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HYDROGEN[i]

Hydrogen has the potential to revolutionize transportation and, possibly, our entire energy system. The simplest and most abundant element in the universe, hydrogen can be produced from fossil fuels and biomass and even by electrolyzing water. Producing hydrogen with renewable energy and using it in fuel cell vehicles holds the promise of virtually pollution-free transportation and independence from imported petroleum.

Hydrogen (H2) is a potentially emissions-free alternative fuel that can be produced from domestic resources. Although not widely used today as a transportation fuel, government and industry research and development are working toward the goal of clean, economical, and safe hydrogen production and hydrogen vehicles. This page lists basic hydrogen topics. To learn more, choose from the following pages.

HYDROGEN AS AN ALTERNATIVE FUEL

The interest in hydrogen as an alternative transportation fuel stems from its clean-burning qualities, its potential for domestic production, and the fuel cell vehicle's potential for high efficiency (two to three times more efficient than gasoline vehicles). Hydrogen is considered an alternative fuel under the Energy Policy Act of 1992.

The energy in 2.2 lb (1 kg) of hydrogen gas is about the same as the energy in 1 gallon of gasoline. A light-duty fuel cell vehicle must store 11-29 lb (5-13 kg) of hydrogen to enable an adequate driving range of 300 miles or more. Because hydrogen has a low volumetric energy density (a small amount of energy by volume compared with fuels such as gasoline), storing this much hydrogen on a vehicle using currently available technology would require a very large tank—larger than the trunk of a typical car. Advanced technologies are needed to reduce the required storage space and weight.

Storage technologies under development include high-pressure tanks with gaseous hydrogen compressed at up to 10,000 pounds per square inch, cryogenic liquid hydrogen cooled to -423°F (-253°C) in insulated tanks, and chemical bonding of hydrogen with another material (such as metal hydrides).

BACKGROUND

Hydrogen as an energy carrier or a fuel has the potential to be a clean, practical, renewable, and sustainable energy source. Collectively, these energy and environmental benefits will help to achieve our National objectives in the development of alternative sources of energy that are plentiful, clean and convenient. Successful development and implementation of hydrogen energy systems will provide the American public with a safe, cost-effective option that can reduce our reliance on fossil fuels which are finite, imported and detrimental to both the global environment and human health. In addition, these initiatives are critical to the success of our Nation in terms of global economic competitiveness, expanding economic growth, decreasing the dependency on imported petroleum fuels, revitalizing our industrial capabilities and reducing the emissions of harmful pollutants.

Currently, hydrogen technologies are being developed for use in the utility (electric generation, process steam, co-generation), commercial and residential, and transportation sectors (light duty ZEV and near-ZEV vehicles). The resulting hydrogen based energy systems and devices, will be safe, practical and competitive. However, various economic and technical issues have prevented the widespread use of hydrogen in energy applications. Therefore, there is a need for a careful review and assessment of all projects and implementation of a new program designed to assist in those projects and/or companies so that their research and development activities will lend themselves to product commercialization.

As a renewable, sustainable and practical energy source, hydrogen has the potential to be produced, stored/transported and utilized at competitive prices. In addition, this initiative is critical to the success of our Nation in terms of reducing oil imports, improving the economy and reducing climate-changing emissions and other pollutants. These goals are being accomplished by investments in research and development programs in the areas of hydrogen production, hydrogen storage/transportation and hydrogen utilization.

HYDROGEN BENEFITS

Hydrogen can be produced from diverse domestic resources, with the potential for near-zero greenhouse gas emissions. Once produced, it generates power without exhaust emissions in fuel cells. It holds promise for economic growth in both the stationary and transportation energy sectors.

Increasing Energy Security

The United States imports more than 60% of its petroleum, two-thirds of which is used to fuel vehicles in the form of gasoline and diesel. The demand for petroleum imports is increasing. With much of the worldwide petroleum reserves located in politically volatile countries, the United States is vulnerable to supply disruptions.

No matter how efficient conventional vehicles become, some of the gasoline and diesel needed to fuel them will need to be imported. Hydrogen can be produced domestically from resources such as natural gas, coal, solar energy, wind, biomass, and nuclear energy. Used to power highly efficient fuel cell vehicles, hydrogen holds the promise of an end to the nation's "addiction to oil."

Protecting Public Health and the Environment

About half of the U.S. population lives in areas where air pollution levels are high enough to negatively impact public health or the environment. Emissions from gasoline and diesel vehicles—such as nitrogen oxides, hydrocarbons, and particulate matter—are a major source of this pollution. Hydrogen-powered fuel cell vehicles emit none of these harmful substances. Their only emission is H_2O—water.

