drop from the current $107 per kilowatt to $30 per kilowatt—nearly a quarter of the current cost—to meet DOE's 2015 target.[7] Stationary fuel cells must have a longer life span than those for vehicles, up to 40,000 hours, equivalent to about 4.5 years of continuous operation.

In the early 1990s, DOE estimated the cost of manufacturing fuel cells at high volume to be about $3,000 per kilowatt. Since then, DOE's focus has been on materials that can reduce costs at high volume. DOE succeeded in reducing manufacturing costs at high volume to $175 per kilowatt in 2004 and about $107 per kilowatt in 2006. The cost reductions have been achieved primarily by reducing the amount of platinum required as a catalyst and developing less expensive membranes. DOE is just beginning to focus R&D efforts on improving processes for commercial scale manufacture of fuel cell components. In particular, DOE has announced its intention to fund R&D for commercial scale manufacture of fuel cells for stationary applications.

DOE has achieved a life span of about 1,600 hours for vehicle fuel cells, but has not yet demonstrated start-up from sub-freezing temperatures. In addition, although DOE has reduced the cost of fuel cells, significant gains in cost remain to be achieved, in part, because fuel cells rely on platinum catalysts. Platinum, which is in high demand primarily for use in catalytic converters for automobiles and as jewelry, is the only catalyst that can sufficiently generate enough power at low operating temperatures to operate a vehicle. To reduce the cost of fuel cells, DOE's target focuses on decreasing the amount of platinum used in 2005 by more than 80 percent in 2015. DOE officials noted that Los Alamos National Laboratory has succeeded in reducing platinum requirements and improving performance of fuel cells, but they also noted that reliance on the current amount of platinum—considering its rising costs—poses significant challenges to reducing the costs enough to meet the 2015 targets. In addition, DOE has not yet met the size and weight packaging requirements of the automobile manufacturers for fuel cells. Complex equipment, such as heat exchangers and humidifiers, must be added to the fuel cell to keep it operating at its current 140 to 176 degrees Fahrenheit in a controlled environment of 80 to 100 percent relative humidity. Furthermore, impurities in the hydrogen

[7]These are projected costs, based on high volume manufacturing of 500,000 units per year.

fuel stream, such as sulfur compounds and carbon monoxide, reduce the performance of the fuel cell. Removing or managing the impurities raises overall costs. Regarding R&D for fuel cells for stationary applications, DOE has demonstrated a life span of about 20,000 hours, about one-half the life span required to meet DOE's targets.

DOE's fuel cell R&D focuses on reducing costs and improving durability by (1) developing alloys that contain less platinum, (2) developing substitutes for platinum, and (3) developing fuel cells that operate at slightly higher temperatures and lower relative humidity to reduce complex equipment and increase tolerance to impurities. More specifically, DOE is conducting R&D to develop new electrodes for fuel cells that can be manufactured with less platinum, but can increase durability. DOE is also pursuing R&D on developing less-expensive, better performing substitutes for platinum, but DOE has not yet found a substitute that matches the performance of platinum, particularly in terms of achieving the power needed to operate a fuel cell vehicle. In addition, DOE has recently focused R&D on developing fuel cells that operate at 248 degrees Fahrenheit and lower relative humidity to reduce or eliminate complex equipment and increase tolerance to impurities. DOE has not yet developed new materials that meet these characteristics. Fuel cells for stationary applications generally do not have the same weight and size restrictions as for vehicle applications, nor do they have the same rapid fluctuation in power demand as vehicles, but they do have similar issues regarding cost and durability.

DOE Has Not Updated Its Plan to Assess the Impact of Delays in Meeting Some Key Target Dates on Technology Readiness or Projected the Initiative's Costs through 2015

DOE has made important progress in many areas of R&D, but some target dates have been pushed back, primarily as a result of technical challenges and budget constraints, according to DOE officials. Although some industry representatives believe that having ambitious targets is good, they noted that the target dates for certain technologies are very ambitious, particularly given the requirements of incorporating the technology into an integrated system that can be commercially deployed in a real-world environment. For example, although DOE has demonstrated considerable progress in developing new materials for storing hydrogen, the current materials being investigated operate in temperatures ranging from minus 300 degrees Fahrenheit to more than 700 degrees Fahrenheit. Of these, only a few fall within DOE's much more narrow target range for operating temperatures and none meet DOE's cost targets.

Table 3 shows that funding for the Hydrogen Fuel Initiative totaled nearly $1.2 billion for fiscal years 2004 through 2008. Some HTAC and industry representatives believe that $1.2 billion over 5 years is insufficient to meet DOE's ambitious technical and cost targets. Furthermore, congressionally directed projects—primarily for activities outside the initiative's R&D scope—accounted for almost 25 percent of the Hydrogen Fuel Initiative's budget for fiscal years 2004 through 2006.

Table 3: Funding for the Hydrogen Fuel Initiative, Fiscal Years 2004 through 2008

Dollars in millions

	Fiscal year					
Office	**2004**	**2005**	**2006**	**2007**	**2008 request[a]**	**Total**
Basic Science	$0	$29.2	$32.5	$36.4	$59.5	**$157.6**
Fossil Energy	4.9	16.5	21.0	23.6	12.5	**78.5**
Nuclear Energy	6.2	8.7	24.1	19.3	22.6	**80.8**
Energy Efficiency and Renewable Energy	144.9	166.8	153.5	193.6	213.0	**871.7**
Total DOE	**$156.0**	**$221.2**	**$231.0**	**$272.8**	**$307.6**	**$1,188.5**
Total DOT	**$0.6**	**$0.5**	**$1.4**	**$1.4**	**$1.4**	**5.36**
Total Hydrogen Fuel Initiative	**$156.5**	**$221.7**	**$232.5**	**$274.2**	**$309.0**	**$1,193.9**
Percent of funds congressionally directed[b]	28	21	20	0	[a]	

Source: DOE.

