Chapter 22
Hydrogen

Introduction

Hydrogen is colorless, odorless, tasteless and nontoxic. It is a gas at temperatures above -423° F and is highly diffuse, having a density approximately 14 times less than that of air. Because it is buoyant and diffusive, hydrogen dissipates quickly in open areas and can move through small spaces, which makes it difficult to store. Hydrogen is flammable over a broad range of gas concentration (from 4 to 74 percent), although its lower flammability limit — that is, the lowest temperature and pressure at which it will combust — is higher than those for some common fuels such as gasoline, propane or diesel.[1]

On Earth, hydrogen is found in combination with other elements such as carbon (hydrocarbons), oxygen (water) and nitrogen (ammonia). Although hydrogen may sometimes be used as a fuel, it is most often used as an energy *carrier*, such as electricity, and not an energy *source*. To make hydrogen a usable, stand-alone fuel, it must be separated from these other elements by chemical, thermal or electrochemical processes. Hydrogen can be separated from water using the heat of the sun, for example, and then used as a power source. After it is combined with oxygen to produce power, the only emission is water (**Exhibit 22-1**).

Even so, hydrogen has been described as "the fuel of the future." Because it is abundant and benign in terms of emissions, proponents say it holds tremendous promise. Due to technical barriers and resulting high costs, however, even its ardent supporters do not see hydrogen power as a short-term solution for America's energy needs. Nonetheless, growing interest in the issue of carbon emissions has spurred hydrogen activity around the world, particularly in Europe, Japan and California. Use of hydrogen for energy purposes is in a developmental stage, so the economic effects in Texas are largely limited to grant funds for research and pilot projects.

History

British scientist Henry Cavendish identified hydrogen as a distinct element in 1766. Subsequent experiments by British and French scientists resulted in the first flight of a hydrogen balloon and the discovery that applying electricity to water can produce hydrogen and oxygen. Further nineteenth-century discoveries included the identification of the fuel cell effect, in which the combination of hydrogen and oxygen results in water and electricity. By the 1920s, German engineers were using early hydrogen and hydrogen-mixed fuel cells to power submarines as well as trucks.[2]

The 1937 explosion of the German dirigible *Hindenburg* in Lakewood, New Jersey led to widespread public concerns about the safety of hydrogen. German and U.S. investigators blamed the accident on static electricity that ignited a hydrogen leak, concluding that static electricity ignited the exterior canvas coating. Further research found that the coatings covering the canvas were materials that would later be used in solid rocket fuel.

Hydrogen has been described as "the fuel of the future."

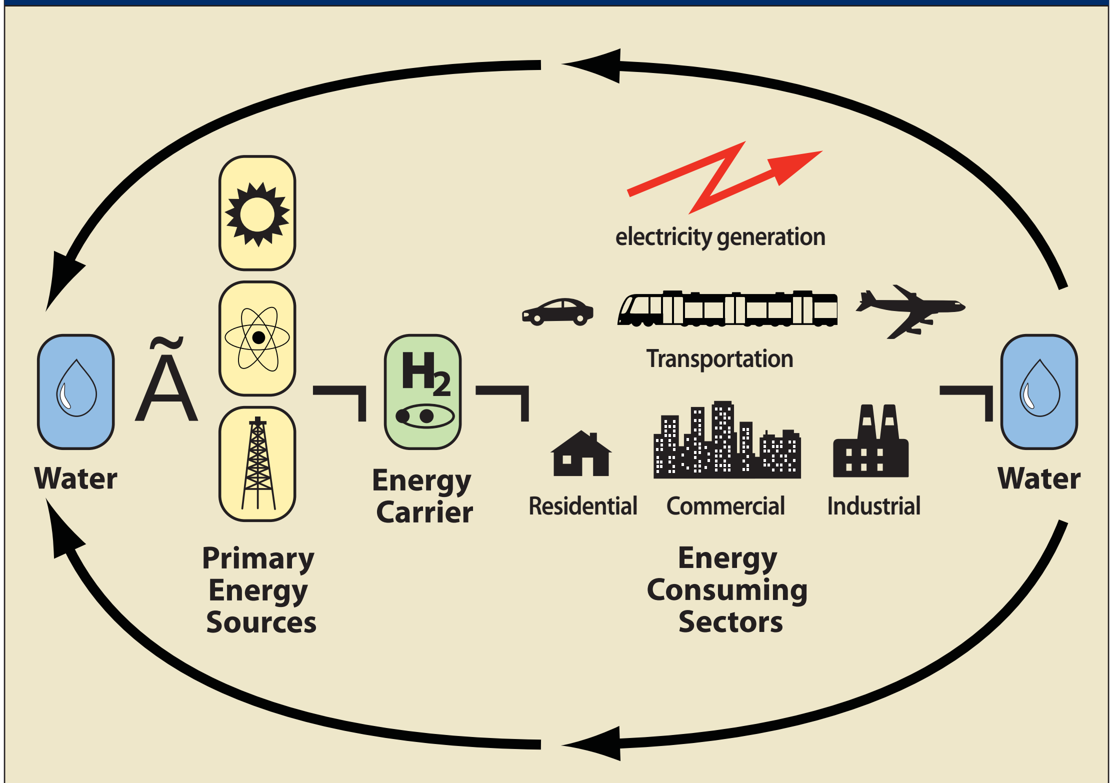
The postwar era saw more development of hydrogen technology. In the 1960s, NASA space capsules used hydrogen fuel cells for onboard electric power, heat and water. The term "hydrogen economy" was coined in 1970 by Australian electrochemist John Bockris during a discussion at the General Motors Technical Center in Warren, Michigan.[3] The first major international hydrogen conference was held in 1974 in Miami Beach, Florida. The theme of the conference was that hydrogen was the answer to depletion of fossil fuels and environmental problems.

The 1990s saw demonstration projects applying previous hydrogen-related research, particularly in Europe. Germany built a solar-powered hydrogen production plant. Daimler Benz demonstrated its NECAR or "New Electric Car," powered by a hydrogen fuel cell. Hydrogen fueling stations opened

The most common modern uses for hydrogen do not involve power production.

Exhibit 22-1

Hydrogen Energy System



Source: United Nations Industrial Development Organization.

in Hamburg and Munich.[4] Commercial-scale power generators based on fuel cells were successfully demonstrated in Japan and the U.S.

In 2002, major U.S. car manufacturers and then U.S. Secretary of Energy Spencer Abraham announced a research program called FreedomCAR to develop hydrogen technology for the production of cars and light trucks and to study how the U.S. transportation system might make the transition to a hydrogen economy.

And in 2003, President Bush announced the Hydrogen Fuel Initiative, a $1.2 billion program to fund hydrogen technology development. Funding for the initiative totaled $269 million in 2007; the Bush Administration has requested more than $309 million in further funding for 2008, the program's final year.[5]

Although biofuels such as ethanol and biodiesel have attracted more public attention in recent years, various states also have begun significant hydrogen initiatives, including California, Florida, New York, Ohio and South Carolina. Most federal hydrogen program funding has gone to states that have created specific hydrogen initiatives.

Uses

The most common modern uses for hydrogen do not involve power production. Hydrogen is widely used in the refining and fertilizer industries, both of which are important Texas businesses. These uses include the manufacture of ammonia-based nitrogen fertilizer and the removal of sulfur in petroleum refining processes that produce gasoline.