The environmental and health benefits are even greater when hydrogen is produced from low- or zero-emission sources such as solar, wind, and nuclear energy and fossil fuels with advanced emission controls and carbon sequestration. Because the transportation sector accounts for about one third of U.S. carbon dioxide emissions, which contribute to climate change, using these sources to produce hydrogen for transportation can slash greenhouse gas emissions.

Fueling the Economy

The potential market for hydrogen vehicles is enormous, but the opportunities don't stop there. Hydrogen and fuel cells can power stationary applications such as backup generators, and grid electricity production. They can also compensate for the intermittency of renewable energy production. For example, wind generators can produce hydrogen when winds are high and electricity demand is low (learn more by going to the National Renewable Energy Laboratory's Wind to Hydrogen page). When the wind slackens or electricity demand peaks, fuel cells consume the stored hydrogen to provide grid electricity.

The United States stands to profit from hydrogen technologies. A recent study projected global annual demand for stationary and transportation fuel cell products to reach $46 billion by 2011 and more than $2.5 trillion by 2021. Government and industry investment in hydrogen and fuel cell technologies has positioned the United States as a leader in this rapidly growing market.

HYDROGEN FUEL CELLS

National effort is under way to make hydrogen-powered fuel cell vehicles a key element of future transportation systems. How do we determine if technological progress is meeting goals for key factors for consumer acceptance?

Hydrogen-powered fuel cell vehicles could play a central role in future transportation systems. They produce only electricity, heat, and water at point of use. They could also use predominantly domestic—potentially renewable—energy supplies instead of imported oil to help meet one of our most pressing energy needs. Consequently, there has been great interest in hydrogen as a primary “energy carrier” displacing petroleum-based fuels.

Moving to extensive use of hydrogen and fuel cells would involve complex and substantial developments and investments in hydrogen production, hydrogen distribution and storage, fuel cell technology, vehicle technology, and other aspects of energy and transportation infrastructure. The U.S. Department of Energy (DOE) has a major program for research and development of hydrogen and fuel cell technology. A key element of that research and development is the five-year, $175-million industry-cost-shared “Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project.”

Through a 2003 competitive solicitation, DOE selected four automobile manufacturer/energy company teams to participate in the project— Chevron/Hyundai-Kia, DaimlerChrysler/BP, Ford/BP, and GM/Shell. DOE is cost-share funding those teams to build small fleets of fuel-cell vehicles plus fueling stations to demonstrate their use in five regions in the United States. The five test regions are in Northern California, Southern California, Southeastern Michigan, the Mid-Atlantic, and Central Florida, covering a range of temperature and humidity conditions.

HYDROGEN FUEL CELL TECHNOLOGY

A fuel cell is an electrochemical conversion device. It produces electricity from fuel (on the anode side) and an oxidant (on the cathode side), which react in the presence of an electrolyte.

The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate virtually continuously as long as the necessary flows are maintained.

Fuel cells are different from electrochemical cell batteries in that they consume reactant from an external source, which must be replenished – a thermodynamically open system. By contrast, batteries store electrical energy chemically and hence represent a thermodynamically closed system.

Many combinations of fuels and oxidants are possible. A hydrogen fuel cell uses hydrogen as its fuel and oxygen (usually from air) as its oxidant. Other fuels include hydrocarbons and alcohols. Other oxidants include chlorine and chlorine dioxide.

The principle of the fuel cell had been demonstrated by Sir William Grove in 1839, and other investigators had experimented with various forms of fuel cell. The first practical fuel cell was developed by Francis Thomas Bacon in 1959.

FUEL CELL DESIGN

A fuel cell works by catalysis, separating the component electrons and protons of the reactant fuel, and forcing the electrons to travel through a circuit, hence converting them to electrical power. The catalyst typically comprises of a platinum group metal or alloy. Another catalytic process puts the electrons back in, combining them with the protons and oxidant to form waste products (typically simple compounds like water and carbon dioxide).