Note: We present funding data solely for background purposes. The reliability of the database from which these data were drawn was thoroughly assessed in our December 2006 report entitled *Department of Energy: Key Challenges Remain for Developing and Deploying Advanced Energy Technologies to Meet Future Needs* (GAO-07-106). For the current report, we updated the prior assessment of data reliability and discussed the accuracy of the hydrogen funding data with cognizant DOE officials. We found these data to be sufficiently reliable for the purposes of this report. The dollar amounts were not adjusted for inflation.

[a]Reflects the President's budget proposal for fiscal year 2008.

[b]Includes funds designated for particular purposes through legislative language or directives in congressional reports.

In response to both budget constraints and technical challenges, DOE has pushed back target dates for certain key technologies—the target date for using wind energy to produce hydrogen was pushed back from 2015 to 2017—and reduced funding for stationary and portable applications that might, through early penetration in small markets, resolve technical issues and stimulate public acceptance of hydrogen vehicles. However, DOE's hydrogen program manager expressed confidence that DOE remains on schedule for the higher priority targets. Nevertheless, because some target dates have been pushed back 2 or more years, what DOE currently projects for technology readiness in 2015 differs from its original set of expectations laid out in the 2004 *Hydrogen Posture Plan*. DOE has not updated its 2006 posture plan for the Congress and industry to more clearly identify what technologies will be ready for industry to consider when making commercialization decisions in 2015, nor has it projected anticipated costs to achieve technology readiness. For example, because some target dates have slipped 2 or more years, the cost of meeting some of the technical targets may exceed DOE's original planned estimates. However, DOE has not updated estimates of the funding needed to achieve its technology readiness target in 2015. DOE's Office of Energy Efficiency and Renewable Energy projects that its hydrogen R&D budget will total $750 million for fiscal years 2009 through 2012.

DOE officials and industry representatives told us that R&D will need to continue beyond 2015 because some interim target dates have been pushed back. Furthermore, they said that even after the initial technical targets are met, R&D will need to continue well beyond 2015 to further refine and sustain the developing hydrogen technologies. DOE officials noted that they had always planned to conduct R&D beyond the 2015 target date. The officials pointed out that DOE is still conducting R&D to improve conventional gasoline engines, even though the engines have been in use for over 100 years, and that they always have been planning to do the same for hydrogen technologies.

Developing the Physical Infrastructure to Support Commercial Deployment of Hydrogen Technologies May Require Decades

Industry would have to match the convenience of the conventional infrastructure to compete with conventional technologies on a commercial scale, particularly gasoline vehicles, requiring investments of tens of billions of dollars that will most likely take decades to accomplish. To meet the production of hydrogen if fuel cell vehicles replaced an estimated 300 million gasoline vehicles, DOE reports that over 70 million tons of hydrogen would need to be extracted from various sources each year, requiring the construction of new production facilities throughout the country. Currently, the United States has approximately 132 operating refineries and 1,300 petroleum product terminals that deliver petroleum products to more than 167,000 retail service stations, truck stops, and marinas located throughout the country. Typical gasoline stations dispense about 1,500 gallons of gasoline each day, but store several times that amount on site, usually in underground tanks. DOE officials acknowledged that investments in a hydrogen infrastructure would be considerable, but noted that the gasoline infrastructure also required investments of tens of billions of dollars and took decades to develop.

Currently, U.S. industries produce over 9 million tons of hydrogen annually, primarily to refine petroleum, manufacture fertilizer, and process foods, most of which are produced near end-use along the Gulf Coast and in California to avoid the high cost of delivery. Current production reflects about one-eighth of the projected need and most of it is localized in specific areas. Facilities capable of extracting hydrogen economically will have to be constructed throughout the country. Some of these facilities could be co-located with existing gasoline fueling stations, but some stations have spatial limitations that raise challenges of using them. Also, the current cost of delivering hydrogen does not meet cost targets and cannot compete with the gasoline infrastructure. Although pipelines represent more attractive economics for delivering hydrogen than delivery by truck at high market penetration, they reflect high initial capital investments, estimated at about $1 million per mile. One industry official estimated that building new pipelines along interstate highways capable of serving about 75 percent of the U.S. population would cost approximately $14 billion, assuming there would be no barriers prohibiting the effort. The development and use of carriers may allow use of the existing pipeline infrastructure and may also resolve some embrittlement concerns, but such carriers also raise other technical and cost challenges, such as storage and recycling of the chemical carriers. For example, existing gasoline stations—already stretched for space—could face additional challenges if equipment were needed on site to separate the hydrogen from a chemical carrier, purify the hydrogen, and store the chemical carrier so it can be returned to a central facility for recycling. Although new fueling stations could be constructed, industry has estimated the construction of new fueling stations at about $1 to $2 million each.

In addition, other issues, such as safety codes and standards, may impact investment decisions. For example, one industry representative noted that safety concerns among local approving officials, among other things, may prevent some conventional hydrogen storage systems from being buried underground, as is common with gasoline tanks. The National Hydrogen Association also reports that industry must put a lot of energy and resources into educating local officials on codes and standards involving hydrogen-related technologies. Even if hydrogen-related technologies are approved, they often carry a cost premium. For example, typical gasoline dispensing nozzles cost about $40 to $110, but hydrogen dispensing nozzles currently cost about $4,000 each. Some high costs could be expected to drop with high-volume manufacturing and competition.

