Hydrogen & Our Energy Future

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Contents

Hydrogen & Our Energy Future

Introduction *p.*1

Hydrogen – An Overview *p.*3

Production *p.*5

Delivery *p.*15

Storage *p.*19

Application and Use *p.*25

Safety, Codes and Standards *p.*33

Summary *p.*35

Glossary *p.*39

Introduction

Hydrogen holds the potential to provide clean, safe, affordable, and secure energy from abundant domestic resources.

In 2003, President George W. Bush announced the Hydrogen Fuel Initiative to accelerate the research and development of hydrogen, fuel cell, and infrastructure technologies that would enable hydrogen fuel cell vehicles to reach the commercial market in the 2020 timeframe. The widespread use of hydrogen can reduce our dependence on imported oil and benefit the environment by reducing greenhouse gas emissions and criteria pollutant emissions that affect our air quality.

The Energy Policy Act of 2005, passed by Congress and signed into law by President Bush on August 8, 2005, reinforces Federal government support for hydrogen and fuel cell technologies. Title VIII, also called the "Spark M. Matsunaga Hydrogen Act of 2005" authorizes more than $3.2 billion for hydrogen and fuel cell activities intended to enable the commercial introduction of hydrogen fuel cell vehicles by 2020, consistent with the Hydrogen Fuel Initiative. Numerous other titles in the Act call for related tax and market incentives, new studies, collaboration with alternative fuels and renewable energy programs, and broadened demonstrations—clearly demonstrating the strong support among members of Congress for the development and use of hydrogen fuel cell technologies.

In 2006, the President announced the Advanced Energy Initiative (AEI) to accelerate research on technologies with the potential to reduce near-term oil use in the transportation sector—batteries for hybrid vehicles and cellulosic ethanol—and advance activities under the Hydrogen Fuel Initiative. The AEI also supports research to reduce the cost of electricity production technologies in the stationary sector such as clean coal, nuclear energy, solar photovoltaics, and wind energy.

Energy Security

The increasing demand for gasoline and diesel fuel used to power our cars and trucks makes our nation more dependent on foreign sources of oil. More than one-half of the petroleum consumed in the United States is imported, and that percentage is expected to rise to 68% by 2025.[1] The U.S. transportation sector relies almost exclusively on refined petroleum products, accounting for over two-thirds of the oil used.[2] Our increasing dependence on foreign sources of oil makes us vulnerable to supply disruptions and price fluctuations that occur outside of our country.

1) U.S. Department of Energy, Energy Information Administration, Annual Energy Outlook 2005, (February 2005), 7.

2) Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 24, (December 2004), "Table 1.13 World Petroleum Production, 1973-2003," 1-4.

In the short term, conservation and the use of highly efficient hybrid-electric vehicles (HEVs) can slow the overall rate of growth of oil consumption. Hybrid-electric vehicle technology is becoming commercially competitive in today's consumer market, and additional research is focused on making hybrid batteries, electronics, and materials more affordable. But over the long term, when projected increases in the number of cars on the road and vehicle-miles-traveled are taken into account, HEV use alone will not reduce oil consumption below today's level.

In addition to the increased use of biofuels, like ethanol, and plug-in hybrid vehicles technology, using hydrogen as an energy carrier can provide the United States with a more efficient and diversified energy infrastructure. Hydrogen is a promising energy carrier in part because it can be produced from different and abundant resources, including fossil, nuclear, and renewables. Using hydrogen, particularly for our transportation needs, will allow us to diversify our energy supply with abundant, domestic resources and reduce our dependence on foreign oil.

Environmental Benefits

Air quality is a significant national concern. The U.S. Environmental Protection Agency estimates that about 50% of Americans live in areas where levels of one or more air pollutants are high enough to affect public health and/or the environment[3]. In addition, the combustion of fossil fuels accounts for the majority of anthropogenic greenhouse gas emissions (primarily carbon dioxide, or CO_2) released into the atmosphere. The largest sources of CO_2 emissions are the electric utility and transportation sectors.

3) U.S. Environmental Protection Agency, "Air Trends: Six Principal Pollutants," (n.d.), retrieved September 15, 2005, from http://www.epa.gov/airtrends/sixpoll.html; and U.S. Bureau of the Census Global Population Profile 2002, "Table A-4 Population by Region and Country: 1950-2050," 5.

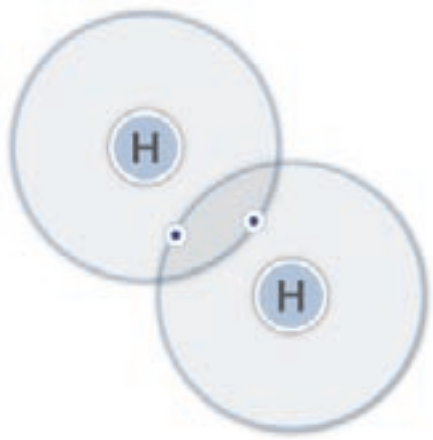
Fuel cells use hydrogen to create electricity, with only heat and water as byproducts. When used to power a vehicle, the only output from the tailpipe is water vapor—no greenhouse gas or criteria emissions. To realize the environmental benefits of hydrogen, however, we must consider the full fuel cycle (also called "well-to-wheels")—from energy source to hydrogen production to end-use. Producing hydrogen from renewable sources or nuclear energy yields virtually zero greenhouse gas emissions. Hydrogen produced from coal, when combined with capture and sequestration of the byproduct carbon dioxide, also results in virtually no greenhouse gas emissions.

Hydrogen – An Overview

Hydrogen can power cars, trucks, buses, and other vehicles, as well as homes, offices, factories, and even portable electronic equipment, such as laptop computers.

What is Hydrogen?

Hydrogen, chemical symbol H, is the simplest element on earth. An atom of hydrogen has only one proton and one electron. Hydrogen gas is a diatomic molecule—each molecule has two atoms of hydrogen (which is why pure hydrogen is commonly expressed as "H_2"). At standard temperature and pressure, hydrogen exists as a gas. It is colorless, odorless, tasteless, and lighter than air.



Hydrogen molecule (H_2)

Like electricity, hydrogen is an ***energy carrier*** (not an energy source), meaning it can store and deliver energy in an easily usable form. Although abundant on earth as an element, hydrogen combines readily with other elements and is almost always found as part of some other substance, such as water (H_2O), or hydrocarbons like natural gas (which consists primarily of methane, with the chemical formula, CH_4). Hydrogen is also found in biomass, which includes all plants and animals.

How is Hydrogen Currently Used?

The United States currently produces about nine million tons of hydrogen per year.[4] This hydrogen is used primarily in industrial processes including petroleum refining, petrochemical manufacturing, glass purification, and in fertilizers. It is also used in the semiconductor industry and for the hydrogenation of unsaturated fats in vegetable oil.

Only a small fraction of the hydrogen produced in the United States is used as an energy carrier, most notably by the National Aeronautics and Space Administration (NASA). This could change, however, as our nation's leaders look to increase our energy security by reducing our dependence on imported oil and expanding our portfolio of energy choices. Hydrogen is the optimum choice for fuel cells, which are extremely efficient energy conversion devices that can be used for transportation and electricity generation.

How Much is Nine Million Tons of Hydrogen?

Enough to fuel approximately 34 million hydrogen cars

Source: DOE Record 5022, www.hydrogen.energy.gov/program_records.html

4) National Academy of Sciences/ National Research Council, "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs," page 17.

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U.S. Department of Energy (DOE) Hydrogen Program: Implementing the President's Hydrogen Fuel Initiative

Under the President's Hydrogen Fuel Initiative, the DOE Hydrogen Program works in partnership with industry, academia, national laboratories, and other federal and international agencies to do the following:

- Overcome technical barriers through the research and development of hydrogen production, delivery, and storage technologies, as well as fuel cell technologies for transportation, distributed stationary power, and portable power applications;
- Address safety concerns and facilitate the development of model codes and standards;
- Validate hydrogen and fuel cell technologies in real-world conditions; and
- Educate key target audiences who can facilitate the near-term use of hydrogen as an energy carrier.

Production

Hydrogen can be produced using diverse, domestic resources at both central and distributed production facilities.

Basics

Although hydrogen is the most abundant element in the universe, it does not naturally exist in its elemental form on Earth. Pure hydrogen must be produced from other hydrogen-containing compounds, such as fossil fuels, biomass, or water. Each production method requires a source of energy, i.e., thermal (heat), electrolytic (electricity), or photolytic (light) energy. Researchers are developing a wide range of technologies to produce hydrogen in economical, environmentally friendly ways so that we will not need to rely on any one energy resource. The great potential for diversity of supply is an important reason why hydrogen is such a promising energy carrier.

The overall challenge to hydrogen production is cost reduction. For transportation, hydrogen must be cost-competitive with conventional fuels and technologies on a per-mile basis to succeed in the commercial marketplace. This means that the cost of hydrogen (which includes the cost of production as well as delivery to the point of use) should be between $2.00 - $3.00 per gallon gasoline equivalent (untaxed).

What is a *gallon gasoline equivalent*?

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

Distributed and Central Production

Hydrogen can be produced in large central plants several hundred miles from the point of end-use; in smaller, semi-central plants within 20-100 miles of the point of end-use; or in small "distributed generation" facilities located very near or at the point of end-use.

Distributed production may be the most viable approach for expanding the use of hydrogen in the near term because it requires less capital investment and less delivery infrastructure. Natural gas or renewable liquid fuel reforming and small-scale water electrolysis at the point of end-use are two distributed technologies with potential for near-term development and commercialization.

Large central hydrogen production facilities that take advantage of economies of scale will be needed in the long term to meet the expected hydrogen demand. Central production can use a variety of resources—fossil, nuclear, and renewable—but an infrastructure will be required to efficiently and cost-effectively deliver the hydrogen to vehicle refueling stations and other points of end-use.

Hydrogen production technologies fall into three general categories –

- Thermal Processes
- Electrolytic Processes
- Photolytic Processes

Pressure Conversion Factors

1 atmosphere (atm) = **14.7** pounds per square inch (psi)

1 atm = **29.92** inches of mercury (in Hg)

1 bar = **14.5** psi

1 mega Pascal (MPa) = **10** bar = **145** psi

Thermal Processes

Thermal processes use the energy in resources including natural gas, coal, or biomass to produce hydrogen. Some "thermochemical" processes use heat combined with closed chemical cycles to produce hydrogen from feedstocks such as water.

Thermal processes include –

- Natural gas reforming
- Gasification
- Renewable liquid fuel reforming
- High temperature water splitting

Steam Reforming Reactions

Methane:

$CH_4 + H_2O$ *(+heat)* $\rightarrow CO + 3H_2$

Propane:

$C_3H_8 + 3H_2O$ *(+heat)* $\rightarrow 3CO + 7H_2$

Gasoline:

(using iso-octane and toluene as example compounds from the hundred or more compounds present in gasoline)

$C_8H_{18} + 8H_2O$ *(+heat)* $\rightarrow 8CO + 17H_2$

$C_7H_8 + 7H_2O$ *(+heat)* $\rightarrow 7CO + 11H_2$

Water-Gas Shift Reaction:

$CO + H_2O \rightarrow CO_2 + H_2$ *(+small amount of heat)*

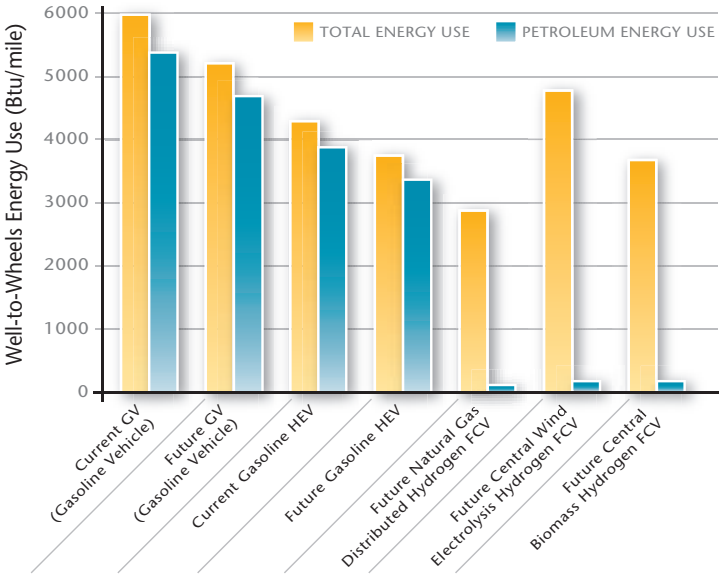
Natural Gas Reforming

Natural gas contains methane (CH_4) that can be used to produce hydrogen via thermal processes including steam methane reforming and partial oxidation.