A typical fuel cell produces a voltage from 0.6 V to 0.7 V at full rated load. Voltage decreases as current increases, due to several factors:

- Activation loss
- Ohmic loss (voltage drop due to resistance of the cell components and interconnects)
- Mass transport loss (depletion of reactants at catalyst sites under high loads, causing rapid loss of voltage)

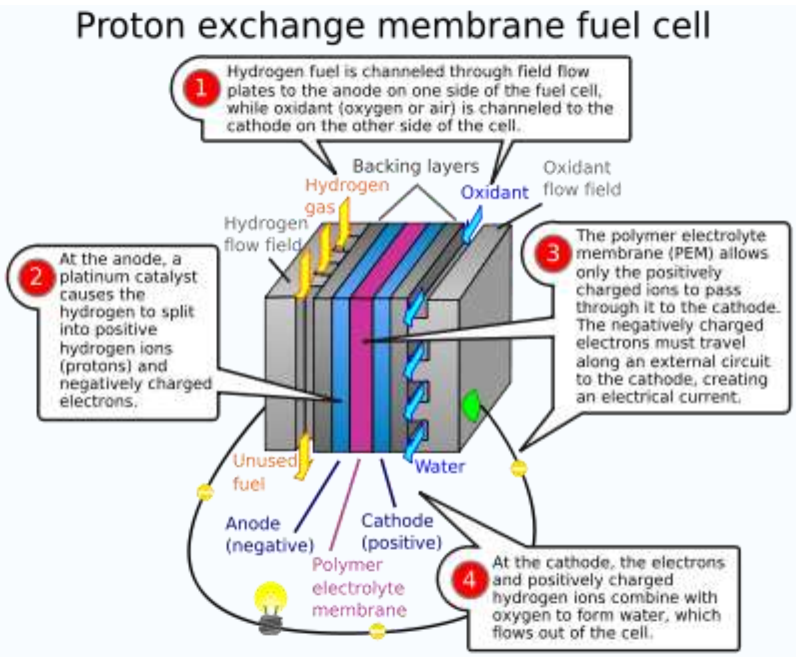
To deliver the desired amount of energy, the fuel cells can be combined in series and parallel circuits, where series yields higher voltage, and parallel allows a stronger current to be drawn. Such a design is called a fuel cell stack. Further, the cell surface area can be increased, to allow stronger current from each cell.

Proton exchange fuel cells

In the archetypal hydrogen–oxygen proton exchange membrane fuel cell (PEMFC) design, a proton-conducting polymer membrane, (the electrolyte), separates the anode and cathode sides. This was called a "solid polymer electrolyte fuel cell" (SPEFC) in the early 1970s, before the proton exchange mechanism was well-understood. (Notice that "polymer electrolyte membrane" and "proton exchange mechanism" result in the same acronym.).

On the anode side, hydrogen diffuses to the anode catalyst where it later dissociates into protons and electrons. These protons often react with oxidants causing them to become what is commonly referred to as multi-facilitated proton membranes (MFPM). The protons are conducted through the membrane to the cathode, but the electrons are forced to travel in an external circuit (supplying power) because the membrane is electrically insulating. On the cathode catalyst, oxygen molecules react with the electrons (which have traveled through the external circuit) and protons to form water — in this example, the only waste product, either liquid or vapor.

In addition to this pure hydrogen type, there are hydrocarbon fuels for fuel cells, including diesel, methanol (see: direct-methanol fuel cells and indirect methanol fuel cells) and chemical hydrides. The waste products with these types of fuel are carbon dioxide and water.



Source: Wikipedia, http://en.wikipedia.org/wiki/File:PEM_fuelcell.svg

Construction of a high temperature PEMFC: Bipolar plate as electrode with in-milled gas channel structure, fabricated from conductive plastics (enhanced with carbon nanotubes for more conductivity); Porous carbon papers; reactive layer, usually on the polymer membrane applied; polymer membrane.

Condensation of water produced by a PEMFC on the air channel wall. The gold wire around the cell ensures the collection of electric current.

The materials used in fuel cells differ by type. In a typical membrane electrode assembly (MEA), the electrode–bipolar plates are usually made of metal, nickel or carbon nanotubes, and are coated with a catalyst (like platinum, nano iron powders or palladium) for higher efficiency. Carbon paper separates them from the electrolyte. The electrolyte could be ceramic or a membrane.

Oxygen ion exchange fuel cells

In a solid oxide fuel cell (SOFC) design, the anode and cathode are separated by an electrolyte that is conductive to oxygen ions but non-conductive to electrons. The electrolyte is typically made from zirconia doped with yttria.

On the cathode side, oxygen catalytically reacts with a supply of electrons to become oxygen ions, which diffuse through the electrolyte to the anode side. On the anode side, the oxygen ions react with hydrogen to form water and free electrons. A load connected externally between the anode and cathode completes the electrical circuit.