DOE officials and industry representatives also acknowledged the high degree of risk for investors, noting that there are other near-term and mid-term options for stationary and vehicle energy technologies. They speculated that transitioning to hydrogen fuel cell technologies will most likely start small, in localized markets relying on the current infrastructure to minimize risk. For example, fuel cell vehicles might start in cities such as Los Angeles or New York, but within limited areas where there is a supporting infrastructure. They agreed that broader expansion of hydrogen fuel cell technologies into the market would likely cost investors tens of billions of dollars in infrastructure costs and will take decades. Several energy companies and electric utilities told us that they were unlikely to invest in the hydrogen infrastructure in the near term because of the high cost and high risk and, although they expressed interest in investing in the long term, they did not have definitive plans about what investments they might make. Nonetheless, DOE officials and industry representatives stated that transitioning to hydrogen technologies will require a sustained commitment by both industry and the federal government. For example, industry representatives stated that federal tax credits for fuel cell technologies have been authorized for only a few years at a time—too short for industry to consider when making long-term investment decisions.

To better understand real-world infrastructure challenges in transitioning to hydrogen fuel cell technologies, DOE has several ongoing demonstration projects and modeling analyses. The primary goal of the technology validation effort is to demonstrate complete, integrated systems in a real-world environment. Although individual components may meet DOE's performance targets, the complete system may not function as intended because of integration problems or unanticipated real-world operating conditions. DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, which has paired auto companies with energy companies, in 2007 is testing 77 hydrogen fuel cell vehicles and 14 hydrogen refueling stations in real-world conditions around the country to evaluate performance in different climates and usage patterns. The demonstration project is expected to grow to 130 hydrogen fuel cell vehicles and at least 18 hydrogen fueling stations in 2008. Individuals drive the hydrogen fuel cell vehicles as they would a gasoline vehicle: to work or to the store and fill up their vehicles at hydrogen fueling stations.

Using information from this demonstration project and from sophisticated modeling analyses, DOE officials and industry representatives reported that the initial deployment of hydrogen technologies in the market will most likely rely on technologies that do not require a new infrastructure. Specifically, they noted that natural gas—using steam reformation—will most likely remain the dominant source of hydrogen in the near- to mid-term. They envisioned that small amounts of hydrogen extracted mostly from natural gas at multiple points distributed around the country would be sufficient to meet initial demand. In addition, this distributed approach requires less capital investment. DOE officials and industry representatives noted that substantial changes to the infrastructure eventually will be needed to not only support large-scale production and delivery of hydrogen, but also to support multiple sources from which to extract hydrogen to minimize reliance on natural gas. As the demand for hydrogen grows, large centralized facilities for extracting hydrogen will be needed to take advantage of economies of scale. The centralized extraction of hydrogen will require deliveries over greater distances and, correspondingly, greater investments in the delivery infrastructure. Similarly, as the demand for hydrogen grows, there must be more stations where consumers can conveniently purchase hydrogen for vehicles or for stationary or portable applications.

DOE Has Partnered Well with Industry on Vehicle Technologies, but Efforts to Develop Stationary and Portable Technologies Are Too New to Evaluate

DOE has effectively solicited industry input and has worked to align R&D priorities, particularly for developing vehicle technologies. However, DOE has just begun to prioritize resources to develop stationary and portable technologies, which are much closer to being ready for commercial application and could play a role in laying the groundwork for vehicle technologies. Industry representatives acknowledge DOE's efforts, but note that they are too new to evaluate. Nevertheless, industry representatives stated that DOE generally has managed and coordinated its hydrogen R&D resources well.

DOE Has Effectively Involved Industry and Other Stakeholders

Industry executives told us that 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. Although industry representatives have sometimes disagreed about DOE's priorities, they generally agreed that DOE has institutionalized processes to effectively solicit feedback from industry. Just as importantly, DOE officials noted that being a presidential initiative with congressional backing has helped Hydrogen Fuel Initiative managers to garner support from industry and within the federal government.

DOE's workshops in 2001 and 2002 involved industry and independent experts at the earliest stages of planning an R&D agenda and laid the groundwork for identifying market challenges and technical targets that could lead to the development and deployment of hydrogen and fuel cell technologies. The launch of Hydrogen Fuel Initiative in 2004 accelerated hydrogen R&D efforts, resulting in a more detailed R&D agenda. DOE asked the National Research Council and the National Academy of Engineering to review this agenda and implemented 46 of the National Academies' 48 recommendations.[8] For example, DOE implemented a systems analysis and integration effort to (1) integrate R&D on hydrogen production, delivery, and storage; and fuel cells; (2) safety codes and standards; (3) monitor progress toward technology targets; and (4) provide education on the benefits of and challenges to transitioning to hydrogen technologies. In addition, the initiative has facilitated ongoing communication with industry through annual merit reviews, workshops, technical teams, HTAC, and other coordination mechanisms.

DOE's annual merit review is a primary way to disseminate information and get feedback on the merit of its hydrogen and fuel cell R&D projects from industry, independent experts, and other DOE officials. The most recent review, held in May 2007, showcased approximately 300 projects, with the principal investigators presenting status and results. Industry representatives stated that annual reviews are useful and have become a valuable tool to provide feedback to DOE on prioritizing the R&D agenda.