Steam Methane Reforming

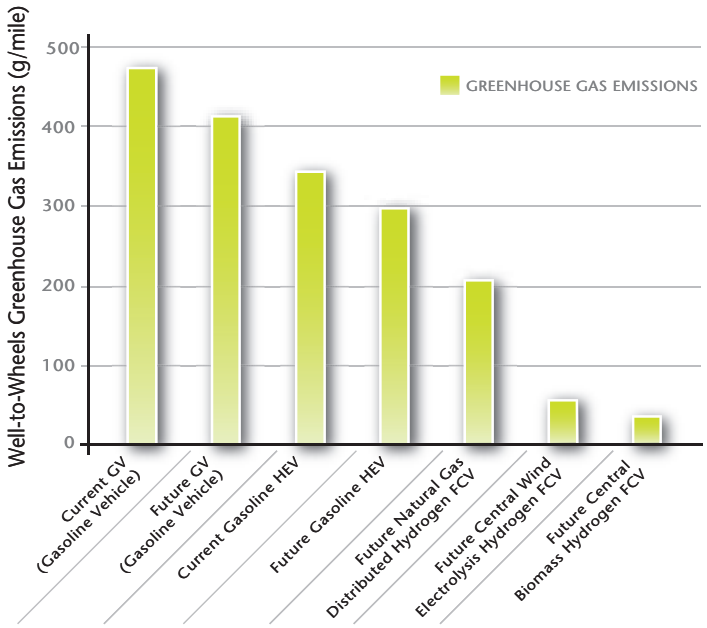
Hydrogen can be produced via steam reforming of fuels including gasoline, propane, and ethanol (see renewable liquid reforming on page 10). But about 95% of the hydrogen produced in the United States today is made via steam methane reforming, in which high-temperature steam (700 – 1000°C) is used to produce hydrogen from a methane source such as natural gas. The methane reacts with steam under 3-25 bar pressure in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. The carbon monoxide and steam are then reacted using a catalyst to produce carbon dioxide and more hydrogen. This is called the "water-gas shift reaction." In the final process step, called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen.

Figure 1. Well-to-Wheels Energy Use



A fuel cell vehicle using hydrogen produced from natural gas would consume 50% less energy than a conventional gasoline vehicle and nearly 15% less energy than a gasoline hybrid electric vehicle on a well-to-wheels basis—which accounts for energy consumed in extracting, refining, transporting, and using a fuel.

Figure 2. Well-to-Wheels Greenhouse Gas Emissions



On a well-to-wheels basis—accounting for greenhouse gases emitted in extracting, refining, transporting, and using a fuel—a fuel cell vehicle using hydrogen from natural gas would produce 50% less greenhouse gas emissions than a conventional gasoline vehicle and 25% less than a gasoline hybrid electric vehicle.

Source for both figures 2 and 3: *Department of Energy Hydrogen Program 2006 Annual Progress Report*, November 2006.

Partial Oxidation

In partial oxidation, the methane and other hydrocarbons in natural gas are reacted with a limited amount of oxygen (typically from air) that is not enough to completely oxidize the hydrocarbons to carbon dioxide and water. With less than the stoichiometric amount of oxygen available for the reaction, the reaction products contain primarily hydrogen and carbon monoxide (and nitrogen, if the reaction is carried out with air rather than pure oxygen), again with a relatively small amount of carbon dioxide and other compounds. The product gas is often referred to as synthesis gas or "syngas," from which hydrogen can be separated for use.

Unlike steam reforming, which is an endothermic process that requires heat, partial oxidation is an exothermic process that gives off heat. Typically, it is much faster than steam reforming and requires a smaller reactor vessel. As illustrated in the chemical reactions (see sidebar), partial oxidation initially produces less hydrogen per unit of the input fuel than is obtained by steam reforming of the same fuel. As in steam reforming, to maximize the amount of hydrogen produced, partial oxidation usually includes a water-gas shift reaction to generate additional hydrogen from the oxidation of carbon monoxide to carbon dioxide by reaction with water (steam).

Partial Oxidation Reactions

Methane:

$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2$ *(+heat)*

Propane:

$C_3H_8 + 1\frac{1}{2}O_2 \rightarrow 3CO + 4H_2$ *(+heat)*

Ethanol:

$C_2H_5OH + \frac{1}{2}O_2 \rightarrow 2CO + 3H_2$ *(+heat)*

Gasoline:

(using iso-octane and toluene as example compounds from the hundred or more compounds present in gasoline)

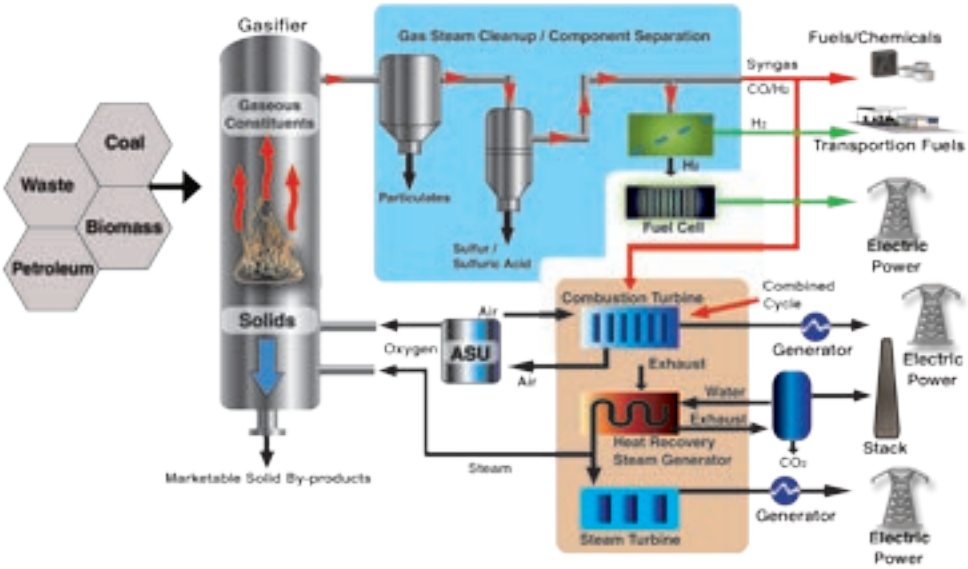
$C_8H_{18} + 4O_2 \rightarrow 8CO + 9H_2$ *(+heat)*

$C_7H_8 + 3\frac{1}{2}O_2 \rightarrow 7CO + 4H_2$ *(+heat)*

Most of the hydrogen produced today in the United States is made from natural gas in large, central facilities. Natural gas will continue to be an important resource for near-term hydrogen production for many reasons. It has a high hydrogen-to-carbon ratio (it emits less carbon dioxide than other hydrocarbons per unit of hydrogen production) and it has an existing pipeline-based transmission, distribution, and delivery infrastructure. But because natural gas resources in the United States are limited, producing large amounts of hydrogen from natural gas is unsustainable for the long term, as it would essentially trade U.S. dependence on imported oil for U.S. dependence on imported natural gas.

Although natural gas reforming is relatively mature compared to other hydrogen production technologies, the capital equipment and operation and maintenance costs associated with distributed natural gas reforming must be reduced to make hydrogen cost-competitive with the conventional fuels we use today.

Gasification



Source: U.S. Department of Energy, Office of Fossil Energy, http://www.fossil.energy.gov/programs/powersystems/gasification/howgasificationworks.html, accessed May 19, 2006.

Coal Gasification Reaction

Chemically, coal is a complex and highly variable substance. In bituminous coal, the carbon and hydrogen may be approximately represented as 0.8 atoms of hydrogen per atom of carbon. Its gasification reaction can be represented by this (unbalanced) reaction equation:

$$CH_{0.8} + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other species}$$

Gasification is a thermal process that converts coal or biomass into a gaseous mixture of hydrogen, carbon monoxide, carbon dioxide, and other compounds by applying heat under pressure and in the presence of steam. Adsorbers or special membranes can separate the hydrogen from this gas stream, and additional hydrogen can be generated by reacting the carbon monoxide in a separate unit with water (forming carbon dioxide and producing hydrogen). To be commercially viable, the capital costs of the gasifier and the equipment to separate and purify hydrogen must be reduced.

Coal

Coal is an abundant and relatively inexpensive domestic resource. The United States has more proven coal reserves than any other country in the world—about half of the electricity produced in the United States today is generated from coal. It is important to note that hydrogen can be produced directly from coal via gasification, rather than by using coal-generated electricity to produce hydrogen. The carbon dioxide created as a byproduct of coal gasification can be captured and sequestered so that the process results in near-zero greenhouse gas emissions. Coal gasification research, development, and demonstration activities seek to ensure that coal can produce clean, affordable, reliable and efficient electricity and hydrogen in the future (see below).

What is Carbon Capture and Sequestration?

If hydrogen is to be produced from coal, the carbon dioxide that is also produced in the process must be handled in an environmentally responsible manner. Carbon capture and sequestration technologies are being developed to separate carbon dioxide at the point of production and store it (in deep underground geologic formations, for example, as natural gas is stored today) where it can be monitored and prevented from escaping.

FutureGen

Announced in February 2003, FutureGen is a $1 billion, 10-year initiative to demonstrate the world's first coal-based, near-zero atmospheric emissions power plant to produce electricity and hydrogen. This DOE effort, although not part of the Hydrogen Fuel Initiative, supports program goals through its objective to establish the technical and economic feasibility of co-producing electricity and hydrogen from coal while capturing and sequestering the carbon dioxide. FutureGen will use gasification technology to produce hydrogen directly, which is a more efficient process for the centralized production of hydrogen than coal-to-electricity-to-hydrogen generation.

www.fossil.energy.gov/futuregen

Biomass

Biomass includes crop or forest residues; special crops grown specifically for energy use like switchgrass or willow trees; and organic municipal solid waste. Because biomass resources often consume carbon dioxide in the atmosphere as part of their natural growth processes, producing hydrogen through biomass gasification may release near-zero net greenhouse gases. Improved agricultural handling practices and breeding efforts, as well as advancements in biotechnology, can reduce the cost of biomass feedstocks—and therefore reduce the cost of hydrogen—in the future.

Biomass Gasification Reaction

Biomass, like coal, is a substance of highly variable chemistry and complexity. Cellulose is a major component in most biomass, along with lignins and other compounds. Cellulose is a polysaccharide that may be represented for the gasification process by glucose as a surrogate:

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow$$
$$CO + CO_2 + H_2 + \text{other species}$$

Renewable Liquid Fuel Reforming

Renewable liquid fuels, such as ethanol or bio-oils made from biomass resources, can be reformed to produce hydrogen in a distributed system—at refueling stations or stationary power sites. Biomass resources, when converted to ethanol, bio-oils, or other liquid fuels, can be transported at relatively low cost to the point of use and reformed onsite to produce hydrogen.

Reforming renewable liquids is similar to reforming natural gas. The liquid fuel is reacted with steam at high temperatures in the presence of a catalyst to produce a reformate gas composed of mostly hydrogen and carbon monoxide. Reacting the carbon monoxide with steam in a water-gas shift reaction produces additional hydrogen and carbon dioxide (see p.6).

Since renewable liquids consist of larger molecules with more carbon atoms, they can be somewhat more difficult to reform than the methane in natural gas. Better catalysts will improve hydrogen yields and selectivity. And like natural gas reforming, operation, maintenance and capital equipment costs must be reduced and the energy efficiency must be improved for the hydrogen produced to be cost-competitive with conventional fuels.

Making Liquid Fuels from Biomass

Ethanol is made by converting the starch in corn into sugars and fermenting the sugars to produce ethanol. Sugars can be extracted from other biomass resources like crop or forest residues through a process involving mild acid or steam and enzyme digestion. These sugars are then fermented, producing ethanol.

Bio-oil is an oil-like liquid similar to diesel fuel. When treated with heat, biomass breaks down to produce a bio-oil.

Renewable Liquid Fuel (e.g., Ethanol) Reforming Reaction

$C_2H_5OH + H_2O$ *(+heat)* $\rightarrow 2CO + 4H_2$

High Temperature Water Splitting

High-temperature water splitting, a longer-term technology in the early stages of development, uses high temperatures to drive a series of chemical reactions that produce hydrogen from water. The chemicals are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen. For both of the "thermochemical" processes described below, scientists have identified cycles appropriate to specific temperature ranges at which heat is available and are researching these systems in the laboratory.

