# Hydrogen
# the
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# fire

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GLOBAL DESIGNS
FOR A SUSTAINABLE
ENVIRONMENT

# Hydrogen: The Invisible Fire

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Graphic design: Clifford and Ann Wilton

## Introduction

Hydrogen can play a dramatic role in our sustainable energy future, but to most it's unclear just how that might work. The potential contribution of hydrogen has been described in various ways from the pragmatic to the fantastic. A lack of adequate information has contributed to confusion that obscures the real promise of hydrogen.

Many proponents of hydrogen claim that it can provide an inexhaustible supply of clean, renewable energy. *But hydrogen is not an energy source.* Like electricity, it must be produced from primary energy sources, some of which are environmentally sound, others which are not. There is clearly a major opportunity for the use of hydrogen derived from renewable energy sources. Furthermore, the notion of an unlimited supply of *any* energy source will perpetuate our wasteful energy consumption patterns. We must encourage an energy philosophy rooted in energy sufficiency, using efficient and environmentally benign technologies. Hydrogen will be a key asset.

This booklet provides a primer on hydrogen, presents future potentials for hydrogen, and concludes with a vision of how hydrogen fits into the sustainable energy future.

## Properties of hydrogen

Hydrogen, symbolized in scientific shorthand as H, is one of the most abundant elements on earth.[1] When not combined with another element, hydrogen exists as a hydrogen molecule consisting of two hydrogen atoms. In this free state, under normal conditions, hydrogen is an odorless, colorless, tasteless gas. It is the lightest known substance. Gaseous hydrogen has a density about one-fourteenth (7%) that of air. Because hydrogen is chemically active, it is almost always found in combination with other elements. In its most common form on earth, it is found combined with oxygen as the water molecule, $H_2O$. It also exists in combination with carbon, oxygen, and trace elements as organic compounds.

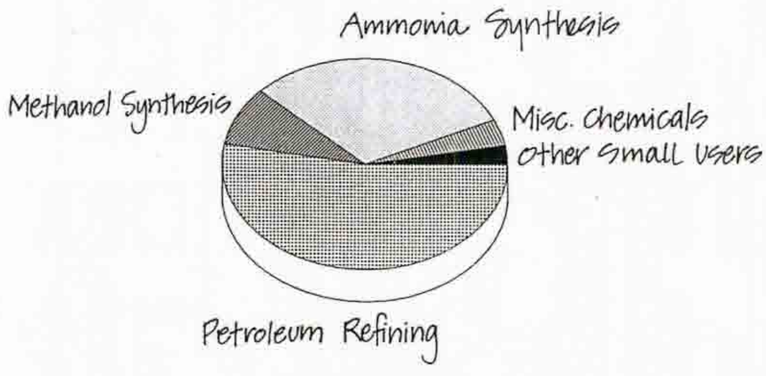
Free hydrogen is relatively stable at room temperature. It combines readily with other elements, but heat or some other form of energy is necessary to initiate such reactions. Hydrogen and oxygen, for example, will exist together at room temperature without combining. However, when hydrogen and oxygen are put together and sufficient heat is added, they combine vigorously, forming water, and releasing substantial amounts of additional heat. Combustion temperatures can reach 2800°C (5,072°F). The products of combustion are primarily heat and water, with trace amounts of nitrous oxides ($NO_x$).[2] Interestingly, hydrogen flames are almost invisible in daylight.

Hydrogen burns over a wide range of temperatures and hydrogen/air mixtures, so combustion can be tailored to minimize pollution. In internal combustion hydrogen engines, the use of very lean fuel/air mixtures, exhaust gas recirculation, or water injection could reduce $NO_x$ emissions to 10-20% of those from equivalent gasoline engines. In residential space or water heating applications, low-temperature catalytic burners would reduce $NO_x$ emissions to negligible levels.[3]

Hydrogen has another very interesting property. When hydrogen and oxygen are placed together with an electrolyte,[4] they will combine to produce water and electricity. And just as oxygen and hydrogen can combine to form water and release energy in the form of heat or electricity, so water can be dismantled into hydrogen and oxygen by the addition of sufficient energy. How these conversions take place is critical to the long term viability of the use of hydrogen.