But hydrogen can also be used in fuel cells for transportation or power generation. According to the U.S. Department of Energy, hydrogen fuel cells have a wide variety of potential applications in several major areas.

Portable applications include consumer electronics or auxiliary power units. In *transportation*, hydrogen fuel cells can be used for basic propulsion. In addition, hydrogen can be burned directly as a fuel in an appropriately adapted internal combustion engine; this is considered a transition strategy toward widespread use of hydrogen for transportation. Finally, hydrogen fuel cells can be used for power at remote locations, in backup power units for conventional power plants or as stand-alone, stationary power plants.[6] Stationary power systems, commonly referred to as Distributed Power Generation, can operate independently or in parallel with an existing power grid.

Today, NASA is a leading user of hydrogen outside of the petrochemical industry. NASA uses it to generate spaceship power, heat and water. Space shuttles use fuel cells to power such things as computers, life-support systems and lighting. In addition, the cells perform double duty by also providing heat and synthesizing pure water for astronauts to drink and use.

Hydrogen fuel cells are being used for stationary and transportation power in various places around the world, mostly notably in Japan, Europe and California. Some emerging commercial products use fuel cell technology as well, such as portable power generation systems and fuel cell modules that can be used to replace battery packs in forklifts. Most economic activity in the fuel cell industry, however, is still focused on research and product development.

Expectations for the evolution of this energy carrier are evident in the official goals of the federally funded Hydrogen Fuel Initiative, which is intended to improve the state of related technology so that various industries including transportation can make a decision on its commercial viability by 2015. The next step would be to have these technologies, including commercially available hydrogen-powered cars, start to penetrate consumer markets by 2020. DOE does not expect hydrogen power to begin displacing petroleum in a significant way before 2030.[7]

Others, however, expect shorter timelines. Energy companies and carmakers continue to tout their progress toward hydrogen-powered transportation.

At this writing, Chevrolet's Project Driveway program is taking applications to place 100 hydrogen vehicles with individuals in California, New York and Washington D.C. as a demonstration project in 2008.[8] Honda says it will begin leasing its new four-door hydrogen-powered sedan, the FCX Clarity, for demonstration purposes to a few California customers in 2008, for about $600 per month.[9]

Hydrogen in Texas

Texas is a major producer and user of hydrogen, but again, most of it is used for fertilizer manufacture and in petrochemical processes. Its use for power purposes is limited mostly to research and demonstration projects, as is the case around the world.

Economic Impact

The new "hydrogen economy," as advocated by its supporters, is based on the idea that the U.S. will shift to new forms of energy that are sustainable, pollution-free and domestically produced. The desired result is a better environment, new economic growth and improved national energy security.

Texas is a major producer and user of hydrogen.

The energy industry (and specifically the vehicle fuels industry) has been steadily moving toward fuels with fewer emissions. Since the 1970s, when lead was phased out of gasoline, there have been continual changes in fuel content, leading to today's ultra-low sulfur diesels and biofuels. Many industry observers expect these changes to continue, leading to fuels with lower carbon "footprints" such as hydrogen. The transition toward hydrogen as a broadly available vehicle fuel source may occur over the next few decades as technical hurdles to its widespread commercial use are overcome.[10]

According to the National Academy of Sciences, two public goals — environmental quality and energy security — are the foundations of the U.S. Department of Energy's hydrogen program. The environmental goals include both the reduction of pollutants that directly affect human health and the reduction of greenhouse gases such as carbon dioxide.[11]

No estimate is available of the economic impact of using hydrogen for energy purposes in Texas because of the developmental nature of these efforts.

Consumption

Today, Texas has only a few stationary hydrogen power facilities, and there is one hydrogen fueling station under construction in Austin, where a fuel cell bus is being operated by University of Texas researchers. There have been several one- and two-day fuel cell demonstrations in the state over the past five years. According to the National Hydrogen Association, the entire nation has 66 hydrogen fueling stations.[12] The U.S. Department of Energy (DOE) does not maintain comprehensive statistics in this area, but the various demonstration projects suggest that there are some hundreds of hydrogen fuel cell vehicles on the road in the U.S.

Texas has only a few stationary hydrogen power facilities, and there is one hydrogen fueling station under construction in Austin, where a fuel cell bus is being operated by University of Texas researchers.

The National Renewable Energy Laboratory reports that about 250 fuel cells are being used for power in hotels, hospitals and office buildings in 19 countries.[13] A 2002 Texas State Energy Conservation Office (SECO) study illustrated the embryonic stage of hydrogen development: in that year, an estimated 300 fuel cells being used in the private and public sectors around the world produced 50 megawatts of electricity, or about enough to power just 20,000 homes.[14]

Production

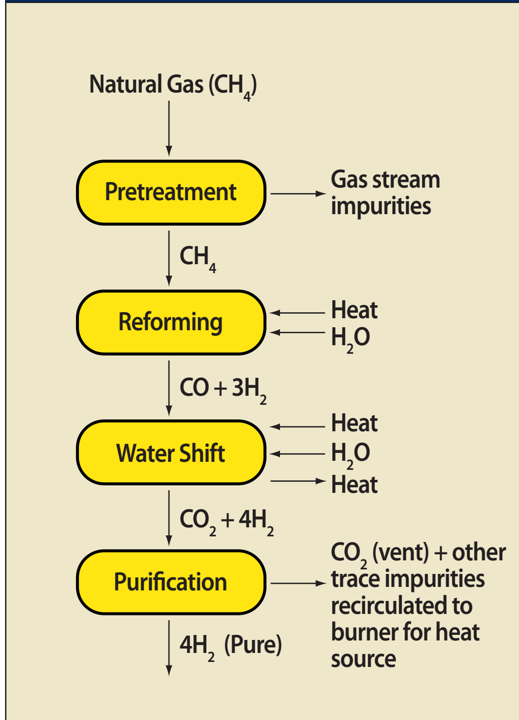
Hydrogen can be produced from a wide range of sources, including fossil fuels such as coal and natural gas as well as nuclear, wind, solar and hydroelectric power.

Current ways to produce hydrogen include:

- *steam methane reforming*. High-temperature steam is combined with methane in the presence of a catalyst to produce hydrogen (**Exhibit 22-2**). This is the most common and least-expensive method of production in use today.
- *electrolysis*. An electric current is used to "split" water into hydrogen and oxygen.
- *gasification*. Heat is applied to coal or biomass in a controlled oxygen environment to produce a gas that is further separated using steam to produce hydrogen.

Exhibit 22-2

Steam Methane Reforming Block Flow Process



Source: Gas Technology Institute.

The following methods for producing hydrogen are in the research and development stage:

- *renewable liquid reforming*. Ethanol or biodiesel derived from biomass reacts with steam to produce hydrogen.
- *nuclear high-temperature electrolysis*. Heat from a nuclear reactor is used to improve the efficiency of electrolysis, again splitting water to make hydrogen.
- *high-temperature thermochemical water-splitting*. Solar concentrators are used to split water.
- *photobiological* microbes. Certain microbes produce hydrogen as part of their metabolic processes. Artificial systems can encourage these organisms to produce hydrogen through the use of semiconductors and sunlight, improving their natural metabolic processes.