High-Temperature Water Splitting Using Solar Concentrators

A solar concentrator uses mirrors and a reflective or refractive lens to capture and focus sunlight to produce temperatures up to 2,000°C. Researchers have identified more than 150 chemical cycles that, in principle, could be used with heat from a solar concentrator to produce hydrogen; more than a dozen of these cycles are under active development.

One such pathway is the zinc/zinc oxide cycle, in which zinc oxide powder passes through a reactor that is heated by a solar concentrator operating at about 1,900°C. At this temperature, the zinc oxide dissociates to zinc and oxygen gas. The zinc is cooled, separated, and reacted with water to form hydrogen gas and solid zinc oxide. The zinc oxide can be recycled and reused to create more hydrogen.

High Temperature Water Splitting Reaction – Zinc/Zinc Oxide Cycle Example

$2ZnO + \text{heat} \rightarrow 2Zn + O_2$

$2Zn + 2H_2O \rightarrow 2ZnO + 2H_2$

High-Temperature Water Splitting Using Nuclear Energy

Similarly, a nuclear reactor produces heat that can drive a series of chemical reactions to create hydrogen by splitting water and recycling the chemical constituents. The next-generation nuclear reactors under development could generate heat at temperatures of 800°C to 1,000°C. These temperatures are much lower than those produced by a solar concentrator, and as such, a different set of chemical reactions would be used to produce hydrogen.

The sulfur-iodine cycle is among the thermochemical cycles being investigated for this purpose. Sulfuric acid, when heated to about 850°C, decomposes to water, oxygen, and sulfur dioxide. The oxygen is removed, the sulfur dioxide and water are cooled, and the sulfur dioxide reacts with water and iodine to form sulfuric acid and hydrogen iodide. The sulfuric acid is separated and removed; the remaining hydrogen iodide is heated to 300°C, where it breaks down into hydrogen and iodine. The net result is hydrogen and oxygen, produced from water—the sulfuric acid and iodine are recycled and used to repeat the process.

Electrolytic Processes

Electrolytic processes use electricity to split water into hydrogen and oxygen in a unit called an electrolyzer. Like fuel cells (see page 25), electrolyzers consist of an anode and a cathode separated by an electrolyte. The electrolyte determines the type of electrolyzer and its operating conditions.

In a polymer electrolyte membrane (PEM) electrolyzer –

- Water at the ***anode*** reacts to form oxygen and positively charged hydrogen ions (protons) and electrons that flow through the external circuit;
- The hydrogen ions move across the PEM to the ***cathode***;
- At the ***cathode***, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.

Alkaline electrolyzers are similar to PEM electrolyzers, but instead use an alkaline solution (of sodium or potassium hydroxide) as the electrolyte. Both PEM and alkaline electrolyzers operate at relatively low temperatures – 80-100°C and 100-250°C, respectively.

A solid oxide electrolyzer, which has a solid ceramic electrolyte, generates hydrogen in a slightly different way and must operate at higher temperatures

High Temperature Water Splitting Reaction – Sulfur-Iodine Cycle Example

$2H_2SO_4$ + heat at 850°C → $2H_2O + 2SO_2 + O_2$

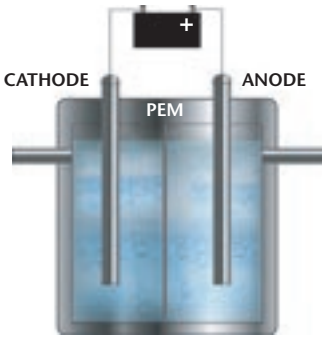
$4H_2O + 2SO_2 + 2I_2 \rightarrow 2H_2SO_4 + 4HI$

$4HI$ + *heat at 300°C* → $2I_2 + 2H_2$

Electrolysis Reactions

Anode Reaction:
$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

Cathode Reaction:
$4H^+ + 4e^- \rightarrow 2H_2$



Electricity in the United States

The average mix of energy resources used today to generate electricity in the United States is:
50% coal
20% nuclear
18% natural gas
9% renewable
3% petroleum

Source: Energy Information Administration, net generation, 2005 data

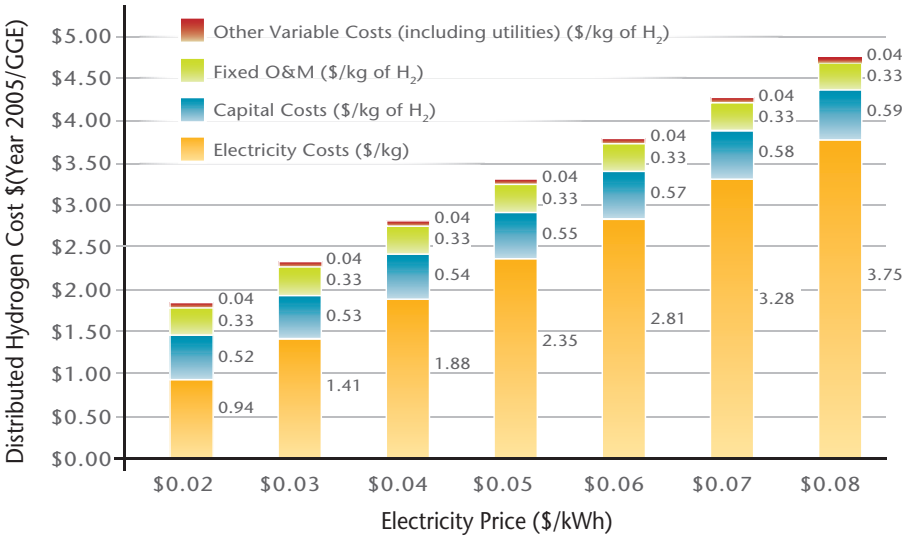
Production

(500-800°C) for the membranes to function properly. Solid oxide electrolyzers can effectively use heat available at these elevated temperatures (from various sources, including nuclear energy) to decrease the amount of electrical energy needed to produce hydrogen from water. In a solid oxide electrolyzer –

- Water at the ***cathode*** combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions;
- The oxygen ions pass through the membrane and react at the ***anode*** to form oxygen gas and give up the electrons to the external circuit.

PEM and alkaline electrolyzers can be smaller, appliance-sized equipment, and well suited for distributed hydrogen production. The source of the required electricity—including its cost and efficiency, as well as emissions resulting from electricity generation—must be considered when evaluating the benefits of hydrogen production via electrolysis.

Figure 3. Effect of Electricity Price on Distributed Hydrogen Production Cost *(assumes 1,500 GGE/day, electrolyzer system at 76% efficiency, capital cost of $250/kW)*



Sources: *Solar and Wind Technologies for Hydrogen Production, Report to Congress* (ESECS EE-3060), December 2005.

Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan, Planned program activities for 2003-2010, Technical Plan - Hydrogen Production, Updated 14 November 2006.

Two electrolysis pathways with near zero greenhouse gas emissions are of particular interest for wide-scale hydrogen production –

- Electrolysis using renewable sources of electricity
- Nuclear high-temperature electrolysis

Among the challenges for cost-effective electrolytic production of hydrogen are reducing the capital cost of the electrolyzer—especially lower cost anodes and cathodes—and improving the energy efficiency.

Renewable Electrolysis

Electricity can be generated using renewable resources such as wind, solar, geothermal, or hydro-electric power. Hydrogen production via "renewable electrolysis" offers opportunities for synergy with variable power generation. For example, though the cost of wind power has continued to drop, the inherent variability of wind impedes its widespread use. Co-production of hydrogen and electric power could be integrated at a wind farm, allowing flexibility and the ability to shift production to match the availability of resources with the system's operational needs and market factors.

Nuclear Hydrogen Activities – Harnessing Heat to Produce Hydrogen From Water

The U.S. Department of Energy is working with partners to demonstrate the commercial-scale production of hydrogen from water using heat from a nuclear energy system. In addition to the emission-free electricity produced by nuclear reactors, some advanced nuclear reactor designs operate at very high temperatures, making them well-suited to drive highly efficient thermochemical and electrolytic hydrogen production processes. Major program elements include the candidate production processes and high temperature interface technologies involved in coupling a thermochemical or high temperature electrolysis plant to an advanced high-temperature reactor. For more information, please visit www.ne.doe.gov/hydrogen/hydrogen.html.

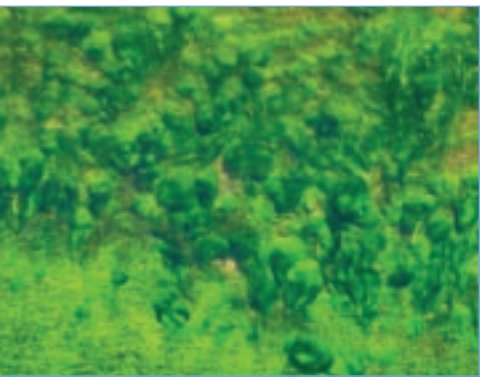
Nuclear High-Temperature Electrolysis

In high-temperature electrolysis, heat from a nuclear reactor generates high-temperature steam that is electrolyzed to produce hydrogen and oxygen. The higher temperature reduces the amount of electricity required to split the water molecules. Because heat is a byproduct of nuclear electricity generation and no greenhouse gases are emitted in the process, nuclear high-temperature electrolysis can be an efficient method for producing hydrogen from water.

Photolytic Processes

Photolytic processes use light energy to split water into hydrogen and oxygen. These processes are in the very early stages of research but offer long-term potential for sustainable hydrogen production with low environmental impact. Photolytic processes include:

- Photobiological Water Splitting
- Photoelectrochemical Water Splitting



Scientists are researching ways in which green algae can produce hydrogen via photobiological processes.

Photobiological Water Splitting

In this process, hydrogen is produced from water using sunlight and specialized microorganisms including green algae and cyanobacteria. Just as plants produce oxygen during photosynthesis, these microbes consume water and produce hydrogen as a byproduct of their natural metabolic processes. Photobiological water splitting is a long-term technology. Currently, the microbes split water at rates too low to be used for efficient commercial hydrogen production. Scientists are researching ways to modify the microorganisms as well as to identify other naturally occurring microbes that can produce hydrogen at higher rates.

Photoelectrochemical Water Splitting

In this process, hydrogen is produced from water using sunlight and photoelectrochemical materials—specialized semiconductors that absorb sunlight and use the light energy to dissociate water molecules into hydrogen and oxygen. Currently, there are materials that can split water efficiently and others that are durable, but to produce hydrogen for widespread use, a material must be developed that is both efficient and durable.

Delivery

The widespread use of hydrogen will require a national infrastructure for transportation, distribution, and delivery.

Basics

Infrastructure is required to move hydrogen from the point of production to the dispenser at a refueling station or stationary power site. Options and trade-offs for hydrogen delivery from central, semi-central, and distributed production facilities to the point of use are complex—the choice of a hydrogen production strategy greatly affects the cost and method of delivery. For example, larger, centralized facilities can produce hydrogen at relatively low costs due to economies of scale, but the delivery costs are high because the point of use is farther away. In comparison, distributed production facilities have relatively low delivery costs, but the hydrogen production costs are likely to be higher—lower volume production means higher equipment costs on a per-unit-of-hydrogen basis.

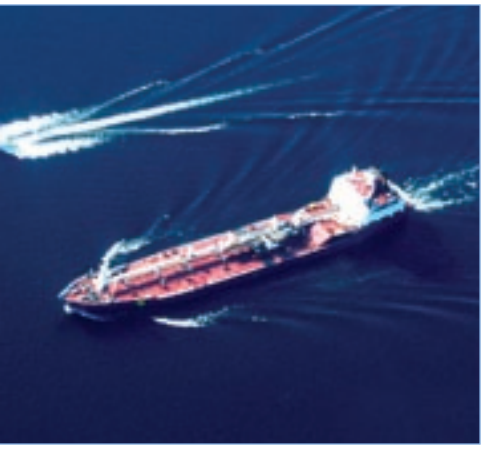
Infrastructure is the term used to describe the pipelines, trucks, railcars, ships, and barges that deliver fuel, as well as the facilities and equipment needed to load and unload them.