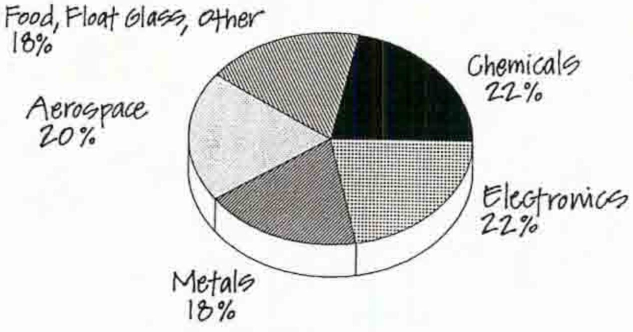
## Current uses of hydrogen

Petroleum refining and chemical industries constitute over 98% of U.S. hydrogen consumption.[5] The oil industry uses hydrogen to purify and refine petroleum products. Hydrogen is an important ingredient in the production of ammonia, ammonia-based fertilizers, and methanol. The remaining 2% of domestic U.S. hydrogen is used in a variety of industrial processes. In metal working, hydrogen is used to alter the characteristics or composition of metals and metal alloys. Hydrogenation of edible oils reduces their propensity to oxidize and become rancid and turns a liquid oil into a solid fat such as margarine. Inedible oils treated with hydrogen can be used to make soap. Gaseous hydrogen is used in a closed system to cool large electrical machines such as motors and generators because hydrogen has greater thermal conductivity and lower fluid friction losses than air.[6] Hydrogen is also used in the production of semiconductors, optical fibers and float glass.[7]



U.S. Hydrogen Uses
(9,000,000 tons per year)

Historically, hydrogen has not been widely used as a fuel. One notable exception is the aerospace industry where tens of millions of pounds of liquid hydrogen are used each year for rocket propulsion. This represents about 0.07% of the hydrogen produced annually in the U.S., or about 20% of the domestic *liquid* hydrogen production.[8]



U.S. Liquid Hydrogen Uses
(30,000 tons per year)

## Hydrogen as an energy carrier

Hydrogen is not a primary source of energy as are sunshine, wind, coal, petroleum, or natural gas. Since hydrogen must be manufactured it is more appropriately called a *synthetic fuel*, an *energy medium*, or an *energy carrier*. The use of hydrogen as an energy carrier is analogous to our current use of electricity. As an energy carrier, hydrogen would be used to store and transmit energy derived from a primary source. A variety of sources would supply the primary energy necessary to produce hydrogen.

A number of synthetic fuels including hydrogen, methane, methanol, ethanol, ammonia, and hydrazine have been considered as candidates for an energy medium of the future. Among these, hydrogen possesses unique properties that have earned it a reputation as a clean and efficient energy carrier.

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**"Hydrogen is not a primary source of energy as are coal, petroleum, or natural gas. It is more appropriately termed a synthetic fuel, an energy medium, or an energy carrier."**

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A hydrogen energy system will not likely replace electricity, but will serve as a valuable compliment, another way of storing and transporting intermittent renewable energy sources to their points of end use.

## Production of hydrogen

The production of hydrogen is more accurately described as *energy conversion*, since the hydrogen is not created. Rather it is liberated from various compounds by the addition of energy sufficient to break the chemical bonds between hydrogen and the materials with which it has combined. In general, the energy initially added to liberate hydrogen is released when the hydrogen recombines, say, in combustion with oxygen. Thus, the process of using hydrogen as a fuel originates in utilizing available energy sources to separate elemental hydrogen from various hydrogen compounds.

The versatility of hydrogen as a raw material for industrial processes, as a clean and efficient energy carrier, and as a premier fuel for aerospace propulsion, has contributed to the development of various methods for the "production" of hydrogen. The suitability of any of these energy conversion methods for use in a global energy system depends largely on the primary energy sources used, the conversion efficiency, and the environmental and economic costs.

### *Stripping hydrogen from hydrocarbons*

The common industrial approach to manufacturing hydrogen has been to strip hydrogen out of hydrocarbon fossil fuels. Some hydrogen is produced through partial oxidation of petroleum products. The major source of hydrogen over the past several decades has been natural gas, the preferred choice among the hydrocarbons because it is easy to handle and its main ingredient, methane ($CH_4$), has the highest ratio (4:1) of hydrogen to carbon.[9] Methane is used to produce hydrogen through a process called steam reforming. Since natural gas is a non-renewable resource with limited reserve supply, it should not be considered a viable long term source of hydrogen.