Molten carbonate fuel cells (MCFCs) operate in a similar manner, except the electrolyte consists of liquid (molten) carbonate, which is a negative ion and an oxidizing agent. Because the electrolyte loses carbonate in the oxidation reaction, the carbonate must be replenished through some means. This is often performed by recirculating the carbon dioxide from the oxidation products into the cathode where it reacts with the incoming air and reforms carbonate.
Unlike proton exchange fuel cells, the catalysts in SOFCs and MCFCs are not poisoned by carbon monoxide, due to much higher operating temperatures. Because the oxidation reaction occurs in the anode, direct utilization of the carbon monoxide is possible. Also, steam produced by the oxidation reaction can shift carbon monoxide and steam reform hydrocarbon fuels inside the anode. These reactions can use the same catalysts used for the electrochemical reaction, eliminating the need for an external fuel reformer.

Proton exchange membrane fuel cell design issues

- Costs. In 2002, typical fuel cell systems cost US$1000 per kilowatt of electric power output. In 2008, the Department of Energy reported that fuel cell system costs in volume production are $73 per kilowatt.[citation needed] The goal is $35 per kilowatt. In 2008 UTC Power has 400kW stationary fuel cells for $1,000,000 per 400kW installed costs. The goal is to reduce the cost in order to compete with current market technologies including gasoline internal combustion engines. Many companies are working on techniques to reduce cost in a variety of ways including reducing the amount of platinum needed in each individual cell. Ballard Power Systems have experiments with a catalyst enhanced with carbon silk which allows a 30% reduction (1 mg/cm² to 0.7 mg/cm²) in platinum usage without reduction in performance. Monash University, Melbourne uses PEDOT instead of platinum.
- The production costs of the PEM (proton exchange membrane). The Nafion membrane currently costs $565.92/m². In 2005 Ballard Power Systems announced that its fuel cells will use Solupor, a porous polyethylene film patented by DSM.
- Water and air management[9] (in PEMFCs). In this type of fuel cell, the membrane must be hydrated, requiring water to be evaporated at precisely the same rate that it is produced. If water is evaporated too quickly, the membrane dries, resistance across it increases, and eventually it will crack, creating a gas "short circuit" where hydrogen and oxygen combine directly, generating heat that will damage the fuel cell. If the water is evaporated too slowly, the electrodes will flood, preventing the reactants from reaching the catalyst and stopping the reaction. Methods to manage water in cells are being developed like electroosmotic pumps focusing on flow control. Just as in a combustion engine, a steady ratio between the reactant and oxygen is necessary to keep the fuel cell operating efficiently.
- Temperature management. The same temperature must be maintained throughout the cell in order to prevent destruction of the cell through thermal loading. This is particularly challenging as the $2H_2 + O_2 \rightarrow 2H_2O$ reaction is highly exothermic, so a large quantity of heat is generated within the fuel cell.
- Durability, service life, and special requirements for some type of cells. Stationary fuel cell applications typically require more than 40,000 hours of reliable operation at a temperature of -35 °C to 40 °C (-31 °F to 104 °F), while automotive fuel cells require a 5,000 hour lifespan (the equivalent of 150,000 miles) under extreme temperatures. Current service life is 7,300 hours under cycling conditions. Automotive engines must

also be able to start reliably at -30 °C (-22 °F) and have a high power to volume ratio (typically 2.5 kW per liter).
- Limited carbon monoxide tolerance of the cathode.

HYDROGEN PRODUCTION

Hydrogen is an energy carrier, not an energy source. Energy is required to separate it from other compounds. Once produced, hydrogen stores energy until it is delivered in a usable form, such as hydrogen gas delivered into a fuel cell.

Hydrogen can be produced from diverse, domestic resources including fossil fuels, nuclear energy, biomass, and other renewable energy technologies. The environmental impact and energy efficiency of hydrogen depends greatly on how it is produced.

The following are some ways to produce hydrogen. Many are in the early stages of development.

- Natural gas reforming—"synthesis gas" is created by reacting natural gas with high-temperature steam or by partial oxidation. The synthesis gas is then reacted with water to produce hydrogen
- Renewable electrolysis—an electric current generated by renewable energy technologies, such as wind or solar, splits water into hydrogen and oxygen
- Gasification—Coal or biomass is converted into gaseous components and then into synthesis gas, which is reacted with steam to produce hydrogen
- Renewable liquid reforming—renewable liquid fuels such as ethanol are reacted with high-temperature steam to produce hydrogen near the point of end-use
- Nuclear high-temperature electrolysis—heat from a nuclear reactor is used to improve the efficiency of water electrolysis to produce hydrogen
- High-temperature thermochemical water-splitting—high temperatures generated by solar concentrators or nuclear reactors drive chemical reactions that split water to produce hydrogen
- Photobiological—microbes such as green algae consume water in the presence of sunlight, producing hydrogen as a byproduct
- Photoelectrochemical—photoelectrochemical systems produce hydrogen from water using special semiconductors and energy from sunlight

Natural gas reforming using steam accounts for about 95% of the approximately 9 million tons of hydrogen produced in the United States annually. This level of hydrogen production could fuel more than 34 million cars. The major hydrogen-producing states are California, Louisiana, and Texas. Almost all of the hydrogen produced in the United States is used for refining petroleum, treating metals, producing fertilizer, and processing foods.