Hydrogen has been used in industrial applications for decades, but today's delivery infrastructure and technology are not sufficient to support widespread consumer use of hydrogen. Because hydrogen has a relatively low volumetric energy density, its transportation, storage, and final delivery to the point of use comprise a significant cost and results in some of the energy inefficiencies associated with using it as an energy carrier. Key challenges to hydrogen delivery include reducing delivery cost, increasing energy efficiency, maintaining hydrogen purity, and minimizing hydrogen leakage. Further research is needed to analyze the trade-offs between hydrogen production and delivery options taken together as a system. Building a national hydrogen delivery infrastructure is a big challenge. It will take time to develop and will likely include combinations of various technologies. Delivery infrastructure needs and resources will vary by region and type of market (e.g., urban, interstate, or rural). Infrastructure options will also evolve as the demand for hydrogen grows and as delivery technologies develop and improve.

Liquid hydrogen is delivered to the California Fuel Cell Partnership hydrogen fueling station in Sacramento. Photo courtesy of CaFCP

Pipelines

There are approximately 700 miles of hydrogen pipelines operating in the United States (compared to more than one million miles of natural gas pipelines). Owned by merchant hydrogen producers, these pipelines are located where large hydrogen refineries and chemical plants are concentrated (for example, in the Gulf Coast region).



Hydrogen is delivered by barge, rail, and truck.

Transporting gaseous hydrogen via existing pipelines is currently the lowest-cost option for delivering large volumes of hydrogen, but the high initial capital cost of new pipeline construction constitutes a major barrier to expanding hydrogen pipeline delivery infrastructure. Research is focused on overcoming technical concerns related to pipeline transmission, including the potential for hydrogen to embrittle the pipeline steel and welds; the need to control hydrogen permeation and leaks; and the need for lower cost, more reliable, and more durable hydrogen compression technology.

One possibility for rapidly expanding the hydrogen delivery infrastructure is to adapt part of the natural gas delivery infrastructure. Converting natural gas pipelines to carry a blend of natural gas and hydrogen (up to about 20% hydrogen) may require only modest modifications to the pipeline; converting existing natural gas pipelines to deliver pure hydrogen may require more substantial modifications.

Another possible delivery process involves producing a liquid hydrogen "carrier," such as ethanol, at a central location, pumping it through pipelines to distributed refueling stations, and processing it at the station to produce hydrogen for dispensing. Liquid hydrogen carriers offer the potential of using existing pipeline and truck infrastructure technology for hydrogen transport.

Trucks, Railcars, Ships, and Barges

Trucks, railcars, ships, and barges can be used to deliver compressed hydrogen gas, cryogenic liquid hydrogen, or novel hydrogen liquid or solid carriers.

Today, compressed hydrogen can be shipped in tube trailers at pressures up to 3,000 psi (about 200 bar). This method is expensive, however, and it is cost-prohibitive for distances greater than about 100 miles. Researchers are investigating technology that might permit tube trailers to operate at higher pressures (up to 10,000 psi), which would reduce costs and extend the utility of this delivery option.

Currently, for longer distances, hydrogen is transported as a liquid in super-insulated, cryogenic tank trucks. Gaseous hydrogen is liquefied (cooled to below -253°C/-423°F) and stored at the liquefaction plant in large, insulated tanks. The liquid hydrogen is then dispensed to delivery trucks and transported to distribution sites, where it is vaporized and compressed to a high-pressure gaseous product for dispensing. Over long distances, trucking liquid hydrogen is more economical than trucking gaseous hydrogen because a liquid tanker truck can

hold a much larger mass of hydrogen than a gaseous tube trailer. But it takes energy to liquefy hydrogen—using today's technology, liquefaction consumes more than 30% of the energy content of the hydrogen and is costly. In addition, some amount of stored liquid hydrogen will be lost through evaporation, or "boil-off," especially when using small tanks with large surface-to-volume ratios. Research to improve liquefaction technology, as well as improved economies of scale, could help lower costs (today's liquefaction units are small to meet minimal demand). Larger liquefaction plants located near hydrogen production facilities would also help reduce the cost of the process.

In the future, hydrogen could be transported as a cryogenic liquid in rail cars, barges, or ships that can carry large tanks—and the larger the tank, the less hydrogen lost to evaporation. Marine vessels carrying hydrogen would be similar to tankers that currently carry liquefied natural gas, although better insulation would be required to keep the hydrogen liquefied (and to minimize evaporation losses) over long transport distances.

Additional research and analysis are needed to investigate novel liquid or solid hydrogen carriers that can store hydrogen in some other chemical state, rather than as free molecules. Potential carriers include ammonia, metal hydrides (see p.23), and carbon or other nanostructures.

Bulk Storage

A national hydrogen infrastructure may require geologic (underground) bulk storage to handle variations in demand throughout the year. In some regions, naturally occurring geologic formations like salt caverns and aquifer structures might be used. In other regions, specially engineered rock caverns are a possibility. Geologic bulk storage is common practice in the natural gas industry. The properties of hydrogen are different from natural gas, however (hydrogen molecules are much smaller than natural gas, for example). Further research is needed to evaluate the suitability of geologic storage for hydrogen and to ensure proper engineering of the storage site and hydrogen containment.

Interface with Vehicles

Technologies for storing hydrogen on-board vehicles affect the design and selection of a hydrogen delivery system and infrastructure. To maximize overall energy efficiency, designs must avoid unnecessary energy-intensive steps, such as liquefaction and compression, and deliver pressurized hydrogen gas directly from a dispenser at a refueling station.

Refueling a hydrogen vehicle is similar to refueling a natural gas vehicle. Photo courtesy of Daimler Chrysler

Refueling a vehicle with hydrogen is very similar to refueling a vehicle with compressed natural gas (CNG). Like CNG refueling systems, hydrogen vehicle refueling is a closed-loop system. The dispensing nozzle must "lock on" to the vehicle receptacle before any hydrogen can flow. Hydrogen dispensers are also equipped with safety devices including breakaway hoses, leak detection sensors, and grounding mechanisms. These controls provide additional safety measures in the case of human error, such as a driver trying to drive away while the dispenser is still connected to the vehicle. In today's demonstration programs, most hydrogen vehicles are refueled by trained personnel. This will become less common as the number of demonstrations increases and hydrogen vehicles become available to consumers.

Storage

Compact on-board hydrogen storage systems for light-duty vehicles are critical to the widespread use of hydrogen as an energy carrier. Vehicles must carry enough hydrogen to travel more than 300 miles between refuelings, without compromising vehicle cargo capacity or passenger space.

Basics

Hydrogen has the highest energy content per unit weight—but not per unit volume—of any fuel. Its relatively low volumetric energy content poses a significant challenge for storage.

Under most scenarios, stationary hydrogen storage systems have less stringent requirements than vehicular storage. Stationary systems can occupy a relatively large area, operate at higher temperatures, and compensate for slower refueling times with larger storage systems. Storage systems for vehicles, however, face much tougher challenges. They must operate within the size and weight constraints of the vehicle, enable a driving range of more than 300 miles (generally regarded as the minimum for widespread driver acceptance based on the performance of today's gasoline vehicles), and refuel at near room temperature and at a rate fast enough to meet drivers' requirements (generally only a few minutes). Because of these challenges, hydrogen storage research is focused primarily on vehicular applications.

Many consider on-board hydrogen storage to be the greatest technical challenge to widespread commercialization of hydrogen fuel cell vehicles. Current approaches (see below) include compressed hydrogen gas tanks, liquid hydrogen tanks, and hydrogen storage in materials. Researchers in government, industry, and academia are working toward technical targets specific to the entire storage system—which includes the tank, storage media, valves, regulators, piping, added cooling capacity, and other "balance-of-plant components." Research is focused on improving the weight, volume (gravimetric and volumetric capacity), and cost of current hydrogen storage systems, as well as identifying and developing new technologies that can achieve similar performance, and at a similar cost, as gasoline fuel storage systems.

How Much is a Kilogram of Hydrogen?

One kilogram of hydrogen contains approximately the same energy as one gallon of gasoline. To achieve a 300-mile range in the full spectrum of light-duty vehicles, approximately 5-13 kilograms (kg) of hydrogen must be stored on-board. (This range depends primarily on vehicle weight and fuel economy).

Compressed Gas

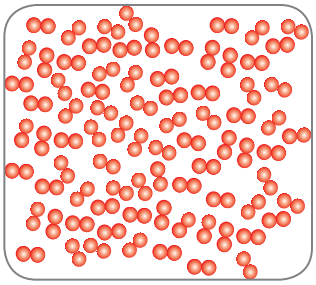
Compressing any gas allows more compact storage. Hydrogen used by industry today is usually stored at pressures up to about 2,000 pounds per square inch

Hydrogen can be stored as a gas or liquid

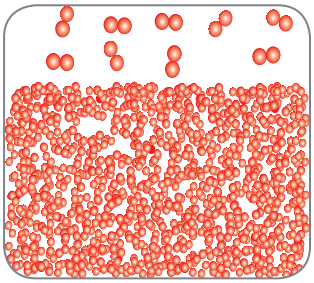
Hydrogen molecule (H_2) =

Hydrogen atom (H) =

Compressed Gas



Cryogenic Liquid



(psi) in steel cylinders or tubes on trailers. The tanks used on demonstration hydrogen vehicles, however, must carry more hydrogen in less space and require compressed gas storage at higher pressures.

Lighter weight composite materials that hold hydrogen at pressures higher than 2,000 psi are being developed to reduce the weight of storage systems. These composite tanks have an inner liner, such as a polymer, that is impermeable to hydrogen. The liner is surrounded by a fiber shell that provides strength for high-pressure load-bearing capacity and an outer shell that provides more impact resistance. Composite tanks for hydrogen gas at pressures of 5,000 psi (~350 bar) and even 10,000 psi (~700 bar) are used in prototype vehicles, but they are still much larger and heavier than what is ultimately desired for light-duty vehicles.

Two approaches are being pursued to increase the gravimetric and volumetric storage capacities of compressed hydrogen gas tanks. The first approach involves cryo-compressed tanks and is based on the principle that gases, such as hydrogen, become denser as temperature decreases. By cooling gaseous hydrogen (for example, at 5,000 psi) from room temperature to -196ºC (or -321ºF, the temperature of liquid nitrogen), its volume will decrease by a factor of about three. This reduction is somewhat offset by the increased volume of insulation and other system components.

The term cryo-compressed also refers to a hybrid tank concept combining high-pressure gaseous and cryogenic storage. Insulated hybrid pressure vessels are relatively lightweight and can be refueled with either liquid hydrogen or high pressure hydrogen gas. High pressure cryogenic tanks have lower evaporative hydrogen losses than conventional cryogenic hydrogen tanks.

A second approach involves developing conformable tanks as an alternative to cylindrical tanks, which do not package well in light-duty vehicles. The gasoline tanks in today's vehicles are highly conformable and take advantage of available space. The walls of non-cylindrical high-pressure tanks, however, typically have to be thicker and heavier to contain pressure. New concepts and geometries are being evaluated to develop structures that are capable of safely containing the high pressures while more efficiently fitting into an automotive space. In general, a key area of research required for high pressure hydrogen tanks, including conformable tanks, is cost reduction.

Cryogenic Liquid

Liquefied hydrogen is denser than gaseous hydrogen and therefore has a higher energy content on a per-unit-volume basis. To convert gaseous hydrogen to

a liquid, it must be cooled to -253°C (-423°F) and must be stored in insulated pressure vessels to minimize hydrogen loss through evaporation, or boil-off. Hydrogen vapor that results from boil-off is released from the tank through safety valves and vented into the atmosphere. Liquid hydrogen tanks can store more hydrogen in a given volume than compressed gas tanks, but there are trade-offs. The energy requirement for hydrogen liquefaction is high, and boil-off must be minimized (or eliminated) for the system to be cost-effective and energy efficient.

Storage in Materials

Hydrogen also can be stored within the structure or on the surface of certain materials, as well as in the form of chemical compounds that undergo a reaction to release hydrogen.

Hydrogen atoms or molecules are tightly bound with other elements in a compound (or storage material), which may make it possible to store larger quantities in smaller volumes at low pressure and near room temperature. Storing hydrogen in materials can occur via absorption, in which hydrogen is absorbed directly into the storage media; adsorption, in which hydrogen is stored on the surface of storage media; or chemical reaction. Materials used for hydrogen storage can employ one or more of these mechanisms and may be grouped into four general categories:

- Metal Hydrides
- Carbon-based Materials or High Surface Area Sorbents
- Chemical Hydrogen Storage
- New Materials and Processes

Metal Hydrides

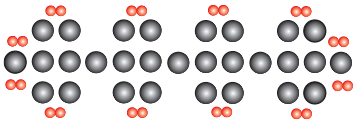
Very broadly, a hydride is a chemical compound containing hydrogen and at least one other element (e.g., nickel). Metal hydrides can store hydrogen via absorption.