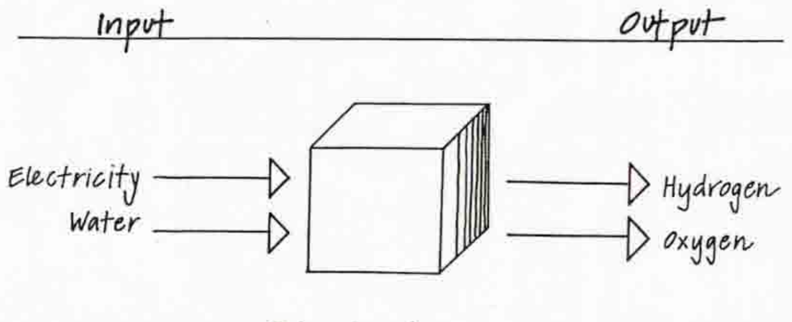
### *Coal gasification*

Coal gasification has also been suggested as a source of hydrogen although coal is considered the "ugly duckling" of the fossil fuels. In its natural state, coal is difficult to handle and process, and it frequently contains impurities that corrode equipment and disrupt processes. Coal gasification is the conversion of coal into a gas, a cleaner, more manageable fuel. Gasification processes vary. Most require that the coal be pulverized into a powder form. Sometimes water is added to form a slurry. The coal is fed into a gasifier, a high temperature vessel (800-1000°C, 1,472-1,832°F), where materials such as steam or oxygen are made to react with the coal. Depending on the exact process, the product may be methane or a mixture of hydrogen and carbon monoxide. Either of these fuels could be further processed to yield hydrogen. Coal gasification facilities may also be configured to produce both hydrogen and electricity.

Coal gasification is viewed by many as a transition technology that will provide a source of energy to supplement our dwindling supplies of oil and natural gas. It could also supply hydrogen as our energy system evolves. Such a strategy might include "scrubbers" to reduce emissions, and underground gasification ("in-situ" gasification). Facilities using the Texaco Coal Gasification Process, claimed to be the "cleanest commercially available method of coal utilization," have emissions levels far below existing EPA standards for sulfur, nitrous oxides, and particulates.[10] In spite of such commendable performance, carbon dioxide emissions are still a problem with any of the hydrocarbon fuels, and it is not clear if "clean coal" technologies would be environmentally acceptable if applied on a large scale.

### *Electrolysis of water*

Electrolysis, on the other hand, is a simple and proven method for separating water into hydrogen and oxygen. It's so simple and safe that it is frequently conducted as a high school or even grade school science experiment! Two electrodes, one positive and one negative, are immersed into pure water that has been made more conductive by the addition of a chemical electrolyte, either acidic or basic, such as sulfuric acid or potassium hydroxide. A direct-current electrical source is applied to the electrodes. The added electrical energy causes the water molecules to separate into hydrogen and oxygen. Hydrogen is attracted to the negatively charged electrode, oxygen to the positively charged electrode. The gases can then be collected as they rise to the surface of the water. An actual electrolysis plant would be considerably more complex than the simple configuration just described, but the basic technology has been around for decades and the process is well understood.



Electrolyzer

Industrial electrolyzers convert electrical energy to hydrogen energy at efficiencies of about 60-75% and laboratory models have reached 85-95%. A reasonable, practical target for improved electrolyzers appears to be nearly 100%.[11] The energy efficiency of electrolysis can be increased by the addition of heat, which is generally more efficiently obtainable and less costly than electricity. With increased temperatures the requirement for electrical energy is significantly reduced. At a temperature of 1000°C (1,832°F), for example, it has been estimated that about 46% of the energy for the decomposition of water is provided by the external heat source.[12] High Operating Temperature Electrolysis experiments conducted in the U.S. and in Germany produced similarly encouraging findings of high overall efficiencies.[13]

Despite the potential for very high electrolyzer efficiency, electrolysis has traditionally been considered one of the more expensive and inefficient methods of hydrogen production. This has been largely true because of the low efficiency and high cost of generating electricity. Electrical power plants are typically 30-40% efficient in converting fossil fuels into electrical energy. So an electrolyzer operating at 90% efficiency coupled to a power plant that is 35% efficient would result in an overall conversion efficiency of 31.5%. It becomes obvious that this combination is far too wasteful and expensive for large scale hydrogen production, due to the reliance on nonrenewable primary sources and numerous energy conversion losses.