DOE also has funded a number of workshops to solicit industry input on a range of topics, including fuel cells, education, and codes and standards. For example, DOE's Office of Science conducted a workshop in May 2003 to identify the key areas where basic science R&D could contribute toward transitioning to hydrogen technologies. The workshop resulted in a report that has served the Office of Science as a guide for continued R&D efforts. In addition, in June 2007, DOE's hydrogen storage program held a 1-day meeting to identify techniques for enhancing research on advanced hydrogen storage materials, with participants from industry, academia, and DOE's national laboratories. Industry representatives stated that workshops are an important collaboration channel.

To solicit industry feedback on the progress, priorities, and direction of the hydrogen R&D program, DOE established 11 technical teams responsible for reviewing R&D progress in specific technologies. These teams, co-chaired by industry and DOE, meet monthly and include industry representatives with requisite expertise in hydrogen technologies. The technical teams exchange information and jointly review all projects

[8]See *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.*

at least once a year. For example, through one of the technical teams on fuel cells, industry provided information on optimal relative humidity when DOE began work on high temperature fuel cells. The technical teams also provide an informal forum outside regular meetings for frequent exchanges among scientists. The National Academies noted the creation of technical teams as an important achievement, and industry representatives stated that tech teams help transfer automakers' requirements to the R&D portfolio.

HTAC, made up of industry executives and outside experts, also provides advice to the Secretary of Energy on technical and programmatic issues related to DOE's hydrogen R&D program. HTAC hosts periodic meetings, which DOE officials attend, to review budget status, discuss R&D plans, and propose changes. In its September 2007 report to the Secretary of Energy, HTAC recommended, among other things, that DOE elevate the role of hydrogen in the national energy portfolio. HTAC also expressed its pleasure with the DOE hydrogen R&D program's use of best management practices, including peer review in its solicitation processes, assessment of technical progress, individual project selection and monitoring, and overall program management.

DOE also obtains feedback from industry and academia through its Centers of Excellence. To facilitate storage R&D, DOE coordinated the creation of three Centers of Excellence to work on R&D in both applied and fundamental science. Each center is led by a DOE national laboratory and has about 15 industry and academic partners.

In addition, a DOE program dedicated to commercialization efforts exchanges information with industry on DOE activities, including hydrogen R&D, and explores potential for commercial development opportunities. Another program focused on market transformation works to build partnerships with industry and federal, state, and local governments to foster the early adoption of hydrogen and fuel cell technologies.

Furthermore, DOE is active at the state and local level and participates in numerous organizations that bring together a range of groups to foster the development and deployment of hydrogen technology. For example, DOE is involved in the California Fuel Cell Partnership, a group of auto, fuel, and fuel cell technology companies and government agencies working to deploy fuel cell vehicles on state roads.

In response to industry feedback, DOE has shifted R&D priorities and expanded industry participation. For example, during the past decade, DOE funded R&D of on-board fuel processing, the concept of embedding equipment in a vehicle to generate hydrogen from a fuel source such as methanol. In 2004, DOE commissioned the National Renewable Energy Laboratory to convene an independent review panel to provide a technical go/no-go recommendation regarding on-board fuel processing R&D. The panel recommended a no-go decision, and DOE concurred. Automakers praised the decision, realizing that on-board fuel processing R&D was too costly for a technology that did not appear to be viable by the target date. In addition, partly as a result of feedback from auto manufacturers, DOE expanded FreedomCAR in 2003 to include energy companies. The idea stemmed from the need to coordinate the development of vehicles with the fueling infrastructure, involving such major energy companies as ConocoPhilips, British Petroleum (BP), Shell, Chevron, and ExxonMobil. Through FreedomCAR, DOE, energy companies, and car companies conduct joint R&D planning and technical activities.

Overall, although industry representatives reflected a wide variety of viewpoints on DOE's priorities, they generally agreed that DOE had done a good job of soliciting input. A general consensus among senior executives noted that DOE's processes to solicit industry input and focus on key areas for R&D has been well-organized. The National Hydrogen Association, an industry group, suggested that DOE's efforts have turned out to be a good investment and praised technical goals and progress. USCAR representatives stated that DOE is placing the right emphasis on the key issues and that domestic auto makers maintain a good relationship with DOE.

DOE Has Begun to Address Industry Concerns on Stationary and Portable Technologies, but Its Efforts Are Too New to Evaluate

Industry representatives note that because stationary and portable technologies may have more near-term market potential than vehicle technologies, they may be integral to resolving technical or infrastructure challenges and developing the public acceptance necessary to deploy hydrogen nationally. According to industry representatives, stationary and portable research can benefit hydrogen technology development and maturation, particularly for fuel cell vehicles. For example, suppliers and manufacturers need near-term opportunities to remain in business and to improve manufacturing processes, which will eventually benefit fuel cell vehicles by creating a supply base and fostering innovation. An industry representative noted that parts suppliers otherwise may not survive until vehicle technologies are ready in 10 to 20 years. In addition, HTAC stated that increasing the level of R&D on portable and stationary power systems would reduce the technical and market risks associated with longer-term vehicle applications.

Industry has expressed concerns that DOE has focused on developing vehicle technologies and has given less priority to stationary and portable technologies. At its May 2007 meeting, HTAC suggested that DOE has not focused enough on stationary and portable fuel cell R&D. Senior executives of companies told us they had urged DOE to focus more on demonstrating near-term stationary and portable technologies. The U.S. Fuel Cell Council and the National Hydrogen Association also stated that stationary fuel cell research had been overlooked and underfunded. DOE noted that it had focused on vehicle R&D because of the significant energy savings in the transportation sector.