- *photoelectrochemical* systems. These use semiconductors and sunlight directly to make hydrogen from water. [15]

Again, natural gas reforming in large central facilities is by far the most common method of creating hydrogen; it is also the most economical, although it is not yet competitive with energy from fossil fuels, primarily because the hydrogen still must be transported and stored for use, which can cost as much as 10 times the actual production cost. Other methods are more expensive and have other drawbacks. Gasification of coal, for instance, results in carbon dioxide releases that some observers say blunt hydrogen's claim to environmental superiority.

Authoritative studies from sources including DOE, however, say that fuel cell-powered vehicles, running on hydrogen derived from natural gas, produce fewer carbon emissions than internal combustion or gasoline-electric hybrid engines.[16]

Hydrogen Fuel Cells

Fuel cells are electrochemical devices that combine hydrogen with oxygen from the air to generate electricity. Fuel cells work by converting the chemical energy in hydrogen into electricity, producing heat and water as byproducts. They can be added together in stacks to generate significant amounts of power. In a fuel cell vehicle, hydrogen flows from a storage tank into the fuel cell, which generates electricity that is used to power an electric motor, often supplemented by batteries or capacitors.

A single fuel cell consists of an electrolyte, which is an electric conductive medium layered between two electrodes, an anode and a cathode. Hydrogen is fed into the anode and oxygen into the cathode. A catalyst causes the hydrogen atom to split into a proton and an electron. The protons pass through the electrolyte while the electrons travel around an external circuit, creating a current that can be used for power before they reunite with the hydrogen ion and oxygen to form water.

All the various fuel cell technologies have the same basic structure, an electrolyte and two electrodes. The type of electrolyte used, however, affects the chemical reaction that takes place and the amount of heat generated.[17] Common fuel cell types include:

- *alkaline*. Used by NASA, these are highly efficient and operate at a relatively low temperature. Alkaline cells are susceptible to carbon contamination in fuel and require pure hydrogen and oxygen to operate.

- *phosphoric acid*. These cells are commercially available today and are used in hospitals, office buildings and wastewater plants; they can also produce steam for heating purposes, using their otherwise wasted heat. They are less efficient than alkaline cells but more tolerant of fuel impurities.

- *polymer electrolyte membrane (PEM) cells*, also called proton exchange membrane exchange cells. These operate at relatively low temperatures and can respond quickly to changes in power demand. They are most adaptable to transportation uses.

- *molten carbonate*. These cells operate at high temperatures and can be used by electric utilities to generate grid power.

- *solid oxide*. These cells operate at very high temperatures and are most suitable for stationary power applications.[18]

PEM fuel cells operate at lower temperatures and have a high "power density" (i.e., they generate a relatively large amount of power with a small device). This makes them the most popular choice for vehicle and portable power applications. Those that operate at a higher heat are more efficient, however, and can be used in large electric generation plants where the waste heat can also be captured to generate power in a process known as cogeneration.

Fuel cells are typically more efficient than gasoline engines. Internal combustion engines are typically 18 to 20 percent efficient, meaning that most of the energy they use is lost in the process. Some hydrogen fuel cells used in vehicles, by contrast, are up to 60 percent efficient.[19] This is because electrochemical reactions are much more efficient than combustion in converting energy to power needed to operate the vehicle.

Natural gas reforming in large central facilities is by far the most common method of creating hydrogen.

Fuel cells contain no moving parts and thus sustain less friction loss. They are, however, dramatically more expensive to manufacture than gas or diesel engines, which have the advantages of more than a century of technological improvement and mass production expertise. Production costs for fuel cells are expected to decline substantially if and when they are produced in large volumes, such as would be needed for vehicle manufacturing. Other efficiency improvements expected in the future would mean that smaller, lighter fuel cells can be used, along with smaller quantities of onboard hydrogen.

Hybrid gas-electric vehicles, for example, have benefited from earlier improvements that reduced vehicle weight, improved aerodynamics and changed various design features. The emergence of inexpensive microprocessors, electronic controls and special software also paved the way for practical hybrids. Fuel cell vehicles are expected to benefit from similar improvements.

While hydrogen-fueled vehicles are commonly associated with fuel cells, hydrogen can also be used in a hydrogen internal combustion engine (HICE), a transitional technology promoted by some carmakers including Ford and BMW. This approach has also been used in public transit applications.

While hydrogen-fueled vehicles are commonly associated with fuel cells, hydrogen can also be used in a hydrogen internal combustion engine, a transitional technology promoted by some carmakers including Ford and BMW.

Transportation and Storage

The Department of Energy has cited the transportation and distribution of hydrogen as two barriers to the commercial development of hydrogen fuel cells. Various delivery methods are being studied and demonstrated by vehicle manufacturers, governmental agencies, energy companies and the industrial gases industry.

At present, the U.S. does not have a widespread distribution network for hydrogen. As a result, most hydrogen is produced near or at the place it is used.

The energy in one kilogram of hydrogen is equal to that in one gallon of gasoline. At normal temperature and air pressure, however, the energy density of hydrogen is low, meaning that relatively large volumes of it must be used to generate power in useful amounts. For example, about 11 tube trailer trucks carrying pressurized hydrogen at 2,400 pounds per square inch would be needed to move the energy equivalent of one gasoline tanker truck.[20]

Hydrogen generally is distributed via pipelines, tube trailers and liquefied hydrogen tankers. According to DOE, transporting hydrogen gas over the road is cost-prohibitive beyond 200 miles because the energy used to move the trailers carrying the heavy tanks costs so much. Hydrogen, like natural gas, also can be super-cooled and transported more efficiently by barge.[21]

DOE and others have identified pipelines as the most cost-effective way to deliver hydrogen, but the U.S. has relatively few lines of this type, at least compared to the web of oil and natural gas pipelines that crisscross the country. The Texas Gulf Coast petrochemical complex, by contrast, has about 1,000 miles of hydrogen pipeline network, as well as a skilled work force experienced in its handling.[22]

There is some potential for conversion of existing natural gas or liquids pipelines to hydrogen. Because of the smaller molecular size of hydrogen, these pipelines would need modification – especially for seals and compression equipment. The tendency of hydrogen to diffuse into and weaken high carbon steels (known as hydrogen embrittlement) will eliminate some pipeline materials from consideration for conversion for hydrogen service; however, a number of natural gas lines have been successfully converted to hydrogen.

Because it is so diffuse, hydrogen is hard to store in relatively small spaces. Efficient, compact and safe storage is major hurdle to the widespread use of hydrogen for energy purposes. This is perhaps the most important key to the wider use of hydrogen, particularly in vehicles. According to DOE, the minimum acceptable driving range for a fuel cell-powered vehicle is 300 miles. With current technology, this would require a tank the size of an average car trunk, which would add considerable weight to the vehicle, reducing fuel economy. In addition, fueling must take only a few minutes to meet consumer expectations.

Existing options for storage include compressing the gas in high-pressure tanks (up to 10,000 pounds per square inch) or cooling it (to -253° C) in insulated tanks. Each approach presents challenges. Compressed gas tanks are very large and heavy, while liquefying hydrogen takes significant amounts of energy, as well as insulated tanks that, again, add to weight and reduce usable space within the vehicle.[23]

Because storage is such as critical technical issue inhibiting hydrogen commercialization, DOE has initiated a multi-year program to research and engineer new methods for storing hydrogen. This initiative directs about $150 million over a five year period toward promising hydrogen storage technologies such as carbon nano-technologies, metal hydrides, and chemical hydrides that may be better alternatives.[24]

Availability

Texas is the nation's second-largest producer of hydrogen, behind California. It is commonly used by Texas industries for refining petroleum, in particular to remove sulfur, as well as for manufacturing fertilizers. The increasing use of "sour," or higher-sulfur, crude oil is increasing the demand for hydrogen production. As a result, petrochemical companies are the largest producers of hydrogen in the world.