Metal compounds with simple crystal structures form simple metal hydrides through absorption. Hydrogen, dissociated into hydrogen atoms, can be incorporated into the crystal lattice framework of atoms in the metal compound. For example, hydrogen atoms fit in the gaps between the lanthanum and nickel atoms in lanthanum nickel ($LaNi_5$) to make lanthanum nickel hydride (a metal hydride, $LaNi_5H_6$). By adding heat, the hydrogen atoms will break loose from the crystal lattice and be released—a process called desorption.

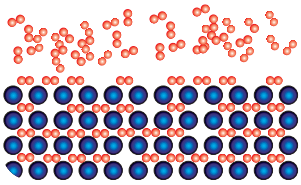
Hydrogen in tanks on the surface of solids *(by adsorption)* or within solids *(by absorption)*

In **adsorption (A)**, hydrogen can be stored on the surface of a material either as hydrogen molecules (H_2) or hydrogen atoms (H). In **absorption (B/C)**, hydrogen molecules dissociate into hydrogen atoms that are incorporated into the solid lattice framework – this method may make it possible to store larger quantities of hydrogen in smaller volumes at low pressure and at temperatures close to room temperature. Finally, hydrogen can be strongly bound within molecular structures, as chemical compounds containing hydrogen atoms **(D)**.

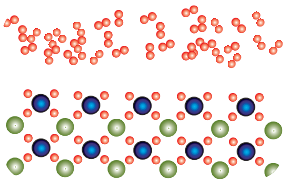
A) Surface Adsorption



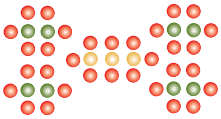
B) Intermetallic Hydride



C) Complex Hydride



D) Chemical Hydride



Solid Metal Hydride with Carbon Fiber Storage Vessel. Photo courtesy of ECD Ovonics

Advanced metal hydrides are under development with potential to store more hydrogen than conventional or simple metal hydrides. The reactions are reversible, and heat or energy is released when hydrogen reacts to form the metal hydride. Adding heat to the hydride reverses the reaction and releases hydrogen. Sodium alanate ($NaAlH_4$), which can store and release hydrogen, is an example of a complex metal hydride.

Metal hydride storage materials are primarily in powder form to increase the surface area available for absorption. They offer great promise, but additional research is required to overcome several critical challenges including low hydrogen capacity, slow uptake and release kinetics, and high cost. Thermal management during refueling is also a challenge, as the significant amount of heat released must be safely rejected or captured for use.

Key Requirements for Hydrogen Storage On-Board a Vehicle

High gravimetric and volumetric densities
(light in weight and conservative in space)

Fast kinetics
(quick uptake and release)

Appropriate thermodynamics
(e.g., favorable heats of hydrogen absorption and desorption)

Long cycle life for hydrogen charging and release, durability, and tolerance to contaminants

Low system cost, as well as total life-cycle cost

Minimal energy requirements and environmental impact

Safety is an inherent assumption and requirement

Carbon-Based Materials or High Surface Area Sorbents

Carbon-based materials store hydrogen via adsorption, in which hydrogen molecules or atoms attach to the surface of the carbon nanostructure. This category of materials, which can exist as solids and potentially as powders or pellets, includes a range of carbon-based materials including nanotubes and nanofibers, aerogels, and fullerenes (cage-like spheres).

Carbon-based materials are still in the early stages of investigation. The focus of research is metal-carbon hybrid systems. Scientists are working to better understand the mechanisms and storage capabilities of these materials and improve the reproducibility of their measured performance, in order to estimate the potential to store and release adequate amounts of hydrogen under practical operating conditions.

Metal organic frameworks (MOFs) are new, cage-like, highly porous materials composed of metal atoms as well as organic linkers. Recent studies have shown that certain MOFs can store hydrogen by adsorption at low temperatures. A key focus area for future research is to tailor materials so hydrogen can be stored within them at room temperature.

Chemical Hydrogen Storage

"Chemical hydrogen storage" describes technologies in which hydrogen is stored and released through chemical reactions. Common reactions involve reacting chemical hydrides with water or alcohols. Chemical hydrides can exist as liquids or solids, and the hydrogen atoms can be bonded to metal or non-metal species. The chemical reactions needed to release the hydrogen produce a byproduct that can be regenerated or "recharged" off-board the vehicle, usually by adding

heat, hydrogen, and perhaps other reactants. Chemical hydride storage systems require management of the heat produced in the hydrogen-releasing reaction, as well as removal of the byproducts, or "spent fuel," created when the hydrogen is released. Hydrolysis reactions, hydrogenation/dehydrogenation reactions, and several new chemical approaches are under investigation.

Hydrolysis Reactions

Hydrolysis reactions involve the oxidation reaction of chemical hydrides with water to produce hydrogen. The reaction of sodium borohydride ($NaBH_4$) is among the most well-studied hydrolysis reactions to date. In this system, sodium borohydride and water react in the presence of a catalyst to produce hydrogen as needed, along with sodium borate as the byproduct. The sodium borate can be converted back to sodium borohydride using heat, water, and hydrogen in an off-board regeneration process. Regeneration efficiency and energy requirements are issues still to be resolved.

Another process that functions by hydrolysis is the reaction of magnesium hydride with water to form magnesium hydroxide and hydrogen. Similar to the sodium borohydride approach, water must be carried on-board the vehicle in addition to a slurry, and the magnesium hydroxide must be regenerated off-board.

Hydrogenation/Dehydrogenation Reactions

Hydrogenation describes the process of "bonding" or "adding" hydrogen to a compound; dehydrogenation describes the removal of hydrogen. Hydrogenation/dehydrogenation reactions do not require water as a reactant and instead use catalysts and heat to release hydrogen. For example, when exposed to heat in the presence of a catalyst, decalin ($C_{10}H_{18}$) releases hydrogen and leaves the byproduct naphthalene ($C_{10}H_8$) at roughly 200ºC. Research is underway to identify chemical hydrides that dehydrogenate at lower temperatures.

New Chemical Approaches

Other new chemical approaches are being evaluated to identify alternatives with higher hydrogen storage capacities, such as ammonia borane (NH_3BH_3). Another example is the concept of reacting lightweight metal hydrides, such as LiH, NaH, and MgH_2, with methanol and ethanol—a process called alcoholysis. Alcoholysis reactions could provide controlled and convenient hydrogen production (and storage) at room temperature and below. A disadvantage, however, is that the alcohol also needs to be carried on-board.

Among the challenges to chemical hydrogen storage on-board vehicles are waste removal and refueling—byproducts must be purged and "fresh" chemical hydrides and other reactants must be put back into the vehicle. Developing chemical hydride regeneration systems at refueling stations or transporting the byproducts to a central regeneration site will also be a challenge. Although the material's hydrogen storage capacity can be high and refueling with a liquid is attractive, issues related to regeneration energy requirements, cost, and life-cycle impacts are key technical barriers currently under research.

New Materials and Processes

Scientists are also exploring several new materials that may have potential for reversible hydrogen storage, including conducting polymers. Initial studies have indicated that a significant amount of hydrogen can be incorporated into conducting polymer structures. These and other new concepts are yet to be explored for their viability to vehicular hydrogen storage applications.

Application and Use

Hydrogen can be converted into usable energy through fuel cells or by combustion in turbines and engines. Fuel cells now in development will not only provide a new way to produce power, but will also significantly improve energy conversion efficiency, especially in transportation applications.

Overview

Hydrogen is a versatile energy carrier that can be used to power nearly every end-use energy need. The fuel cell—an energy conversion device that can efficiently convert and use the power of hydrogen—is key to making it happen. Stationary fuel cells can be used for backup power, power for remote locations, distributed power generation, and cogeneration (in which excess heat released during electricity generation is used for other applications). Fuel cells can power almost any portable application that uses batteries, from hand-held devices to portable generators. Fuel cells can also provide primary and auxiliary power for transportation, including personal vehicles, trucks, buses, and marine vessels.

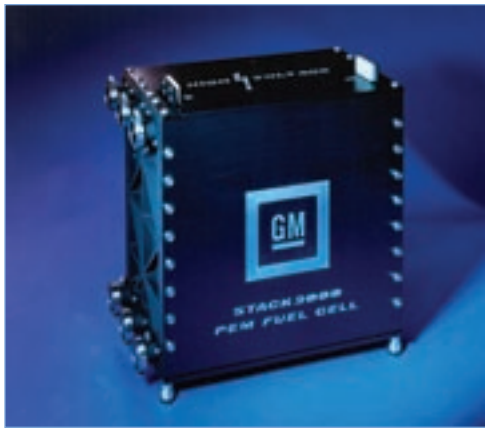


Photo courtesy of General Motors

Why Fuel Cells?

Fuel cells directly convert the chemical energy in hydrogen to electricity and heat. Inside a fuel cell, hydrogen electrochemically combines with oxygen from the air to create electricity, with pure water and potentially useful heat as the only byproducts.

Hydrogen-powered fuel cells are not only pollution-free, but also can have two to three times the efficiency of traditional internal combustion technologies. A conventional combustion-based power plant typically generates electricity at efficiencies of 33 to 35%, while fuel cell systems can generate electricity at efficiencies of up to 60% (and even higher with cogeneration). In normal driving, the gasoline engine in a conventional car is less than 20% efficient in converting the chemical energy in gasoline into power that moves the vehicle. Hydrogen fuel cell vehicles, which use electric motors, are much more energy efficient and use up to 60% of the fuel's energy. This corresponds to more than a 50% reduction in fuel consumption, compared to a conventional vehicle with a gasoline internal combustion engine.[6] In addition, fuel cells operate quietly, have fewer moving parts, and are well suited to a variety of applications.

6) U.S. Department of Energy, Energy Information Administration, Supplemental Tables to the Annual Energy Outlook 2005, "Transportation Demand Sector," Table 47, (2005), 45.

Fuel Cell Basics

A single fuel cell consists of an electrolyte sandwiched between two electrodes, an anode and a cathode. The power produced by a fuel cell depends on several factors, including the fuel cell type, size, temperature at which it operates, and pressure at which gases are supplied to the cell. A single fuel cell produces 1 volt of electricity or less. To generate more electricity, individual fuel cells are combined in a series to form a stack. (The term "fuel cell" is often used to refer to the entire stack, as well as to the individual cell). Depending on the application, a fuel cell stack may contain hundreds of individual cells layered together. This "scalability" makes fuel cells ideal for a wide variety of applications, from laptop computers (50-100 Watts) to homes (1-5kW), vehicles (50-125 kW), and central power generation (1-200 MW or more).

Types of Fuel Cells

In general, all fuel cells have the same basic configuration—an electrolyte sandwiched between two electrodes—but there are different types of fuel cells, classified primarily by the kind of electrolyte used. The electrolyte determines the kind of chemical reactions that take place in the fuel cell, the operating temperature range, and other factors that affect the applications for which the fuel cell is most suitable, as well as its advantages and limitations.

Figure 4. Fuel Cell Comparison Chart

Fuel Cell Type	Common Electrolyte	Operating Temp.	System Output	Electrical Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)*	Solid organic polymer poly-perfluorosulfonic acid	50 – 100°C 122 – 212°F	<1kW - 250kW	53-58% (transportation) 25-35% (stationary)	• Back-up power • Portable power • Small distributed generation • Transportation	• Solid electrolyte reduces corrosion and electrolyte management problems • Low temperature • Quick start-up	• Requires expensive catalysts • High sensitivity to fuel impurities • Low temperature waste heat • Waste heat temperature not suitable for combined heat and power (CHP)
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90 – 100°C 194 – 212°F	10kW - 100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, higher performance	• Expensive removal of CO_2 from fuel and air streams required (CO_2 degrades the electrolyte)
Phospohoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	150 – 200°C 302 – 392°F	50kW - 1MW (250kW module typical)	32-38%	• Distributed generation	• Higher overall efficiency with CHP • Increased tolerance to impurities in hydrogen	• Requires expensive platinum catalysts • Low current and power • Large size/weight
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600 – 700°C 1112 – 1292°F	<1kW - 1MW (250kW module typical)	45-47%	• Electric utility • Large distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature speeds corrosion and breakdown of cell components • Complex electrolyte management • Slow start-up
Solid Oxide (SOFC)	Solid zirconium oxide to which a small amount of yttria is added	650 – 1000°C 1202 – 1832°F	5kW - 3MW	35-43%	• Auxiliary power • Electric utility • Large distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte reduces electrolyte management problems • Suitable for CHP • Hybrid/GT cycle	• High temperature enhances corrosion and breakdown of cell components • Slow start-up • Brittleness of ceramic electrolyte with thermal cycling

**Direct Methanol Fuel Cells (DMFC) are a subset of PEM typically used for small portable power applications with a size range of about a subwatt to 100W and operating at 60-90°C.*

PEM Fuel Cells

Polymer electrolyte membrane fuel cells (also called proton exchange membrane or "PEM" fuel cells) use a solid polymer as the electrolyte and porous carbon electrodes containing a platinum catalyst. PEM fuel cells require hydrogen, oxygen, and water to operate. They are typically fueled with hydrogen supplied from storage tanks and oxygen drawn from the air.