Industry representatives stated that DOE has responded to industry's input. Senior executives from industry told us that DOE's support for stationary and portable R&D has grown substantially in the past year and that DOE has done a good job of incorporating this R&D into its program. In June 2007, to facilitate early adoption of hydrogen and fuel cell technologies, DOE sought input from industry, non-profit organizations, and local, state, and federal agencies to identify hydrogen and fuel cell applications in stationary and portable power. Such applications could include, for example, backup power installations for telecommunications providers and public schools designated as emergency shelters, warehouse lift-trucks currently employing battery or internal combustion systems, and portable fuel cells for battery operated devices. DOE has also begun to emphasize near-term stationary and portable market applications by providing a grant opportunity for hydrogen and fuel cell systems manufacturing R&D focusing on technologies that are near commercialization.

Industry representatives acknowledged DOE's efforts but noted that these efforts are too new to evaluate because DOE had not devoted as many resources to them as it had to vehicle technologies. A representative from the National Hydrogen Association, however, stated that DOE's recent emphasis on high-volume manufacturing is a good sign and could facilitate early market penetration of fuel cells.

DOE Has Effectively Coordinated with Other Federal Agencies at the Working Level, but Efforts at the Policy Level Have Just Begun

DOE's interagency coordination efforts among working level managers and scientists have been productive and useful, but coordination with senior officials at the policy level just began with the August 2007 establishment of the Interagency Task Force. At the working level, DOE has established several interagency bodies to facilitate cooperation and share knowledge—in particular, the Interagency Working Group on Hydrogen and Fuel Cells (IWG) has contributed to implementing hydrogen technology partnerships between DOE, DOT, and DOD and has created Web-based tools and joint workshops to facilitate coordination of research activities. At the policy level, however, the Interagency Task Force has not yet clearly defined its overall role and strategy, but members intend to formulate a plan by May 2008.

DOE Has Effectively Coordinated with Other Federal Agencies at the Working Level

Overall, working level officials—program managers, analysts, engineers and others who implement hydrogen R&D—at the federal agencies primarily involved in hydrogen-related activities generally told us they were satisfied with the level of interagency coordination. The primary coordination mechanism, the IWG, was created in 2003 and is jointly chaired by DOE and the Office of Science and Technology Policy. It provides a forum for coordinating interagency policy, programs, and activities related to safe, economical, and environmentally sound hydrogen and fuel cell technologies. The IWG meets monthly to help prioritize and coordinate the roughly $500-million portfolio of federal hydrogen and fuel cell R&D, part of which is funded by the Hydrogen Fuel Initiative. In addition to DOE, the primary federal agencies involved in hydrogen R&D include:

- DOT's hydrogen program, with approximately $1.4 million in annual Hydrogen Fuel Initiative funding, is focused on conducting R&D and deployment activities necessary to safely and reliably prepare the transportation system for hydrogen technology use. Its activities include pipeline technology research aimed at developing methods to safely and efficiently transport hydrogen, codes and standards formulation to ensure an appropriate regulatory regime, and capacity planning to smooth operation of the transportation infrastructure. In addition, DOT has a separately funded a $49 million bus demonstration program to facilitate the development of commercially viable fuel cell technologies in real-world environments.[9]

- DOD receives no funding under the Hydrogen Fuel Initiative; however, it has several entities involved in hydrogen-related activities. For example, the Defense Logistics Agency has spent $11.7 million on a fuel-cell powered fork lift program and a solid hydrogen storage program,[10] the Army supports a small amount of fuel cell R&D, and the Navy has deployed fuel cells at several installations and is conducting R&D in several areas, including for unmanned underwater vehicles.

- NASA is the largest user of hydrogen in the United States, employing it as fuel for rocket launches. NASA conducts limited hydrogen-related R&D but is interested in coordinating with DOE on a proposed project to demonstrate stationary fuel cells to generate electricity at NASA's White Sands Test Facility.

- The U.S. Postal Service conducted a 3-year hydrogen fuel cell demonstration program with mail delivery vehicles at test sites in Virginia and California. Plans are underway to continue the effort using the next generation of hydrogen vehicles in partnership with General Motors and DOE. In addition, the Postal Service is considering hydrogen technology as an option for its planned replacement of its fleet of about 215,000 vehicles in 2018.

- The Department of Commerce's National Institute of Standards and Technology (NIST) is working with federal agencies and standards organizations on a variety of activities including certification of hydrogen fuel dispensers, hydrogen quality standards, building safety standards, and pipeline safety standards. In partnership with DOE, NIST also is conducting manufacturing R&D and imaging research to investigate how water moves through fuel cells to better understand their operation.

As the main interagency coordination vehicle, the IWG has contributed to implementing hydrogen technology partnerships among agencies and

[9]Buses have potential for early market penetration because they generally refuel at central locations and have room to store an amount of hydrogen that enables a practical driving range.

[10]The Defense Logistics Agency's fiscal year 2007 funding included $11.7 million for a congressionally directed project to demonstrate fuel-cell powered fork lift technology.

created communication channels to coordinate R&D activities, such as ad-hoc groups, joint workshops, and Web-based tools. In August 2007, DOE and NIST signed an interagency agreement to coordinate development of standards, test procedures, and test methods for hydrogen fuel purchase and delivery. DOE has also partnered with the Postal Service to field test fuel-cell-powered mail delivery trucks. In addition, recent IWG efforts to highlight near-term opportunities for federal agencies to procure commercially available hydrogen and fuel cell technologies have been successful. For example, the Defense Logistics Agency has announced plans to deploy over 70 fuel-cell-powered forklifts at three defense parts depots in the United States, an initiative that spurred additional cooperation with DOT. Moreover, the Army is demonstrating mobile fuel-cell auxiliary power units, and the Navy has installed solid-oxide stationary fuel cells that supply power for shore facilities.