In addition, major industrial gas companies including Praxair, Air Products and Chemicals and Air Liquide have hydrogen production operations in Texas. Air Liquide recently announced an expansion of its production, storage and pipeline capacity on the Gulf Coast, including 90 miles of new pipeline to support petroleum-refining operations.[25] Praxair also has started supplying hydrogen to its customers from a unique storage facility in an underground cavern located northwest of Winnie.[26]

Despite its extensive use along the Gulf Coast, however, the use of hydrogen for transportation and power generation in Texas is very limited, as it is in the rest of the country and the world. Texas has only recently begun constructing its first hydrogen fueling station to support a small number of hydrogen-fueled vehicles in Austin. Texas has only a few stationary power facilities that employ hydrogen.

The U.S. Department of Defense (DOD) has used hydrogen fuel cells to create nine stationary power stations at locations in Texas, including Fort Bliss in El Paso; Fort Hood, near Killeen; Brooks City Base in San Antonio; and Camp Mabry in Austin. In addition, DOD previously funded an incentive program that provided $1,000 per kilowatt of electricity to encourage the installation of fuel cells in various locations for demonstration purposes, up to a maximum of $200,000 per project. This program, funded as part of a federal climate change initiative, resulted in the installation of fuel cells at Austin Energy's facilities in Austin and at a Chevron office park in Bellaire.[27]

In 2006, the Texas Commission on Environmental Quality (TCEQ) provided a grant to Gas Technology Institute (GTI) to build the state's first hydrogen fueling station and a fuel cell-powered medium- or heavy-duty vehicle. GTI teamed with the University of Texas, Center for Electromechanics (CEM) to install the station at Austin's J.J. Pickle Research Campus. CEM provided additional funding through a Federal Transit Administration program to complete the cost of building and operating a hybrid electric fuel cell shuttle bus.

Texas is the nation's second-largest producer of hydrogen, behind California.

The bus is designed so that an onboard fuel cell and battery pack jointly operate an electric drive train, resulting in a true zero-emissions vehicle (the first in the state). The bus initially will operate only on the research site, but the university eventually plans to put it into service either on a local metro bus route or perhaps as a shuttle for a local mall (**Exhibit 22-3**).

Greenfield Compression, a Richardson, Texas-based company, provided major equipment components for the fueling station and plans to commercialize GTI's integrated fueling station design. Other sponsors in the project include DOE, GTI, University of Texas, the U.S. Department of Transportation, and the Texas State Energy Conservation Office (**Exhibit 22-4**).

Project goals include validating the technology, providing hydrogen fuel for other demonstration uses and establishing a hydrogen education program. At this writing, the bus manufacturer, Ebus, has completed the vehicle; the hydrogen supply station, which will use natural gas to manufacture hydrogen, is undergoing testing and expected to begin operation in 2008. GTI asserts that the station design can attain the DOE's goal

Exhibit 22-3

Hybrid Electric Fuel Cell Shuttle Bus

Source: Gas Technology Institute.

Private companies, research organizations and Texas universities are involved in research projects concerning hydrogen and fuel cells.

of commercial hydrogen costs between $2 to $3 per gallon of gasoline equivalent (gge).[28]

The bus and supply station are estimated to cost about $2.5 million.[29] Most of the project's funding went for research and design.

Private companies, research organizations and other Texas universities are involved in other research projects concerning hydrogen and fuel cells. Dow Chemical and General Motors, for instance, have created a fuel cell demonstration project at Dow's Freeport chemical plant that is running endurance tests on fuel cells to simulate real-world driving conditions. This privately funded venture also tests fuel cells intended for stationary power.

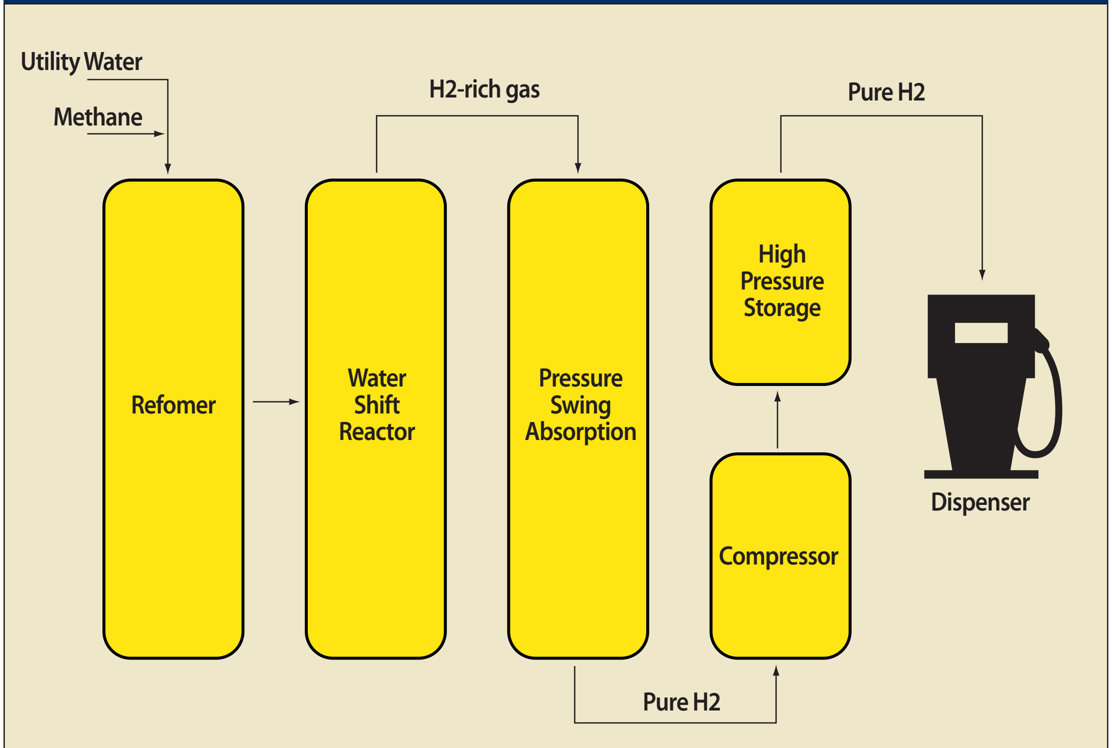
Both the Houston Advanced Research Center and the Southwest Research Institute in San Antonio have programs to test fuel cells. Texas State Technical Institute in Waco and Lamar University in Beaumont have fuel cells for demonstration and training purposes.[30]

In 2002, the Texas State Energy Conservation Office (SECO) completed a legislatively mandated study on fuel cell commercialization. The report described the promise of hydrogen fuel cells and the classic problem facing emerging technologies: the need for money for research and development *before* mass marketing, which would provide sales needed to accumulate capital.

SECO's report described the benefits of and obstacles to hydrogen power and called for the state to support research and demonstration projects and to buy fuel cells as they become available.[31] Other recommendations included the creation of a

EXHIBIT 22-4

GTI/Greenfield Fueling Station



Source: Gas Technology Institute.

public-private partnership to guide fuel cell policy and the creation of a plan to foster its commercialization. The report's major recommendations have not been implemented, however.