Compared to other kinds of fuel cells, PEM fuel cells operate at relatively low temperatures, around 80°C, which allows them to start quickly (less warm-up time is needed) and results in less wear on system components. For these and other reasons, including the ability to produce sufficient power within the size and weight constraints of a vehicle, PEM fuel cells are widely regarded as the most promising fuel cells for light-duty transportation applications.

How Do They Work?

Like all fuel cells, a single PEM fuel cell consists of two electrodes separated by a membrane. The polymer electrolyte membrane (PEM) is a solid organic compound, typically the consistency of plastic wrap and thinner than a single sheet of paper.

On one side of the cell, hydrogen gas flows through channels to the electrically negative electrode, or anode. The anode, which is porous so that hydrogen can pass through it, is composed of platinum (catalyst) particles uniformly supported on carbon particles and surrounded by a thin layer of proton-conducting ionomer. Hydrogen fuel on the anode side moves through the electrode and encounters the platinum catalyst, which causes the hydrogen molecules to separate into protons and electrons. This is an oxidation reaction (see sidebar). The PEM—the key to this fuel cell technology—allows only the protons to pass through it. While the protons are conducted through the ionomer and PEM to the other side of the cell, the stream of negatively-charged electrons follows an external circuit to the cathode. This flow of electrons through the external circuit is electricity that can be used to do work, such as power a motor.

On the other side of the cell, oxygen gas, typically drawn from ambient air, flows to the electrically positive electrode, or cathode. Like the anode, the cathode is made of platinum particles uniformly supported on carbon particles —it is porous and oxygen can move through it. A reduction reaction, involving the gaining of electrons, takes place at the cathode (see sidebar). When the electrons (which have traveled through the external circuit) return from doing work, they react with oxygen and the hydrogen protons (which have moved

Chemical Reactions

All electrochemical reactions, including those that take place in a fuel cell, consist of two separate reactions: an oxidation half-reaction at the anode, and a reduction half-reaction at the cathode. Oxidation involves a loss of electrons by one molecule, and reduction involves a gain of electrons by another. Both oxidation and reduction occur simultaneously and in equivalent amounts during any reaction involving either process.

Oxidation half reaction

$2H_2 \rightarrow 4H^+ + 4e^-$

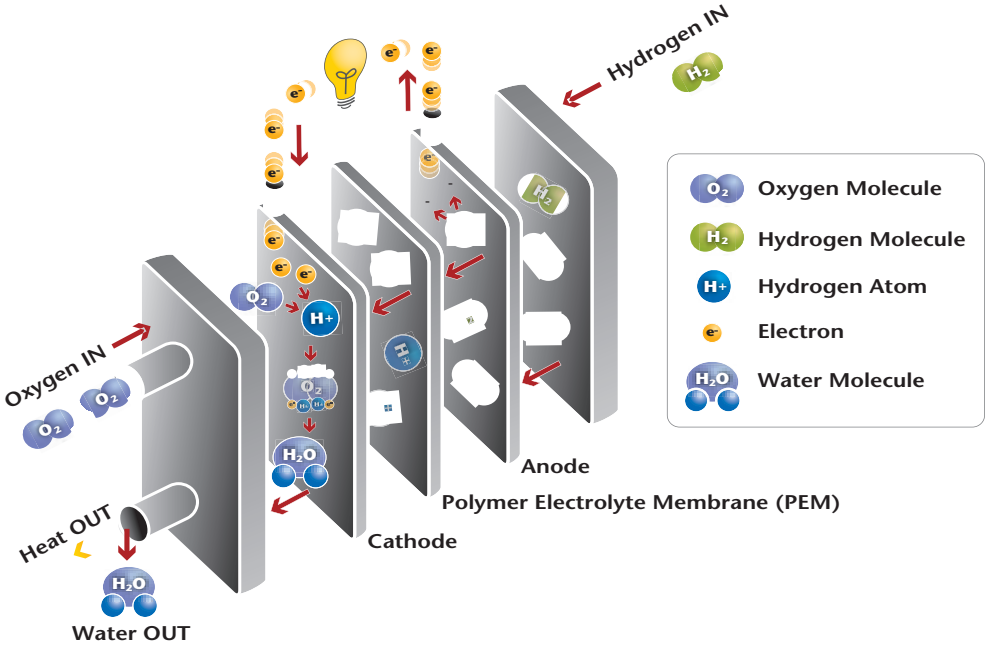
Reduction half reaction

$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Fuel cell reaction

$2H_2 + O_2 \rightarrow 2H_2O$

through the PEM) at the cathode to form water. Most of the water is collected and reused within the system, but a small amount is released in the exhaust as water vapor (how much water?...see sidebar). Heat is generated from this union (an exothermic reaction) and from the frictional resistance of ion transfer through the membrane. This thermal energy can be used outside the fuel cell.



A Closer Look at the Details

Catalyst

Platinum-group metals are critical to catalyzing reactions in a PEM fuel cell. The fuel cells typically use a catalyst made of platinum powder very thinly coated onto carbon paper or cloth. The catalyst is rough and porous to expose the maximum surface area of the platinum to the hydrogen or oxygen. The use of platinum adds to the cost of the system, however. Platinum catalysts are also sensitive to "poisoning" by contaminants such as carbon monoxide or sulfur—molecules that can bind to the platinum and prevent it from reacting with hydrogen at the anode, for example. This sensitivity requires high purity hydrogen or additional purification steps, which can add to the cost.

Membrane Electrode Assembly and Bipolar Plates

The electrodes, catalyst, PEM, and gas diffusion layers (GDLs) together form the membrane electrode assembly, or MEA. The GDLs—one next to the anode, the other next to the cathode—are usually made of a porous carbon paper

Fuel Cells Generate Electricity, Heat, and Water – But How Much Water?

Hydrogen fuel cell vehicles (FCVs) emit approximately the same amount of water per mile as vehicles using gasoline-powered internal combustion engines (ICEs).

How far will one gallon go and how much water will it produce?

Gasoline ICE Vehicle
➔ 25 miles per gallon (mpg)

1 gallon gasoline = 2.7 kg of fuel
(may be represented approximately as CH_2)

$CH_2 + 3/2\ O_2 \rightarrow CO_2 + H_2O$ *(water)*

2.7 kg + 9.3 kg ➔ 8.5 kg + 3.5 kg

3.5 kg water/25 miles = 0.14 kg water/mi

Hydrogen FCV
➔ 60 miles per gallon gasoline equivalent (mpgge)

1 gallon of gasoline equivalent of hydrogen very nearly equals 1.0 kg H_2

$H_2 + 1/2\ O_2 \rightarrow H_2O$ (water)

1.0 kg + 8.0 kg ➔ 9.0 kg

9.0 kg water/60 miles = 0.15 kg water/mi

Note: The calculations above assume that a gasoline ICE vehicle averages 25 miles per gallon and a hydrogen FCV averages 60 mpgge of hydrogen. (One gge of hydrogen has the same energy content as a gallon of gasoline [in terms of their lower heating values] and is approximately equal to one kg of hydrogen.) The fuel cell is a valuable system because it is 2.4 times as energy efficient as traditional combustion systems, achieving 2.4 times as many miles per gallon of gasoline equivalent. Source: Argonne National Laboratory

or cloth about as thick as 4-12 sheets of paper. The layers must be made of a material like carbon that can conduct electrons leaving the anode and entering the cathode. Its porous nature helps ensure effective diffusion of both hydrogen and oxygen to the entire surface area of the catalyst layers on the MEA.

The GDLs also help manage water in the fuel cell. The membrane must remain moist to operate effectively; the diffusion material allows the right amount of water vapor to reach the MEA and keep the membrane humidified. The GDL is often coated with Teflon™ to ensure that some pores in the carbon cloth (or carbon paper) do not clog with water.

The outer-most layer of each fuel cell, pressed against the surface of each GDL, is the bipolar plate. Channels formed into the face of the plate provide a "flow field," carrying the hydrogen and oxygen gases to where they are used in the fuel cell. Bipolar plates, which can be carbon composites or metal, also act as current collectors. Electrons produced by the oxidation of hydrogen must (1) be conducted through the anode and GDL, along the length of the fuel cell stack, and through the plate before they can exit the cell; (2) travel through an external circuit; and (3) re-enter the cell at the cathode.

Challenges

Reducing cost and improving durability are the two most significant challenges to fuel cell commercialization. Fuel cell systems must be cost-competitive with, and perform as well or better than, traditional power technologies over the life of the system.

Materials and manufacturing costs are currently too high for catalysts, bipolar plates, membranes, and gas diffusion layers. Today, the costs for automotive internal combustion engine power plants are about $25-$35/kW; for transportation applications, a fuel cell system needs to cost approximately $30/kW (at volumes of 500,000 units per year) for the technology to be competitive. For stationary systems, the acceptable price point is considerably higher – $400-$750/kW is considered necessary for widespread commercialization ($1,000/kW for initial "early adopter" applications). (Data current as of March 2007. For the most up-to-date numbers, please refer to the Hydrogen Program Multi-Year Research, Development, and Demonstration Plan www.eere.energy.gov/hydrogenandfuelcells/mypp/)

In addition to cost-related challenges, adequate fuel cell system durability has not been established. To be considered ready for widespread use in transportation, fuel cell power systems must demonstrate durability and reliability similar

Fuel Cells – Specialty Applications

Fuel cells for certain specialty or niche applications are commercially available today. Fuel cells used in non-transportation applications can help develop manufacturing capabilities and a supplier base while transportation fuel cells are under development. These applications include power generation:

- In remote locations where the electricity grid is not accessible
- Where portable power is needed – at construction sites, instead of generators, and campgrounds, for flexible and moveable power
- For fork lifts inside warehouses and other indoor environments

- For smaller applications, such as laptops and cell phones, that typically use batteries

- For auxiliary power applications, such as powering the cabin of an 18-wheele while the engine is not running

- For instant emergency backup power to supplement the grid, where constant power is required, at places such as banks, hospitals and telecommunications towers

Hybrid electric and fuel cell vehicles share technologies

Technologies developed for today's gasoline hybrid-electric vehicles can help accelerate the development of fuel cell vehicles. For example, hybrid vehicles use electric motors for propulsion and require advanced drive control electronics and software, much like fuel cell vehicles. Further research will improve the affordability and performance of hybrid technology available to consumers in the near-term and also advance fuel cell technology development for the long-term.

Photo courtesy of CaFCP

to today's automotive engines. Specifically, this means a 5,000-hour operating lifespan (the equivalent of 150,000 miles) and the ability to perform over the full range of dynamic vehicle operating conditions, including temperatures and climates (various degrees of humidity and ambient temperatures of -40°C to +40°C, for example). Requirements for stationary applications are slightly different because the associated duty cycles are less demanding. To compete with other distributed power generation systems, stationary fuel cells must demonstrate more than 40,000 hours (nearly 5 years) of reliable operation in ambient temperatures of -40°C to +50°C to be considered ready for the mainstream market.

For both transportation and stationary applications, research is needed to identify and develop new materials to reduce the cost and extend the life of fuel cell stack components. Low cost, high volume manufacturing processes will also help to make fuel cell systems competitive with traditional technologies.

The Solid State Energy Conversion Alliance – Focusing on Solid Oxide Fuel Cell R&D

The Solid State Energy Conversion Alliance (SECA) is a joint government-industry effort led by the U.S. Department of Energy to reduce cost and achieve technology breakthroughs in solid oxide fuel cells (SOFCs), primarily used for electric utility and stationary applications. SECA aims to develop 3-10kW SOFCs by 2010 that can be mass-produced in modular form (the technology will then be scaled-up to serve as building blocks for FutureGen-type plants – for more on FutureGen, see page 9). SECA fuel cells will be used for a wide range of applications, including auxiliary power and combined heat and power. For detailed program goals, requirements, milestones, and activities, please visit www.seca.doe.gov.