Other IWG activities have resulted in the creation of ad-hoc groups. As a result of a 2005 memorandum of understanding on hydrogen R&D, DOE and the Department of Agriculture established an Ad Hoc Committee on Biomass Production of Hydrogen, which meets just prior to regular IWG meetings and focuses on collaboration related to advancing hydrogen production from biomass and hydrogen-related agricultural applications. Also in 2005, as part of the IWG, DOT established an Ad Hoc Committee on a Regulatory Framework for the Hydrogen Economy that includes DOE, the Environmental Protection Agency, the U.S. Coast Guard, and the Department of Labor. The committee has developed a framework for the safe commercial application of hydrogen and fuel cell technologies.

The IWG also facilitated the creation of joint workshops. In April 2005, DOE, DOD, NASA, and the National Science Foundation facilitated a session on small business innovation at the National Hydrogen Association's annual meeting. That session featured success stories from several small business owners. DOE, NASA, and DOD held a workshop on modeling and simulating hydrogen combustion in February 2006. More recently, in August 2007, NIST and DOE participated in a conference on understanding potential impacts of delivering hydrogen through pipelines.

The IWG also has created a publicly accessible Web site, which includes links to federal hydrogen related activities, news, funding opportunities, and regulatory authorities to encourage collaboration among the public sector, private sector, academia, and international scientific community. One tool available online is the regulatory authorities inventory, a DOT-led effort to create a single point of reference for stakeholders to view current U.S. statutes and regulations that may be applicable to hydrogen.

DOE established the International Partnership for the Hydrogen Economy (IPHE) in 2003 to provide a working-level coordinating mechanism for more than a dozen partner countries to organize, coordinate, and implement international research, development, demonstration, and commercial utilization activities. IPHE also provides a forum for advancing common policies, technical codes, and standards, and it educates stakeholders on the benefits of, and challenges to, transitioning to hydrogen technologies. Although participation is voluntary, IPHE has contributed to international information exchange, facilitated engagement from senior level officials, and influenced the creation of hydrogen technology road maps in China and other countries. In addition, DOE, DOD, and DOT are collaborating through the IPHE to standardize data collection for all hydrogen fuel vehicles and hydrogen-fueling demonstrations. While IPHE highlights its accomplishments, it also acknowledges room for improvement by, for example, better defining its role and developing performance metrics in the future.

DOT officials told us that while overall DOE has ably managed its hydrogen program, some areas of interagency coordination have been more effective than others. For example, DOT and the Defense Logistics Agency conduct joint R&D planning and information sharing, a successful relationship that grew out of the IWG. However, DOT's Pipeline R&D Program was not included in early discussions at DOE, hampering collaboration and communication on technology development. DOT officials acknowledged that they now are involved in these discussions but cited the importance of ensuring DOT representation at the onset of coordination efforts.

Efforts with Other Federal Agencies at the Policy Level Have Just Begun

To ensure appropriate authority inside each agency for making hydrogen-related budget and policy decisions, HTAC recommended in October 2006 that the IWG be elevated to require participation of an assistant secretary or higher. In response, DOE created the Interagency Task Force—a new entity composed of deputy assistant secretaries, program directors, and other senior officials—which held its inaugural meeting August 2007. Because the organization was created recently, its membership is still in flux as the most appropriate participants are being identified. The goals of the task force are to

- increase understanding of available hydrogen and fuel cell technologies and how they can contribute to the agencies' energy and environmental goals,

- work together to identify concrete opportunities for the federal government to provide leadership by being an early adopter,
- use government procurement and leadership to rapidly deploy technology and facilitate its introduction into the marketplace, and
- define new opportunities through interaction and exchange of ideas.

Although the task force outlined a set of broad goals, it did not clearly define its responsibilities or strategy for achieving these goals. Member agencies intend to develop a more detailed plan that will guide efforts, identify actions that can be taken, and establish targets by May 2008. The task force assigned IWG the responsibility for creating the plan and agreed to review each agency's role, responsibilities, and stake in hydrogen technology at the IWG's December 2007 meeting.

In August 2007, HTAC criticized DOE for taking too long to respond to HTAC's recommendation and for not securing participation of assistant secretaries, participation that HTAC believes is necessary for making hydrogen budget and policy decisions. Similarly, DOT officials told us that the Interagency Task Force was supposed to be created specifically at the senior level so participants could influence budget and policy matters, but too many alternates were present at the first meeting, reducing its potential effectiveness. DOT officials added that if membership continues to shift or be inconsistent, then lack of continuity will hinder progress and make it difficult to achieve goals. DOE officials stated that the level of membership is adequate because deputy assistant secretaries, program directors, and other senior officials are high enough to make decisions, influence policy, and impact the implementation of programs. Some task force members have expressed concerns about lack of a common vision among agencies, including a shared view of timelines, milestones, and approaches, in part because of differing roles, responsibilities, and stakeholders and because of the fact that no overarching authority guides all government hydrogen R&D. For example, although DOE has clearly outlined a 2015 technology readiness goal suitable for its mission, DOT may need to develop a regulatory framework earlier to address industry's intent to begin deploying fuel cell vehicles as early as 2012.