In 2006, the Texas Department of Transportation (TxDOT) completed a strategic plan for hydrogen vehicles and fueling stations in response to a 2005 legislative mandate requiring the agency to seek funding from public and private sources to operate hydrogen-fueled vehicles and establish hydrogen fueling stations. The plan discussed the potential benefits of hydrogen and the significant technical hurdles to such a program. Since then, however, there has been no movement toward the creation of a hydrogen fuel fleet at TxDOT or any other Texas public agency. The key hurdle cited in the TxDOT report is the immaturity of the technology.[32]

In 2006, industry and university groups formed the Texas H_2 Coalition to promote hydrogen power in Texas. Its goal is to move the state into a leadership role in this nascent industry, building on its significant advantages in hydrogen. The coalition's focus is to establish Texas as an early market for the commercial use of hydrogen and fuel cell products and to produce economic opportunities for the state. The organization is pursuing a demonstration project that would operate a hydrogen-fueled public transportation bus in Houston, as well as a separate hydrogen-powered shuttle at the San Antonio airport.

Legislation introduced in the 2007 session of the Texas Legislature would have spurred the development of hydrogen vehicles. Several bills would have issued bonds to support a $250 million loan program to expand the use of hydrogen energy in Texas, and would have partially exempted hydrogen-related property from local property taxes. While these bills did not pass, a provision to exempt hydrogen vehicles from sales taxes did become law.[33]

In 2008, the Houston Advanced Research Center expects to begin work on a State Energy Conservation Office funded hydrogen study that could serve as the first step to a hydrogen "roadmap" — a strategic plan — similar to those developed in several other states. The final report is expected in fall 2008.

Costs and Benefits

The costs of widespread commercial applications using hydrogen for power generation or transportation appear prohibitive in today's energy market. Because of the industry's developmental nature, estimates of its costs vary widely. There are, however, some specific applications for which hydrogen-powered vehicles appear to be commercially viable. The nearest-term application is for fuel cell lift trucks (forklifts). Several industrial truck companies have announced commercial fuel cell products that can replace battery-powered forklifts. These have been extensively tested and are available for commercial purchase today. The federal government has been a major buyer of these systems.

One likely early path for the development of hydrogen is using the wide availability of natural gas and its distribution pipelines to create hydrogen for on-site fueling.

There is no market price for hydrogen intended for alternative energy use comparable to that for gasoline, for example. Hydrogen as an alternate energy carrier is in an early phase of development. Estimates of the cost of hydrogen per gallon of gas equivalent range from \$2.10 to \$9.10.[34] According to DOE, hydrogen produced from natural gas, the cheapest available method, is three to four times as expensive as gasoline, in terms of equivalent amounts of energy. In response to a recent survey, DOE said that it received some information on hydrogen prices. The average price per gasoline gallon equivalent from seven respondents was \$17.69.

Fuel cells are up to 10 times more expensive than internal combustion engines.[35] According to the U.S. Government Accountability Office, a fuel cell vehicle stack costs about \$35,000 and a fuel cell-powered vehicle costs about \$100,000.[36] Five years ago, the stack price alone would have exceeded \$100,000, indicating the progress being made toward cost reduction.

DOE's goal is to reduce the cost of hydrogen to \$2 to \$3 per gasoline gallon equivalents by 2015. Its previous goal of \$1.50, set before gasoline prices went up, was based on the use of natural gas as a source for hydrogen. The new goal is independent of the method of production, in response to questions about the environmental effects of using natural gas for hydrogen production.[37]

Environmental Impact

The environmental benefits of hydrogen are a very positive attribute. When used in a fuel cell to power an electric vehicle, the emissions include only water and heat. But hydrogen is produced using energy from natural gas, coal, solar, wind or nuclear power, each of which has its own environmental effects; the tradeoffs are much like those related to fuels used for electricity production.

One likely early path for the development of hydrogen is using the wide availability of natural gas and its distribution pipelines to create hydrogen for on-site fueling. This is the concept being used for the first Texas station in Austin. Similarly, hydrogen can be produced from the nation's abundant coal reserves. Most analyses show that the higher efficiency of hydrogen applications can result in lower greenhouse gas emissions, even when the hydrogen is produced from coal. Observers say transitional approaches relying on natural gas could facilitate the use of hydrogen technologies until production methods using other, more environmentally friendly resources become available.[38]

Other Risks

Safety is often mentioned in any discussion of hydrogen as a fuel or energy carrier.

Like many other fuels, hydrogen is highly flammable and must be handled properly to ensure its safety. In this way it is comparable to fuel sources such as gasoline or compressed natural gas (CNG), all of which are subject to safety codes and standard industrial safety practices.

Hydrogen's lightness can be an advantage in case of a leak. Since hydrogen is 14 times lighter than air, it will float upward and disperse quickly, unlike heavier fuels that may pool at ground level. But its unique properties — its small molecular size and buoyancy — mean that different techniques are required to transport, store and use hydrogen.

Hydrogen is made, shipped and used today in many industries worldwide and has an established track record in industrial use. It is only beginning to be implemented as an energy carrier on a commercial basis, however. As a result, DOE sees development of codes and standards as essential for bringing hydrogen energy systems to market.

Although some codes and standards do exist, many of these are under further development at the national level, including regulations being developed by the U.S. Department of Transportation, National Highway Traffic Safety Administration, and Environmental Protection Agency in cooperation with industry groups. The goal is to have the necessary codes and standards in place by 2012 to support the early commercialization of hydrogen energy technology.[39]

State and Federal Oversight

The National Energy Policy Act of 2005 (EPAct 2005) authorized federal funding and laid out the priorities for the development of a national hydrogen program. It also provides a guideline for federal agencies to manage specific activities related to the program.[40]

Subsidies and Taxes

The federal government has no production incentives for hydrogen. Instead, it is funding basic research and demonstration projects. Again, federal funding for the nation's Hydrogen Fuel Initiative totaled $274 million in 2007, and the administration has requested more than $309 million for 2008.[41]

Hydrogen fuel cells are eligible for funding under TCEQ's Texas Emissions Reductions Plan program and the New Technology Research and Development Program. These programs, which distribute more than $150 million annually, are primarily focused on near-term diesel engine breakthroughs to reduce vehicle emissions, but fuel cells are eligible as well.

The 2007 Texas Legislature considered several initiatives to fund hydrogen incentives; the one bill that passed provides a sales tax exemption for hydrogen vehicles.

Other States and Countries

California is arguably the world leader in adopting hydrogen power. In 2004, an executive order by California Governor Arnold Schwarzenegger initiated the California Hydrogen Highway Network, to facilitate the transition to what state leaders describe as a "clean hydrogen transportation economy."

The program, which comprises a series of hydrogen fueling stations, fleet vehicle demonstration projects and state purchases of hydrogen vehicles, is intended to create a hydrogen infrastructure to support the commercialization of this technology. It is expected to reduce emissions of greenhouse gases, improve air quality, spur economic growth and reduce the state's dependence on foreign oil. The California Air Resources Board is in charge of the program.

Today, largely as a result of these efforts, California has more hydrogen fuel cell-powered cars and buses on the road and more fueling stations than any other place in the world. At the end of 2006, 126 hydrogen vehicles and eight hydrogen buses were operating in California. The state had 24 hydrogen fueling stations in operation and another 13 in the planning stages. Fifteen of the 24 stations are open to the public, while the rest are used by vehicle fleets or in demonstration and test projects. The state goal is to have 50 stations operating by 2010.