The volume of water necessary for large scale hydrogen production does not appear to be cause for concern. The electrolysis of two liters of water produces an amount of hydrogen equivalent in energy to one liter of gasoline. Since the per capita water use in the U.S. is more than 100 times the volume of per capita petroleum consumption, the water requirement for enough hydrogen to replace current petroleum use would add only about 2% to the average per capita water use in the United States.[14] Therefore, the feasibility of producing hydrogen by electrolysis (which is considered one of the most promising options because of its simplicity and reliability) ultimately depends on a clean, safe, and efficient source of electricity.

### *Photolysis*

Another promising option, photolysis, the splitting of the water molecule using sunlight aided by a catalyst, is still in the very early stages of research. One approach is to mimic photosynthesis using organic compounds and the study of plant physiology. Photosynthesis is the process by which certain organisms, notably green plants, utilize sunlight and chlorophyll to dissociate the water molecule. The liberated hydrogen is then recombined with carbon atoms from carbon dioxide to produce carbohydrates. For production of hydrogen, the dissociation of water must be decoupled from the rest of the photosynthesis process. Some types of algae or bacteria appear to offer favorable characteristics for the production of hydrogen. Genetic engineering also offers promise for the creation of plant or bacteria strains that generate hydrogen. Scientists are also investigating the use of synthetic compounds to emulate photosynthesis using similar substances in non-cellular processes. Supporters of this approach feel that synthetic materials will be more stable and controllable than modified biological systems.

In a fascinating experiment, Elias Greenbaum, of Oak Ridge National Laboratory, fabricated a novel composite material that responded to light by simultaneously generating hydrogen and oxygen from water. This unique material consisted of platinum deposited on a thylakoid membrane from the chloroplasts of a spinach plant.[15] While it's too soon to anticipate the consequences of such research, it's exciting to think of the prospects of producing hydrogen through tailored photosynthesis. In another experiment, Greenbaum has produced light-to-hydrogen conversion efficiencies of up to 10% -- as good as many solar cells -- by harnessing the photosynthetic talents of green algae.[16]

### *Thermal dissociation*

Thermal Dissociation is another method for producing hydrogen. If heated sufficiently, the water molecule will split into hydrogen and oxygen. Unfortunately, the temperatures required are so high (3000°C, 5,432°F) that this process is currently impractical, both in terms of generating the required heat and fabricating container materials that will withstand the heat. Since thermal dissociation of water in one step requires extreme temperatures, scientists have explored the use of a multi-step process consisting of a series of chemical reactions that can be conducted at considerably lower temperatures. With this approach, the splitting of water is structured to occur in two or three steps using highly reactive chemicals such as bromide or iodide and moderately high temperatures derived from solar or advanced nuclear sources. This approach, called *thermochemical splitting* holds promise, although there are numerous difficulties that need to be resolved before the process can be considered viable. The most significant problems facing this approach are: required temperatures are still inconveniently high (300-1000°C, 572-1,832°F), toxic or corrosive chemicals are often required, and the efficiency of this approach remains in doubt.

## Potential energy sources for hydrogen production

Since electrolysis is currently the most reliable method of manufacturing hydrogen from water, the near term viability of a hydrogen-based energy system is clearly dependent on safe, clean, and abundant sources of heat or electricity. In the long run, a tailored photosynthesis process, or something equally novel and elegant, may emerge as a provider of hydrogen. For now, the sources that have demonstrated practical potential should be examined. Some very attractive and promising options for generating electricity are renewable energy sources such as solar, hydro, and wind.

**"...the viability of a hydrogen-based energy system is clearly dependent on safe, clean, and abundant sources of heat or electricity."**

### *Photovoltaics*

Photovoltaic (PV) cells, which use semiconductor materials to directly convert sunlight into electricity, are considered by many to be the one of the most promising sources of electricity for producing hydrogen through electrolysis of water. An exciting study, *Solar Hydrogen: Moving Beyond Fossil Fuels* (World Resources Institute, 1989), by Drs. Joan Ogden and Robert Williams of Princeton University, examines the feasibility of a PV hydrogen system. The discussion that follows is drawn largely from their findings.