Conclusions

The Hydrogen Fuel Initiative has made important progress in developing hydrogen technologies in all of its technical areas in both fundamental and applied science. DOE and industry officials attribute this progress to DOE's (1) planning process that involved industry and university experts from the earliest stages; (2) use of annual merit reviews, technical teams, centers of excellence, and other coordination mechanisms to continually involve industry and university experts to review the progress and direction of the program; (3) emphasis on both fundamental and applied science, as recommended by independent experts; and (4) continued focus on such high priority areas as hydrogen storage and fuel cell cost and durability. Although DOE has made important R&D progress, its 2015 technology readiness target is very ambitious, requiring scientific breakthroughs in hydrogen storage, for example. Budget constraints and technical challenges have led DOE to push back its targets for providing certain technologies to automakers from 2015 to 2017 or later, which according to DOE, generally still lies within the window for the automobile companies to provide hydrogen fuel cell vehicles by 2020. However, DOE has not updated its 2006 *Hydrogen Posture Plan's* overall assessment of what the department reasonably expects to achieve by its technology readiness date in 2015 and how this updated assessment may differ from prior posture plans. DOE also has not identified R&D funding needed to achieve the 2015 target. This information is important to the Congress and industry as they set priorities and make funding decisions. Furthermore, developing a nationwide commercial market for hydrogen fuel cell vehicles is expected to cost tens of billions of dollars for production facilities, fueling stations, pipelines, and other support infrastructure and take decades to achieve, requiring a sustained investment by government and industry in R&D and the infrastructure.

Recommendation

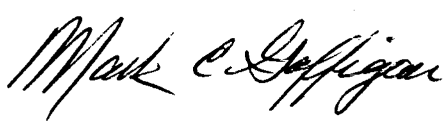
To accurately reflect progress made by the Hydrogen Fuel Initiative and the challenges it faces, we recommend that the Secretary of Energy update the *Hydrogen Posture Plan's* overall assessment of what DOE reasonably expects to achieve by its technology readiness date in 2015, including how this updated assessment may differ from prior posture plans and a projection of anticipated R&D funding needs.

Agency Comments and Our Evaluation

We provided DOE with a draft of this report for its review and comment. In written comments, DOE agreed with our recommendation, stating that it plans to update the *Hydrogen Posture Plan* during 2008 to reflect the progress made and any changes to the activities milestones, deliverables, and timeline. (See app. II.) However, DOE found the title of the draft report to be confusing, stating that R&D on hydrogen technologies would inevitably continue beyond 2015. In response, we revised the title to highlight the need for DOE to update what it expects to achieve by its 2015 target. DOE also disagreed with our statement that it has not determined what reasonably can be achieved by 2015 for use in a 2020 vehicle, citing extensive efforts to assess the R&D program's progress. In response, we clarified that our concern is that the *Hydrogen Posture Plan*, which provides the Congress and other outside stakeholders with an assessment of progress, needs to be updated to identify what DOE reasonably expects to achieve by its technology readiness date in 2015. In addition, DOE provided comments to improve the draft report's technical accuracy, which we have incorporated as appropriate.

As agreed with your offices, unless you publicly announce the contents of this report, we plan no further distribution of it until 30 days from the date of this letter. At that time, we will send copies of this report to the appropriate congressional committees, the Secretary of Energy, the Director of the Office of Management and Budget, and other interested parties. We will also make copies available to others upon request. In addition, the report will be available at no charge on the GAO Web site at http://www.gao.gov.

If you or your staff have any questions about this report, please contact me at (202) 512-3841 or gaffiganm@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made major contributions to this report are listed in appendix III.



Mark E. Gaffigan
Acting Director, Natural Resources
and Environment

Appendix I: Scope and Methodology

To assess the extent to which the Department of Energy's (DOE) Hydrogen Fuel Initiative has made progress in meeting its R&D targets, we reviewed documents and interviewed DOE program managers, national laboratory scientists, company and industry association executives, independent experts, and state government officials. More specifically, we reviewed DOE's 2004 and 2006 *Hydrogen Posture Plans* and R&D project reports, attended DOE's annual review of its projects in May 2007, and interviewed DOE hydrogen program managers and scientists at DOE's National Renewable Energy Laboratory and Los Alamos National Laboratory. We also reviewed the R&D plans, technology roadmaps, assessments and reviews from each of DOE's programs, including Energy Efficiency and Renewable Energy, Fossil Energy, Nuclear Energy, and Science, and from several of the technical teams that DOE established to review R&D progress in specific technologies. In addition, we spoke with members and attended meetings of the Hydrogen and Fuel Cell Technical Advisory Committee, interviewed industry representatives, and reviewed industry assessments of DOE's progress in developing and demonstrating vehicle, stationary, and portable technologies. Furthermore, we reviewed reports of the National Academies of Sciences and Engineering on the hydrogen R&D program and spoke with cognizant officials.

To determine the extent to which DOE has worked with industry to set and meet R&D targets, we reviewed pertinent documents, assessed DOE's processes for soliciting industry input, and attended a meeting of the fuel cell technical team at Los Alamos National Laboratory. We also interviewed cognizant DOE managers and scientists and executives of car manufacturers, energy companies, utilities, hydrogen producers, fuel cell manufacturers, and suppliers of hydrogen-related components about DOE's processes for soliciting industry input and we toured several industry facilities.