The primary challenge for hydrogen production is reducing the cost of production technologies to make the resulting hydrogen cost competitive with conventional transportation fuels. Government and industry research and development projects are reducing the cost as well as the environmental impacts of hydrogen production technologies.

HYDROGEN DISTRIBUTION

Most hydrogen used in the United States is produced at or very near where it is used, typically at large industrial sites. As a result, there is not yet an effective infrastructure for distributing hydrogen to the nationwide network of fueling stations that is required for widespread use of fuel cell vehicles.

Currently, hydrogen is most often distributed in the following three ways.

- Pipelines—This least-expensive way to deliver large volumes of hydrogen is limited, with only about 700 miles of pipelines in the United States located near large petroleum refineries and chemical plants in Illinois, California, and the Gulf Coast.
- High-pressure tube trailers—Transporting compressed hydrogen gas by truck, railcar, ship, or barge in high-pressure tube trailers is expensive and used primarily for distances of 200 miles or less.
- Liquefied hydrogen tankers—Cryogenic liquefaction enables hydrogen to be transported more efficiently over longer distances by truck, railcar, ship, or barge compared with using high-pressure tube trailers, even though the liquefaction process is expensive.

Creating an infrastructure to distribute hydrogen to thousands of individual fueling stations presents many challenges. Because hydrogen contains less energy per unit volume than fuels such as gasoline, transporting, storing, and delivering it to the end use are more expensive. Building a new hydrogen pipeline network involves high initial capital costs, and hydrogen's properties present unique challenges to pipeline and compressor design. However, because hydrogen can be produced from a wide variety of resources, regional or even local production of hydrogen can maximize use of local resources and minimize issues with distribution.

There are tradeoffs between centralized and distributed production to consider. Producing hydrogen centrally in large plants cuts production costs but boosts distribution costs. Producing hydrogen at the point of end-use—at fueling stations, for example—cuts distribution costs but boosts production costs because of relatively low production volumes.

Government and industry research and development projects are overcoming the barriers to efficient hydrogen distribution.

THE PLAN

The program is designed to explore the development of hydrogen as an energy system for widespread use in utility, commercial, residential, and transportation sectors. As a renewable, sustainable and practical energy source, hydrogen has the potential to be produced, stored, transported and utilized at competitive prices. In addition, the use of hydrogen can reduce oil imports and reducing climate-changing emissions and other pollutants. The goals of the Hydrogen Programs is being accomplished by investments in research and development projects in the areas of hydrogen production, hydrogen storage/transportation and hydrogen utilization.

Specifically, the approach can be segmented into the following activities.

1. **Feasibility Studies**: includes identification (informal screening): pre-selection; analysis (market and technical); and evaluation (social profitability analysis).

2. **Technology Reviews:** includes an understanding of "what the technology should do", "how does it work", and "what are proposed performance criteria"; technical study analysis (utilization of available technology, material and equipment availability, technological alternatives, resource limitations and regulatory involvement); development planning; tactics and strategies; competitive assessment (performance, features/packaging, and price); and product evaluation and analysis.

3. **Research, Development, and Technology Validation Planning**: includes the outlined approach to identify and resolve technical hurdles associated with the hydrogen technologies; the testing and validation of bench-scale, scale-up, pre-commercial, and first-of-a-kind prototypes; development plans and strategies; competitive assessment (performance, features/packaging, and price); and product evaluation and analysis.

4. **Manufacturing Planning**: includes technological alternatives; identify viable production technologies; determine side effects with National and Company policies, goals, restrictions and regulations; research and validation tests to confirm technical feasibility; estimates of fixed investments, manufacturing and start-up costs; financial analysis; detail production process; design of production organization and manufacturing plan.

5. **Marketing Planning**: includes market analyses; formal market study and marketing plan; collect available data; characterize present markets; and develop sales plan.

6. **Financial Planning**: includes estimated total project cost; estimated financing needs; prepare pro forma income statement; prepare cash flow projections; prepare pro forma balance sheet and determine project feasibility.

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[i] Information contained in this White Paper was obtained from the DoE, NREL and Wikipedia web sites.