California has more hydrogen fuel cell-powered cars and buses on the road and more fueling stations than any other place in the world.

At present, these vehicles and stations are clustered in the state's two largest population centers, the San Francisco Bay area and greater Los Angeles. In 2005, the California Legislature allocated $6.5 million for purchase of more fueling stations and vehicles. Recent legislation also included a goal that at least 33 percent of the hydrogen used in the new transportation system should be produced from renewable resources.[42]

New York and Florida also have taken steps to encourage the development of hydrogen power.

The New York State Energy Research and Development Authority (NYSERDA) produced *The New York State Hydrogen Energy Roadmap* in 2005. This plan defines the state's goals for using hydrogen as both a transportation fuel and a stationary power source by 2020.

Strategies proposed by NYSERDA include supporting research and development, demonstrating innovative technologies, developing a supportive business climate and promoting early adoption of the new technologies. The plan calls for placing hydrogen fueling stations along roads running from Buffalo to New York City to complement the development of commercially available hydrogen-powered vehicles. In 2007, NYSERDA funded 11 research and demonstration projects valued at $2.9 million.[43]

In 2003, Florida launched "H_2 Florida" to speed the commercialization of hydrogen technology. The program's goal is to showcase new technologies and educate consumers about hydrogen. In May 2007, Florida Governor Charlie Crist and other dignitaries officially opened the state's first hydrogen energy demonstration station. Located in Orlando, it fuels shuttle buses at the Orlando International Airport and Orange County Convention Center. These Ford shuttle buses burn hydrogen in internal combustion engines.[44]

European countries have made significant efforts, individually and collectively, in hydrogen-related research and demonstration activities. Perhaps the best-known project is Clean Urban Transport for Europe (CUTE). This 2003 through 2005 project was co-financed by the European Commission (EC) and its member nations. Its focus was a demonstration project that put 27 fuel cell buses into operation in public fleets in nine cities in seven countries. Companion projects took place in Australia, China and Iceland.

Many energy industry participants say that hydrogen has a potentially important role as part of a the state's energy portfolio.

The CUTE project used various approaches to fuel its buses. Natural gas was used to generate hydrogen, as was the electrolysis of water; in some instances, hydrogen was trucked in from refineries. All of the buses used PEM fuel cells.[45] Since the conclusion of the first demonstration project, the EC has initiated another public-private partnership with industry for hydrogen research and development. The plan is to create more hydrogen supply and improve fuel cell technology for stationary as well as portable applications. The EC will provide the equivalent of $664 million while industry matches that amount. The goal is to develop the technology enough to make it commercially viable.[46]

Japan's Ministry of Economy, Trade and Industry (METI) is planning to spend the equivalent of $1.7 billion over the next five years to develop new power trains and fuels to cut reliance on petroleum and cut carbon dioxide emissions. The plan includes work on batteries and clean diesel but the biggest focus is on hydrogen. METI's goal is to spend the equivalent of $1.3 billion on research and development to create fuel cell vehicles that could be produced at the same cost as gasoline vehicles by 2030.[47]

Outlook for Texas

There are no major controversial public issues related to hydrogen in Texas today. While most of the proposed legislation related to hydrogen failed in the 2007 legislative session, there was no negative testimony or public controversy.

Many energy industry participants say that hydrogen has a potentially important role as part of a the state's energy portfolio, and may provide a reasonable alternative for specific transportation applications such as fleet vehicles and for certain power generation applications requiring "clean" power. Stricter vehicle emission standards have been a key factor in spurring hydrogen research by carmakers.

Supporters of hydrogen power cite three major benefits: energy security, environmental benefits and economic growth.[48] Hydrogen can be produced from various domestic energy sources including both fossil and renewable fuels. If it is produced using renewable or nuclear sources, or fossil fuels with carbon-capturing technology, it will produce almost no emissions. The technology is flexible and can be used for transportation and large or small-scale power needs.

Fuel cells are two to three times more efficient in converting fuel to power than internal combustion engines. They yield almost no pollutants and are quiet.[49]

According to DOE, "the greatest technical challenge to hydrogen is cost reduction."[50] Costs for fuel cells and the hydrogen needed to run them are significantly higher than costs for internal combustion engines and fossil fuels. The durability of fuel cells poses another hurdle to commercialization, because they do not yet operate as long as a gasoline or diesel engine. The size and weight of hydrogen storage tanks and the resulting costs are the biggest barriers to hydrogen production and distribution.[51]

The U.S. government has chosen to invest significant public funds to overcome these barriers. With the completion of the President's Hydrogen

U.S. Vision for a Hydrogen Economy

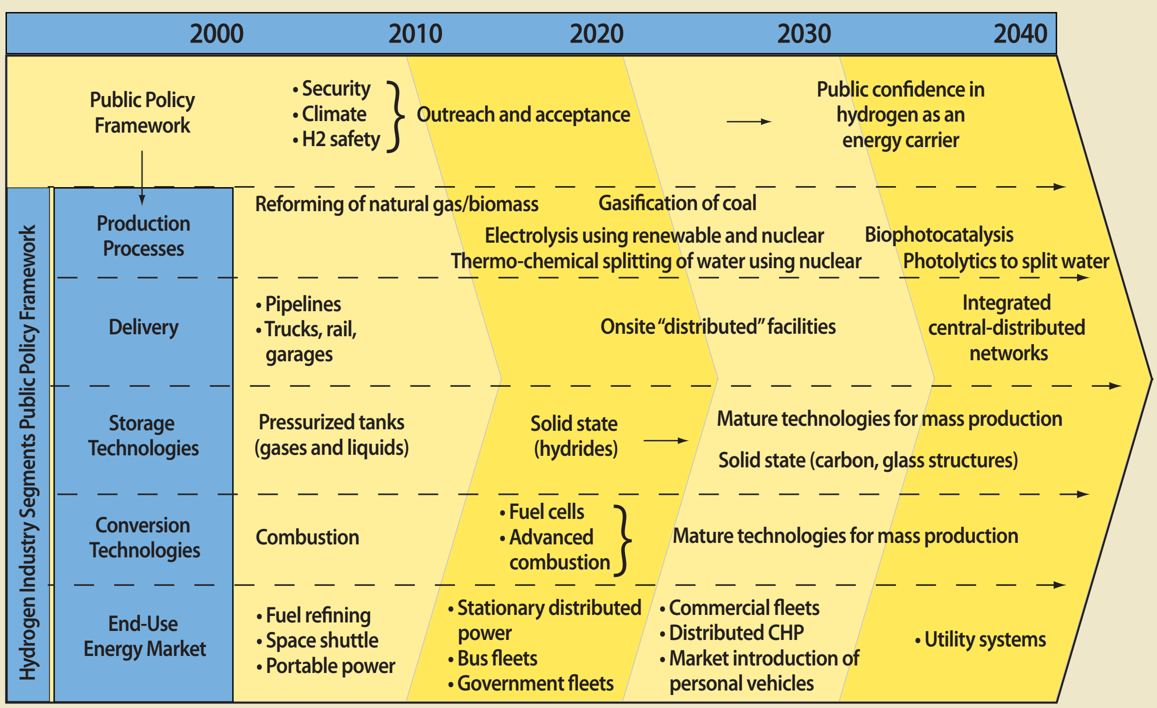
In 2001, the U.S. Department of Energy held a meeting of 53 senior executives representing energy and transportation industries, universities, environmental organizations, federal and state agencies and national laboratories to discuss the potential role of hydrogen systems in America's energy future. Billed as a forum to create a national vision for hydrogen, the meeting's participants discussed the timeframe and key milestones that would have to be met for hydrogen to become a premier energy carrier. The five major findings of the report are quoted verbatim below:

- Hydrogen has the potential to solve two major energy challenges that confront America today: reducing dependence on petroleum imports and reducing pollution and greenhouse gas emissions.
- There is general agreement that hydrogen could play an increasingly important role in America's energy future. Hydrogen is an energy carrier that provides a future solution for America. The complete transition to a hydrogen economy could take several decades.
- The transition toward a so-called "hydrogen economy" has already begun. We have a hydrocarbon economy, but we lack the know-how to produce hydrogen from hydrocarbons and water, and deliver it to consumers in a clean, affordable, safe, and convenient manner as an automotive fuel or for power generation.
- The "technology readiness" of hydrogen energy systems needs to be accelerated, particularly in addressing the lack of efficient, affordable production processes; lightweight, small volume, and affordable storage devices; and cost-competitive fuel cells.
- There is a "chicken-and-egg" issue regarding the development of a hydrogen energy infrastructure. Even when hydrogen utilization devices are ready for broad market applications, if consumers do not have convenient access to hydrogen as they have with gasoline, electricity, or natural gas today, then the public will not accept hydrogen as "America's clean energy choice."[52]

Exhibit 22-5 summarizes DOE's vision of the transition to a hydrogen economy.

Exhibit 22-5

Transition to a Hydrogen Economy



Source: U.S. Department of Energy.

Fuel Initiative in 2008, however, it is not certain that the current level of federal funding available to the field will continue. It appears, though, that higher energy prices have again stirred at least a temporary national interest in alternative and renewable energy, as they did in the aftermath of the energy crisis of the 1970s. Even more importantly, growing interest in carbon reduction strategies at the national level may spur hydrogen's use as an alternative energy carrier or fuel.

California has embraced hydrogen's potential and has committed significant state resources to become a leader in this new industry. As a result, if the transition to hydrogen indeed occurs, the state will be well placed to enjoy its economic benefits. New York, Ohio, Michigan, South Carolina, and Florida have chosen to support development of hydrogen as well.

Texas has some potential advantages over these states in the development of hydrogen as an energy source. Texas has a large and knowledgeable energy sector with experience in handling hydrogen, as well as a hydrogen pipeline network. It also has an extensive natural gas production and transmission infrastructure, important since natural gas is the most common material used to create hydrogen. On the demand side of the equation, Texas has both metropolitan bus fleets and passenger vehicle fleets that could use hydrogen.

But the state has made relatively few investments to capitalize on its advantages, and has lagged behind other states in attracting federal funds for research and demonstration projects, probably because many federal grants require local or state matching contributions.

Hydrogen power presents significant technological challenges, and its further development will depend upon advancements that may require a longer time frame than other options such as biofuels. New, lower-cost technologies needed to commercialize it may never materialize. But many in industry and the research community remain convinced that these hurdles will be overcome, and without additional financial commitments, Texas may be left behind in the transition to a new energy source — and a new economy.

Endnotes

1 New York State Energy Research and Development Authority, "Hydrogen Fact Sheet: The Basics of Hydrogen," pp. 1-3, http://www.getenergysmart.org/Files/HydrogenEducation/4TheBasicsofHydrogen.pdf.(Last visited January 29, 2008.)

2 The National Hydrogen Association, "The History of Hydrogen," http://www.hydrogenassociation.org/general/factSheets.asp. (Last visited November 13, 2007.)

3 New York State Energy Research and Development Authority, "Hydrogen Fact Sheet: History of Hydrogen," p. 2, http://www.getenergysmart.org/Files/Schools/Hydrogen/3HistoryofHydrogen.pdf. (Last visited April 29, 2008.)

4 The National Hydrogen Association, "The History of Hydrogen."

5 U.S. Department of Energy, "Hydrogen Program Budget," http://www.hydrogen.energy.gov/budget.html. (last visited November 13, 2007.)

6 U.S. Department of Energy, Fuel Cell Report to Congress (Washington, D.C, February 2003), p. 4, www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb2003.pdf. (Last visited November 13, 2007.)

7 U.S. Department of Energy, *Roadmap on Manufacturing R&D for the Hydrogen Economy* (Washington, D.C., December 2005), p. ES-1, http://www.hydrogen.energy.gov/pdfs/roadmap_manufacturing_hydrogen_economy.pdf. (Last visited November 13, 2007.)

8 General Motors Corporation, "Chevrolet to Launch World's Largest Fuel Cell Vehicle Fleet," http://www.gm.com/explore/technology/news/2006/fc_fleet_launch_091806.jsp. (Last visited November 13, 2007.)

9 John Reed, "Honda to Put its Zero-Emission Hydrogen Car on Roads Next Year," *Financial Times* (November 15, 2007), http://www.ft.com/cms/s/0/2ae5abda-9320-11dc-ad39-0000779fd2ac.html. (Last visited November 15, 2007.)

10 Email communication from Brian Weeks, associate director, Advanced Energy Systems, Gas Technology Institute, January 19, 2008.

11 National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Barriers, and R&D Needs* (Washington, D.C., 2004), pp. 14-19, available as a series of pdf documents at http://www.nap.edu/openbook.php?isbn=0309091632. (Last visited November 29, 2007.)

12 National Hydrogen Association, "Hydrogen Fueling Stations," http://www.hydrogenassociation.org/general/fuelingSearch.asp. (Last visited July 16, 2007.)

13 National Renewable Energy Laboratory, *Power Technologies Energy Data Book*, Fourth Edition (Golden, Colorado, August 2006), p. 41, http://www.nrel.gov/analysis/power_databook/chapter2.html. (Last visited November 14, 2007.)

14 Texas State Energy Conservation Office, *Accelerating the Commercialization of Fuel Cells in Texas* (Austin, Texas, 2002), p. 6, http://www.seco.cpa.state.tx.us/zzz_feulcell-initiative/fciac_finalreport.pdf. (Last visited November 14, 2007.)

15 U.S. Department of Energy, "Hydrogen Production," http://www.hydrogen.energy.gov/pdfs/doe_h2_production.pdf. (Last visited November 14, 2007.)

16 U.S. Department of Energy and U.S. Department of Transportation, *Hydrogen Posture Plan: An Integrated Research, Development and Demonstration Plan* (Washington, D.C., December 2006), p. 12, www.science.doe.gov/bes/Hydrogen_Posture_Plan_DEC06.pdf. (Last visited November 13, 2007.)

17 U.S. Department of Energy, "Hydrogen Fuel Cells," http://www.hydrogen.energy.gov/pdfs/doe_fuelcell_factsheet.pdf. (last visited November 14, 2007.)

18 Fuel Cells 2000, "Fuel Cell Basics," http://www.fuelcells.org/basics/types.html. (Last visited July 16, 2007.)

19 National Hydrogen Association, "The Basics," http://www.hydrogenassociation.org/general/basics.asp. (Last visited July 17, 2007.)