To determine the extent to which DOE has worked with other federal agencies to develop and demonstrate hydrogen technologies, we reviewed pertinent documents and spoke with officials at DOE, the Department of Transportation, the Department of Defense, the Department of Commerce, the National Aeronautics and Space Administration, and the U.S. Postal Service. We also attended the Interagency Task Force's first meeting in August 2007.

We conducted this performance audit from March through December 2007 in accordance with generally accepted government auditing standards. These standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Appendix II: Comments from the Department of Energy

Department of Energy
Washington, D.C. 20585

January 3, 2008

Mr. Mark E. Gaffigan
Acting Director, Natural Resources and Environment
U.S. Government Accountability Office
441 G Street, NW
Washington, DC 20548

Dear Mr. Gaffigan:

Thank you for the opportunity to comment on the draft Government Accountability Office (GAO) report entitled *"Hydrogen Fuel Initiative: DOE Has Made Important Progress and Involved Industry and Other Agencies, but R&D Will Continue Past Its 2015 Target Date (GAO-08-305)."* The Department of Energy (DOE) has partnered with industry, academia, Federal laboratories and other Federal agencies in taking a leadership role in the research and development (R&D) of hydrogen and fuel cell technologies that have the potential to reduce U.S. oil use and greenhouse gas emissions. We commend the GAO for taking the time to interview experts within the Department, our national laboratories and industry in preparation for this report. We have reviewed the report in detail and provide our general response below, as well as detailed comments and clarifications as an enclosure to this letter.

The Department agrees with the GAO findings that the Hydrogen Program has made significant progress in the research and development of hydrogen and fuel cells over the past four years, and that the program has worked effectively with industry and other Federal agencies. However, we disagree with the underlying premise that forms the basis for the report's title, which implies that DOE did not envision the need for R&D of hydrogen and fuel cell technologies beyond 2015. The Department never stated that R&D of hydrogen technologies would end in 2015. As indicated in the Hydrogen Posture Plan[1], the program established a milestone of 2015 to complete the critical path technology development that would enable industry to make commercialization decisions for market introduction in the 2020 timeframe, and clearly stated that R&D would continue beyond this point to support renewable and nuclear-based hydrogen production, infrastructure development, and basic science. Just as we continue to support research on the internal combustion engine today, over 100 years after its introduction, the Department will continue to improve hydrogen and fuel cell technologies beyond 2015.

We also disagree with the report's statement that "DOE has not determined what reasonably can be achieved by 2015 for use in a 2020 vehicle." As the GAO report points out, the program has

[1] Hydrogen Posture Plan, December 2006, http://www.hydrogen.energy.gov/pdfs/hydrogen_posture_plan_dec06.pdf

1

engaged experts from industry, academia, and national labs to identify the major barriers and to plan a path forward. The program's detailed multi-year R&D plans[2] describe hundreds of tasks, milestones, and deliverables in hydrogen production, delivery, storage, and fuel cells based on system requirements, the current status of the technology, and the pace of technology progress over the past 15 years. The program's Technology Validation efforts have shown that significant progress has been made in the critical path technology development efforts. Vehicles in the learning demonstration include laboratory fuel cell technology developed by the program three to five years ago. These first generation vehicles include fuel cell systems demonstrating up to 58 percent efficiency, 1600 hour durability (48,000 miles), and up to 190-mile range. We expect laboratory stacks demonstrating greater than 2,000 hours durability today to be in second generation vehicles by 2009, and membranes demonstrating 5,000 hours durability (our 2015 target) in the laboratory today to be in fuel cell vehicles in 2015. We agree that significant challenges remain, particularly in hydrogen storage; however, based on the progress to date, we have determined what reasonably can be achieved by 2015.

We are pleased that the GAO has recognized the program's increased efforts in stationary and portable fuel cell technology. These applications offer significant benefits today and will help to reduce cost, to promote consumer acceptance, and to develop infrastructure and a domestic supply base – paving the way for fuel cell vehicles in the future. We will continue the work of the newly launched Hydrogen and Fuel Cell Interagency Task Force to promote the use of hydrogen and fuel cell technologies to meet energy needs within the Federal Government. The Hydrogen Posture Plan will be updated during 2008 to reflect the progress made in all areas of the program and any changes to the activities, milestones, deliverables and timeline.

Thank you again for the effort you put into the preparation of the GAO report on the Hydrogen Fuel Initiative, and for giving us the opportunity to comment on the report.

Sincerely,

S. Chalk

Steven G. Chalk
Deputy Assistant Secretary for Renewable Energy
Office of Technology Development
Energy Efficiency and Renewable Energy

Enclosure

[2] Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development, and Demonstration Plan, http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/; Hydrogen from Coal R&D Plan, http://www.fossil.energy.gov/programs/fuels/publications/programplans/2007_Hydrogen_Program_Plan.pdf; Nuclear Hydrogen R&D Plan, http://www.hydrogen.energy.gov/pdfs/nuclear_energy_h2_plan.pdf; Basic Research Needs for the Hydrogen Economy, http://www.sc.doe.gov/bes/hydrogen.pdf.

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Appendix III: GAO Contact and Staff Acknowledgments

GAO Contact

Mark Gaffigan, (202) 512-3841 or gaffiganm@gao.gov

Staff Acknowledgments

In addition to the individual named above, Richard Cheston, Assistant Director; Robert Sanchez; Thomas Kingham; Marc Castellano; and Alison O’Neill made key contributions to this report. Also contributing to this report were Kevin Bray, Virginia Chanley, Patrick Gould, Anne Stevens, and Hai Tran.

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