Frequently Asked Question: *When Can I Buy One?*

The answer to that question depends on what you want to buy.

The widespread use of hydrogen as an energy carrier requires a combination of technological breakthroughs, market acceptance, and large investments in a national hydrogen energy infrastructure. This evolutionary process will happen over decades, wherein hydrogen will phase in as the technologies and their markets are ready.

Fuel cells for some portable and small stationary applications are available to commercial customers today. Fuel cell vehicles and hydrogen fueling stations are also operating in certain parts of the country as part of demonstration programs, although hydrogen fuel cell vehicles face greater technical challenges that extend the timeline for their commercial market introduction.

Government, industry, and others continue to research, develop, and validate hydrogen and fuel cell technologies to meet specific technical targets based on customer requirements for cost and performance. As fuel cells for portable and stationary applications begin to penetrate the market, experience will be gained in fuel cell manufacturing, standards for hydrogen transport and storage containers, and integration with the electricity grid that will support the expanded use of hydrogen in all sectors of the economy and help integrate hydrogen into our nation's energy portfolio.

Technology Validation on a Large Scale: The National Hydrogen Learning Demonstration

In March 2005, the U.S. Department of Energy (DOE) announced the National Hydrogen Learning Demonstration, a unique collaboration of automobile and energy industry partners, their suppliers, and the federal government to evaluate hydrogen fuel cell vehicle and infrastructure technologies together in real-world conditions and assess progress toward technology readiness for the commercial market. Industry is providing half the cost of the demonstration.

The learning demonstration will validate hydrogen fuel cell technology against targets for fuel cell durability and efficiency, vehicle range, and hydrogen fuel cost. It will also help ensure seamless integration of vehicle and infrastructure interfaces.

Learning Demonstration Projects

The National Hydrogen Learning Demonstration currently involves the work of the following four teams operating fuel cell vehicles and hydrogen fueling stations to collect data both in controlled test conditions and on the open road in a variety of geographic areas and climates.

- Chevron Corporation is building hydrogen fueling stations in northern and southern California and in Michigan; Hyundai-Kia Motor Company is working in partnership with Chevron to test vehicles with fuel cells manufactured by United Technologies Corporation.
- DaimlerChrysler is testing vehicles with Ballard Power System's fuel cells; the vehicles will refuel at hydrogen stations built by project partner BP in northern and southern California and in Michigan.
- Ford Motor Company is testing vehicles with Ballard fuel cells; the vehicles will refuel at hydrogen stations built by project partner BP in northern California and Michigan, as well as Florida.
- General Motors Corporation is testing vehicles with its own fuel cell technology in partnership with Shell Hydrogen, LLC, which is building hydrogen fueling stations in several locations: New York, Detroit, California, and Washington, D.C.

Project Outcomes

The National Hydrogen Learning Demonstration will help DOE guide its hydrogen and fuel cell component and materials research and may also uncover new technical challenges that have not yet been considered. Because component data gathered in the demonstration will be obtained from an integrated system and under real operating conditions, stakeholders will have the information they need to validate DOE economic, energy, and environmental models/analyses, as well as technology status important to customer requirements (vehicle fuel economy, fuel cell efficiency/durability, freeze start ability, hydrogen cost, and operating range). By involving major stakeholders who will be responsible for bringing vehicle and energy technologies to consumers, the demonstration also provides a "real" environment for the sharing of safety, codes, and standards issues across teams, as well as an opportunity for hands-on public education that can introduce consumers to their future energy options.

Safety, Codes and Standards

The United States safely produces and uses more than nine million tons of hydrogen each year, primarily in controlled industrial environments. Hydrogen can be used safely in consumer environments as well, when users understand its basic properties and observe guidelines.

Hydrogen Safety

Like gasoline or natural gas, hydrogen is a fuel that must be handled appropriately. The characteristics of hydrogen are different from those of other fuels, but it can be used as safely as other common fuels when guidelines are observed.

Photo courtesy of CaFCP

Hydrogen has a number of properties that are advantageous with regard to safety. It is much lighter than air and has a rapid diffusivity (3.8 times faster than natural gas), which means that when released in an open environment, it disperses quickly into a non-flammable concentration. Hydrogen rises at a speed of almost 20 meters per second, twice as fast as helium and six times faster than natural gas.

With the exception of oxygen, any gas can cause asphyxiation in high enough concentrations. But because hydrogen is buoyant and disperses rapidly, it is less likely to be confined than other gases and therefore poses less risk as an asphyxiant.

Hydrogen is non-toxic and non-poisonous. It will not contaminate groundwater and is a gas under normal atmospheric conditions with a very low solubility in water. A release of hydrogen is not known to contribute to atmospheric pollution or water pollution.

Hydrogen is odorless, colorless, and tasteless, and thus undetectable by human senses. By comparison, natural gas is also odorless, colorless, and tasteless, but industry adds a sulfur-containing odorant to make it readily detectable by people. Odorants are not added to hydrogen because currently, there is no known odorant light enough to "travel with" hydrogen or disperse in air at the same rate. Odorants also contaminate fuel cells. Industry considers these properties when designing structures where hydrogen is used or stored and includes redundant safety systems that include leak detection sensors and ventilation systems.

Hydrogen burns with a pale blue, nearly invisible, flame. Hydrogen flames also have low radiant heat compared to hydrocarbon flames. Detection sensors built into hydrogen systems can quickly identify any leak and eliminate the potential for undetected flames. Since hydrogen flames emit relatively low levels of heat, (the flame itself is just as hot), the risk of secondary fires by ignition of other combustibles in the vicinity is lower.

An explosion cannot occur in a tank or any contained location with only hydrogen. An oxidizer, such as oxygen, must be present. Hydrogen does burn very quickly, however, sometimes making a loud noise that can be mistaken for an explosion. Under optimal combustion conditions, the energy required to initiate hydrogen combustion is significantly lower than that required for other common fuels including natural gas or gasoline. At low concentrations of hydrogen fuel in air, the energy required to initiate combustion is similar to that of other fuels.

What are Codes and Standards?

Model building codes are guidelines for the design of the built environment (buildings and facilities, for example). Codes are generally adopted by local jurisdictions, thereby achieving force of law. Codes often refer to or invoke standards for equipment used within the built environment.

Standards are rules, guidelines, conditions, or characteristics for products or related processes, and generally apply to equipment or components. Standards achieve a regulatory-like status when they are referred to in codes or through government regulations.

Codes and Standards

Hydrogen codes and standards are being developed to provide the information needed to safely build, maintain, and operate hydrogen and fuel cell systems and facilities; ensure uniformity of safety requirements; and provide local officials and safety inspectors with the information needed to certify hydrogen systems and installations. Developing codes and standards provides a systematic and accurate means of minimizing risk and ensuring public safety. Many organizations are cooperating to develop hydrogen codes and standards. Today, hydrogen components are built to meet strict manufacturer and published guidelines and undergo third-party testing for safety and structural integrity.

Summary

There are several technical challenges to the commercialization and widespread use of hydrogen as an energy carrier. The great promise of hydrogen to provide clean, safe, reliable, and abundant energy has prompted both government and industry to make significant investments in research, development, and demonstration activities needed to bring hydrogen and fuel cell technologies to the commercial market.

"Critical path" technology barriers:

- ***Reducing the cost of hydrogen.*** The cost of hydrogen, which includes the cost of production and delivery, must be competitive with conventional fuels (on a cost-per-mile basis).
- ***Improving hydrogen storage technology.*** The low volumetric energy density of hydrogen makes storage a challenge. No current hydrogen storage technology enables a hydrogen fuel cell vehicle to travel the desired 300 miles or more per fill while meeting vehicular packaging, cost, and performance requirements.
- ***Reducing fuel cell cost and improving durability.*** The cost of fuel cell power systems must be reduced and durability must be improved for fuel cells to compete with conventional technologies.

Production and Delivery

The greatest technical challenge to hydrogen production is cost reduction. Hydrogen is produced, stored, delivered, and used today, but not in ways appropriate or at costs low enough for widespread use in transportation. Distributed production from natural gas offers a cost-effective near-term option. Given the limited supply of natural gas, however, it is not a sustainable long-term pathway. A diverse portfolio of low cost and efficient hydrogen production technologies with great potential is emerging. Ongoing research seeks to reduce the capital cost of equipment and increase distribution efficiency so that hydrogen can be cost-competitive with conventional fuels and technologies in the range of $2.00 - $3.00 per gge (untaxed).

The estimated cost of centrally-produced, delivered hydrogen using currently available technologies is considerably higher than that of conventional fuels. The investment risk to develop a hydrogen delivery infrastructure is currently too great, given technology status and current hydrogen demand. Government and industry partners are gathering data and analyzing the options and trade-offs of hydrogen production (central, semi-central, and distributed) and delivery infrastructure to help lower costs.

Storage

Delivery and vehicle storage systems require advanced technologies to compensate for the low volumetric energy density of hydrogen. Current hydrogen storage systems for vehicles are inadequate to meet customer expectations for driving range (greater than 300 miles per fill) without intrusion into cargo or passenger space. Furthermore, durability of the storage system over the expected life of the vehicle must also be verified and validated. To meet these challenges, scientists and engineers in government, industry, academia, and at national laboratories are researching a wide variety of storage systems, with particular emphasis on materials-based technologies.

Photo courtesy of Ford Motor Company

Fuel Cells

Cost and durability are the major challenges to fuel cell commercialization, although fuel cells are being demonstrated on a limited scale today. Some portable and stationary fuel cells are now available for critical needs applications such as backup power, and a small number of fuel cell vehicles are on the road as part of "technology validation" projects. To be considered ready for mainstream consumers, however, fuel cell systems must be cost-competitive and perform as well or better than traditional power technologies over the life of the system. That means fuel cells for transportation must prove 5,000 hours durability, or the equivalent of 150,000 miles, and cost approximately $30/kW. Stationary fuel cells have slightly different customer requirements, with targets for 40,000 hours durability and $400-750/kW to compete with comparable, traditional power generation technologies.

Technology Acceptance

Using hydrogen as a mainstream energy carrier also requires codes and standards specific to hydrogen, as well as a sustained public education effort focused on specific target audiences.

- Safety and code officials must be familiar with hydrogen technologies to facilitate permitting processes and emergency responders must know how to handle potential incidents.
- State and local government officials must understand near-term realities of hydrogen technology to make sound decisions about current opportunities and lay the foundation for long-term change.

- Local communities will embrace the opportunity to host hydrogen demonstration and validation projects if they are familiar with hydrogen and understand the facts about hydrogen safety. Early adopters and potential end users must understand their options for choosing hydrogen and fuel cell technologies as an alternative to traditional power systems.

- Government, industry, and academia also need a steady stream of educated students who will comprise the next generation workforce of hydrogen and fuel cell researchers, engineers, scientists, and technicians.

- Today's younger students are tomorrow's hydrogen fuel cell users. Introducing students to hydrogen fuel cells in the classroom facilitates long-term market acceptance and engages children in the study of science and technology.

Educating these individual subpopulations will facilitate early adoption and market transformation as well as help ensure long-term market success.

The Benefits Outweigh the Costs

Expanding the use of hydrogen as an energy carrier requires a fundamental change in the way we produce, deliver, store, and use energy—putting it all together is the ultimate challenge. To achieve the goal of commercially-viable hydrogen and fuel cell systems, research and development efforts are focused on the most promising technologies, and demonstrations are validating fully integrated systems operating in real world conditions. While there are barriers to overcome, the benefits outweigh the costs. Developing and expanding the use of hydrogen, along with other domestic energy resources and energy-efficient technologies, will ensure that the United States has an abundant, reliable, and affordable supply of clean energy to maintain the nation's prosperity throughout the 21st century.

Glossary

ABSORPTION

The process in which molecules or dissolved substances are taken up into the pores or interstices of another substance.

ADSORPTION

The adhesion of the molecules of gases, dissolved substances, or liquids in more or less concentrated form, to the surface of solids or liquids with which they are in contact.

ALKALINE FUEL CELL (AFC)

A type of hydrogen/oxygen fuel cell in which the electrolyte is concentrated potassium hydroxide (KOH), and hydroxide ions (OH–) are transported from the cathode to the anode. Temperature of operation can vary from <120°C to approximately 250°C depending upon electrolyte concentration. This type of fuel cell has been used in U. S. space vehicles for the last forty years and continues to be used in the space shuttles.