20 Texas Commission on Environmental Quality, *On-site Hydrogen Generation and Fueling System with a Hydrogen-fueled Vehicle*, by Ken Kriha, Tony Lindsay, Brian Weeks and David Zuckerman, Gas Technology Institute, (Austin, Texas, July 2007), p. 3.

21 National Hydrogen Association, "The Basics."

22 Texas Department of Transportation, TxDOT *Strategic Plan for Hydrogen Vehicles and Fueling Stations, Final Report*, (Austin, Texas, Austin 2006), p. 2, http://www.sfcc.tv/TxDOT%20Strategic%20Plan%20Report%20FINAL.pdf. (Last visited January 25, 2008.)

23 U.S. Department of Energy, "Hydrogen Storage," http://www.hydrogen.energy.gov/pdfs/doe_h2_storage.pdf. (Last visited November 29, 2007.)

24 U.S. Department of Energy, "The 'National Hydrogen Storage Project,'" http://www1.eere.energy.gov/hydrogenandfuelcells/storage/national_proj.html. (Last visited January 30, 2008.)

25 Air Liquide, "Major Expansion of Hydrogen System in Texas," http://www.airliquide.com/en/press/press-releases/major-expansion-of-hydrogen-system-in-texas.html. (Last visited December 5, 2007.)

26 Praxair, "Praxair Commercializes Industry's Only Hydrogen Storage," http://www.praxair.com/praxair.nsf/AllContent/3C9CAB9B7369BA3185 25737C005D2168?OpenDocument. (Last visited December 5, 2007.)

27 Texas Department of Transportation, *TxDOT Strategic Plan for Hydrogen Vehicles and Fueling Stations, Final Report*, p. 18.

28 Texas Commission on Environmental Quality, *On-Site Hydrogen Generation and Fueling System with a Hydrogen-fueled Vehicle*, by Ken Kriha, Tony Lindsay, Brian Weeks and David Zuckerman, Gas Technology Institute (Austin, Texas, July 2007), p. 5.

29 Interview with Robert Hebner and Richard Thompson, Center for Electromechanics, University of Texas at Austin, and Brian Weeks, associate director, Gas Technology Institutes' Hydrogen Energy System Working Group, Austin Texas, May 11, 2007.

30 Texas Department of Transportation, *TxDOT Strategic Plan for Hydrogen Vehicles and Fueling Stations, Final Report*, pp. 18-19.

31 Texas State Energy Conservation Office, *Accelerating the Commercialization of Fuel Cells in Texas*, pp. iv-v.

32 Texas Department of Transportation, *TxDOT Strategic Plan for Hydrogen Vehicles and Fueling Stations, Final Report*, p. iii.

33 E-mail communication from Patrice "Pete" Parsons Marshall, executive director, Texas H2 Coalition, June 11, 2007; and interview with Patrice "Pete" Parsons Marshall, executive director, Texas H2 Coalition, Austin, Texas, April 25, 2007.

34 The National Hydrogen Association, "Frequently Asked Questions: How Much Does Hydrogen Cost?" http://www.hydrogenassociation.org/general/faqs.asp#cost (Last visited January 31, 2008).

35 U.S. Department of Energy, "President's Hydrogen Fuel Initiative: A Secure Energy Future," www.hydrogen.energy.gov/presidents_initiative.html. (Last visited November 14, 2007.)

36 U.S. Government Accountability Office, *Crude Oil: Uncertainty About Future Oil Supply Makes it Important to Develop a Strategy for Addressing a Peak and Decline in Oil Production* (Washington, D.C., February 2007), p. 66, http://searching.gao.gov/query.html?qt=gao-07-283&rf=2&amo=0&ayr=0&bmo=0&byr=0&col=audprod&col=lglview&charset=iso-8859-1. (Last visited November 14, 2007.)

37 U.S Department of Energy, "DOE Announces New Hydrogen Cost Goal," http://www.hydrogen.energy.gov/news_cost_goal.html. (Last visited December 10, 2007.)

38 Email communication from David Hitchcock, director, Sustainable Transportation Programs, Houston Advanced Research Center, November 1, 2007.

39 U.S. Department of Energy, *Hydrogen Fuel Cells and Infrastructure Technologies Program Multiyear Research Development and Demonstration Plan* (Washington, D.C., October 2007), pp. 3.7-1 – 3.7-3, http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/codes.pdf. (Last visited January 30, 2008.)

40 U.S. Department of Energy, *Roadmap on Manufacturing R&D for the Hydrogen Economy* (Washington, D.C., December 2005), p. 1, http://www.hydrogen.energy.gov/pdfs/roadmap_manufacturing_hydrogen_economy.pdf. (Last visited November 13, 2007.)

[41] U.S. Department of Energy, "Hydrogen Program Budget."

[42] California Air Resources Board, *California Hydrogen Highway Network: Year End Progress Report to the Legislature* (Sacramento, California, December 2006), pp. 1-4, http://www.hydrogenhighway.ca.gov/facts/yepr_fa.pdf. (Last visited November 29, 2007.)

[43] New York State Energy Research and Development Authority, "$2.88m for 11 NYSERDA Hydrogen Development and Demo Projects; Major NY Corporations and Universities Pursue New Uses for Clean Fuel, February 6, 2007," http://www.nyserda.org/Press_Releases/2007/PressRelease20070602.asp (last visited November 11, 2007); and New York State Energy Research and Development Authority, "Hydrogen Energy Roadmap to Future Economic Development Report Released: Report Cites State Resources and Benefits for Energy and Economic Security," October 31, 2005, http://www.nyserda.org/Press_Releases/2005/PressRelease20053110.asp. (Last visited November 11, 2007.)

[44] Florida Department of Environmental Protection, "Governor Crist Celebrates Opening of Florida's First Hydrogen Demonstration Station," http://www.dep.state.fl.us/secretary/news/2007/05/0523_01.htm. (Last visited November 15, 2007.)

[45] European Commission, Directorate for Energy and Transport, "Clean Urban Transportation for Europe: Detailed Summary of Achievements," http://ec.europa.eu/energy/res/fp6_projects/doc/hydrogen/deliverables/summary.pdf. (Last visited December 6, 2007.)

[46] Green Car Congress, "European Commission Adopts 940M Fuel Cells and Hydrogen Joint Technology Initiative," www.greencarcongress.com/2007/10/european-commis.html. (Last visited November 16, 2007.)

[47] Green Car Congress, "Japan Plans to Spend $1.72 Billion Over 5 Years to Spur Development of Low-Carbon Powertrains and Fuels," www.greencarcongress.com/2007/05/japan_plans_to_.html. (Last visited November 16, 2007.)

[48] National Hydrogen Association, "Key Hydrogen Messages," p. 2, http://www.hydrogenassociation.org/pdf/keyHydrogenMessages.pdf. (Last visited November 14, 2007.)

[49] U.S. Department of Energy, "U.S. Department of Energy Hydrogen Program," http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_program.pdf. (Last visited November 15, 2007.)

[50] U.S. Department of Energy, "Hydrogen Production."

[51] U.S. Department of Energy, *Fuel Cells and Infrastructure Technologies: Transition Strategies*, by Sig Gronich (Washington, D.C., March 8, 2006), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/transition_wkshp_strategies2.pdf. (Last visited December 6, 2007.)

[52] U.S. Department of Energy, *A National Vision of America's Transition to A Hydrogen Economy—to 2030 and Beyond* (Washington D.C. February 2002) p. iii, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/vision_doc.pdf (last visited January 29, 2008.)