ALTERNATIVE FUEL

An alternative to gasoline or diesel fuel that is not produced in a conventional way from crude oil. Examples include compressed natural gas (CNG), liquefied petroleum gas (LPG), liquefied natural gas (LNG), ethanol, methanol, and hydrogen.

ANODE

The electrode at which oxidation (a loss of electrons) takes place. For fuel cells and other galvanic cells, the anode is the negative terminal; for electrolytic cells (where electrolysis occurs), the anode is the positive terminal.

ATMOSPHERIC PRESSURE

The force exerted by the weight of air in the atmosphere, usually measured in units of force per unit area. One atmosphere is the standard pressure at mean sea level.

ATOM

The smallest physical unit of a chemical element that can still retain all of the physical and chemical properties of that element. An atom has a dense central core (the nucleus) consisting of positively charged particles (protons) and uncharged particles (neutrons). Negatively charged particles (electrons) are scattered in a relatively large space around the nucleus and move about it in orbital patterns at extremely high speeds. An atom contains the same number of protons as electrons and thus is electrically neutral (uncharged) and stable under most conditions.

BATTERY

An energy storage device that produces electricity by means of electrochemical reaction. It consists of one or more electrochemical cells, each of which has all the chemicals and parts needed to produce an electric current.

BIOMASS

Organic matter including crop or forest residues, organic municipal solid wastes, or special crops that can be grown specifically for energy production, such as switchgrass or willow trees.

BRITISH THERMAL UNIT (BTU)

The British Thermal Unit is 1/180 of the heat required to raise the temperature of one pound (1 lb) of water from 32°F to 212°F at a constant atmospheric pressure. It is approximately equal to the amount of heat required to raise 1 lb of water by 1°F.

CARBON SEQUESTRATION

One or more processes for capturing and permanently isolating carbon dioxide from the exhaust of an energy-generating process or device, which carbon dioxide could otherwise contribute to global climate change.

CARBON DIOXIDE (CO_2)

A colorless, odorless, noncombustible gas that is slightly more than 1.5 times as dense as air and becomes a solid (dry ice) below -78.5°C. It is present in the atmosphere as a result of the decay of organic material and the respiration of living organisms, and it represents about 0.033% of the air. Carbon dioxide is produced by the burning of any fuel containing carbon, such as wood, coal, coke, oil, natural gas, or petroleum fuels.

CARBON MONOXIDE (CO)

A colorless, odorless, tasteless, poisonous gas that results from incomplete combustion of carbonaceous fuels with oxygen.

CATALYST

A chemical substance that increases the rate of a reaction without itself being consumed; after the reaction it can potentially be recovered from the reaction mixture chemically unchanged. The catalyst lowers the activation energy required, allowing the reaction to proceed more quickly or at a lower temperature.

CATHODE

The electrode at which reduction (a gain of electrons) occurs. For fuel cells and other galvanic cells, the cathode is the positive terminal; for electrolytic cells (where electrolysis occurs), the cathode is the negative terminal.

COGENERATION

Generation of electricity and useful thermal energy from a single integrated system. Sometimes called Combined Heat and Power (CHP).

COMBUSTION

Burning; fire produced by the proper combination of fuel, heat, and oxygen. In the engine, the rapid burning of the air-fuel mixture that occurs in the combustion chamber.

COMPRESSED NATURAL GAS (CNG)

Mixtures of hydrocarbon gases and vapors, consisting principally of methane in gaseous form and under greater than atmospheric pressure; can be used as a vehicular fuel.

DENSITY

The amount of mass in a unit volume. Density varies with temperature and pressure.

DIATOMIC MOLECULE

Molecules formed of exactly two atoms, of the same or different elements; examples include hydrogen (H_2) and carbon monoxide (CO).

DIFFUSION

The flow of gas molecules from a region of high concentration to a region of low concentration

DIRECT METHANOL FUEL CELL (DMFC)

A type of fuel cell in which the fuel is methanol (CH_3OH), in gaseous or liquid form. The methanol is oxidized directly at the anode instead of first being reformed to produce hydrogen. The electrolyte is typically a PEM.

DISSOCIATE

The process by which a change in physical condition (as in temperature or pressure) or the action of a solvent causes a molecule to split into less complex groups of atoms, single atoms, or ions.

DISTRIBUTED GENERATION

Any small-scale power generation technology that provides electric power at or closer to the customer's site than centrally sited generation stations.

ELECTROLYSIS

A process that uses electricity, passing through an electrolytic solution or other appropriate medium, to cause a reaction that breaks chemical bonds, e.g., electrolysis of water to produce hydrogen and oxygen.

ELECTROLYTE

A substance that conducts charged ions from one electrode to the other in a fuel cell, battery, or electrolyzer.

ELECTRON

A stable atomic particle that has a negative charge; the flow of electrons through a substance constitutes electricity.

ENDOTHERMIC

A chemical reaction that absorbs or requires energy (usually in the form of heat).

ENERGY CARRIER

Something that can store and deliver energy in a usable form (note: energy carriers such as electricity and hydrogen are not energy sources – they must be produced using energy sources).

ENERGY CONTENT

The amount of energy for a given mass of fuel.

ENERGY DENSITY

The amount of energy for a given volume of fuel. Thus, energy density is the product of the energy content and the density of a given fuel.

EXOTHERMIC

A chemical reaction that gives off heat.

FLAMMABILITY LIMITS

A range defined in terms of lower flammability limit (LFL) and upper flammability limit (UFL). Between the two limits is the flammable range in which the gas and air are in the right proportions to burn when ignited. Below the lower flammability limit, there is not enough fuel to burn. Above the higher flammability limit, there is not enough air to support combustion.

FUEL

A material used to create heat or power through chemical conversion in processes (including combustion or electrochemical).

FUEL CELL

A device that uses hydrogen and oxygen to create electricity through an electro-chemical process.

FUEL CELL STACK

Individual fuel cells that are connected in series. Fuel cells are stacked to increase voltage.

GALLON GASOLINE EQUIVALENT (gge)

The energy content equivalent to one gallon of gasoline (114, 320 Btu).

HEATING VALUE (TOTAL)

The amount of heat released when a fuel is burned.

Lower (LHV)

The heat of combustion of a fuel as measured by allowing the product water, if any, to remain in the gaseous state, with the reactants and the products all being at 25°C and 1 atm.

Higher (HHV)

The lower heating value plus the heat released by the condensation of the product water, if any, to the liquid state at 25°C and 1 atm.

HYBRID ELECTRIC VEHICLE (HEV)

A vehicle combining a battery-powered electric motor with another power source. The vehicle can run on either the battery or the primary engine (such as an internal combustion engine, etc.) or both simultaneously, depending on the performance objectives for the vehicle.

HYDRIDES

Chemical compounds formed when hydrogen gas reacts with metals or other solids; among the materials under research for hydrogen storage.

HYDROCARBON (HC)

An organic compound containing only carbon and hydrogen, usually derived from fossil fuels, such as petroleum, natural gas, and coal.

INTERNAL COMBUSTION ENGINE (ICE)

An engine that converts the chemical energy contained in a fuel inside the engine into mechanical energy. Combustion engines use the pressure created by the expansion of the gases to do mechanical work.

ION

Atom or molecule that carries a positive or negative charge because of the loss or gain of electrons.

KILOGRAM (kg)

Metric unit of mass. One kilogram is equal to approximately 2.2 lb. Related units are the gram (g) at 1000 per kg, and the metric tonne at 1000 kg.

KILOWATT (kW)

A unit of power equal to 1000 Watts, or about 1.34 hp. The Watt is named for James Watt, Scottish engineer (1736-1819), a pioneer in steam engine development.

LIQUEFIED NATURAL GAS (LNG)

Natural gas in liquid form. Natural gas is a liquid at -162 °C (-259°F) at ambient pressure.

LIQUEFIED PETROLEUM GAS (LPG)

Any material that is composed predominantly of any of the following hydrocarbons or mixtures of hydrocarbons: propane, propylene, butanes (normal or iso), and butylenes.

MEMBRANE

The separating layer in a fuel cell that acts as electrolyte (ion-exchanger) as well as a barrier film separating the gases in the anode and cathode compartments of the fuel cell.

METHANE (CH_4)

See NATURAL GAS.

METHANOL (CH_3OH)

An odorless, clear liquid alcohol made from natural gas, coal, or biomass, such as wood fiber (methyl or wood alcohol).

MOLTEN CARBONATE FUEL CELL (MCFC)

A type of fuel cell that contains a molten carbonate electrolyte. Carbonate ions (CO_3^{-2}) are transported from the cathode to the anode. Operating temperatures are typically near 650°C.

NATURAL GAS

A naturally occurring gaseous mixture of simple hydrocarbon components (primarily methane) used as a fuel.

NITROGEN OXIDES (NO_x)

Any chemical compound of nitrogen and oxygen. Nitrogen oxides result from high temperature and pressure in the combustion chambers of automobile engines and other power plants during the combustion process. When combined with hydrocarbons in the presence of sunlight, nitrogen oxides form smog. A basic air pollutant; automotive exhaust emission levels of nitrogen oxides are regulated by law.

OXIDANT

A chemical, such as oxygen, that consumes electrons in an electrochemical reaction.

OXIDATION

Loss of one or more electrons by an atom, molecule, or ion.

PHOSPHORIC ACID FUEL CELL (PAFC)

A type of fuel cell in which the electrolyte consists of concentrated phosphoric acid (H_3PO_4), and protons (H^+) are transported from the anode to the cathode. The operating temperature range is generally 160-220°C.

POLYMER

Natural or synthetic compound composed of repeated links of simple molecules.

POLYMER ELECTROLYTE MEMBRANE (PEM)

A solid membrane, similar in consistency to thick plastic wrap, used as an electrolyte in fuel cells. The membrane allows positively charged ions to pass through it, but blocks electrons. *See also POLYMER ELECTROLYTE MEMBRANE FUEL CELL.*

POLYMER ELECTROLYTE MEMBRANE FUEL CELL (PEMFC)

A type of fuel cell in which the transport of protons (H^+) from the anode to the cathode is through a solid, aqueous or humidified membrane impregnated with an appropriate acid. The electrolyte is a called a polymer electrolyte membrane (PEM). The fuel cells typically run at low temperatures (<100°C). PEMFCs are also sometimes called Proton Exchange Membrane Fuel Cells.

PROPANE (C_3H_8)

See LPG.

PROTON

A subatomic particle in the nucleus of an atom that carries a positive electric charge.

PROTON EXCHANGE MEMBRANE (PEM)

See POLYMER ELECTROLYTE MEMBRANE.

REACTANT

A chemical substance that is present at the start of a chemical reaction.

REDUCTION

The gaining of one or more electrons by an atom, molecule, or ion.

REFORMER

Device used to extract hydrogen from fuels, such as natural gas, propane, gasoline, methanol, and ethanol, for use in fuel cells.

REFORMING

A chemical process in which hydrogen-containing fuels react with steam, oxygen, or both into a hydrogen-rich gas stream.

SOLID OXIDE FUEL CELL (SOFC)

A type of fuel cell in which the electrolyte is a solid, nonporous metal oxide, typically zirconium oxide (ZrO_2) doped with Y_2O_3, and O_2^- is transported from the cathode to the anode. Any carbon monoxide (CO) in the reformate gas is oxidized to carbon dioxide (CO_2) at the anode. Temperatures of operation are typically 800-1,000°C.

SORBENT

Material that takes up and holds another; i.e., has the capacity or tendency to take it up either by adsorption or absorption.

STEAM REFORMING

The process of reacting a fuel, such as natural gas or ethanol, in the presence of steam to form hydrogen as a product.

VOLUMETRIC ENERGY DENSITY

Energy in a given volume of fuel.

Glossary and Other Information Resources

Information included in the glossary was obtained from the following sources:

- Hydrogen, Fuel Cells and Infrastructure Technologies Program Glossary, U.S. Department of Energy, www.eere.energy.gov/hydrogenandfuelcells/glossary.html.
- FreedomCAR and Vehicle Technologies Program Glossary, U.S. Department of Energy, www.eere.energy.gov/vehiclesandfuels/resources/fcvt_glossary.shtml.

Additional information about hydrogen and fuel cell technologies is available on the DOE Hydrogen Program web site, www.hydrogen.energy.gov.

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