Intensive research in the 1970s indicated that it would be technically feasible to produce PV hydrogen and use it for transport, heating, and power. However, economic assessments published in the 1980s concluded that it was unlikely that PV hydrogen would become cost-competitive with other fuels due to the high costs of PV cells.[17] Revolutionary advancements in PV technology in the last decade have led to dramatic increases in efficiency and reductions in manufacturing costs. Particularly rapid progress is being made with thin-film amorphous silicon (a-Si) solar cells. Ogden and Williams use this technology as a basis for their cost and feasibility projections. Other promising thin-film technologies include polycrystalline copper indium diselinide ($CuInSe_2$) and cadmium telluride (CdTe). Higher cost single-crystal silicon solar cells coupled with concentrating solar collectors may also become competitive because of their increased efficiency.[18] Concentrating collectors serve to multiply the effective area of a PV cell using components that are less expensive than PV materials, thereby lowering the overall power production costs.

The cost of production of PV electricity has gone from over $5 per kilowatt-hour (kWh) in the early 1970s to about 28 cents per kWh in 1988, and is predicted to drop to 2 to 3.5 cents per kWh by the year 2000. These costs in the year 2000 would allow hydrogen to be produced at a price roughly equivalent in cost of energy to gasoline selling for $1.68 to $2.35 per gallon.[19]

If electricity were produced in 15% efficient PV systems and converted to hydrogen at 84% efficiency in a relatively sunny area such as the southwestern United States, hydrogen production equivalent to total 1986 U.S. oil consumption would require a collector field of about 24,000 square miles (64,000 square kilometers). This is an area the size of the state of West Virginia, roughly 0.5% of total U.S. land area or about 7% of the desert area in the United States. Hydrogen production equivalent to the world's fossil fuel consumption would require 205,000 square miles (530,000 square kilometers) -- less than 2% of the world's deserts. In practice, numerous smaller PV hydrogen systems rather than one large array would be built.[20] Deserts are not the only potential sites for photovoltaic collectors. Solarex, for example, is working with a roofing company to develop dual-purpose collectors that not only generate electricity but also act as shingles to keep out the weather.[21]

These roof-top solar arrays are attractive in that they require no additional land area.

The water requirements for PV hydrogen production by electrolysis would be equivalent to about 2 to 3 centimeters per year of rainfall (about an inch) on the area of the PV collector field. For example, even though El Paso, Texas, is in one of the driest areas in the United States -- with only 20 centimeters (8 inches) annual rainfall -- the water required for electrolysis is only 12 to 17% of total precipitation.[22]

The world's first prototype solar hydrogen production facility opened near Nuremberg, Germany on September 25, 1990. This facility utilizes photovoltaic cells and is rated as a 300 kilowatt power plant capable of producing 50,000 cubic meters (about 13 million gallons) of hydrogen annually. Although relatively small-scale, this is the first formal solar-based plant to generate hydrogen for commercial purposes.[23]

A 350 kilowatt photovoltaic hydrogen plant has been constructed near Riyadh, Saudi Arabia. This plant is part of a joint German-Saudi Arabian project to demonstrate and evaluate the solar generation and utilization of hydrogen. The intense solar radiation available in the deserts of North Africa and Saudi Arabia could be used to produce large amounts of solar hydrogen that would then be transported to Europe in pipelines or tankers.

*Solar thermal*

Solar thermal refers to those systems which gather the sun's energy in the form of heat. The solar thermal technologies which are most relevant to hydrogen production are those which concentrate the sun's energy in order to produce higher temperatures than would normally be encountered in naturally distributed sunlight.

Focusing collectors use parabolic dishes or troughs to collect sunlight over a large area and reflect the energy to a focal zone. These systems have generated temperatures of 300 to 400°C (572-752°F) and are expected to reach 500 to 800°C (932-1,472°F) in the near future.[24] This energy could be converted to hydrogen, for example, by using the heat to produce steam. The steam would then be used to power a turbine-driven generator, thereby providing electricity for electrolysis. Cummins Power Generation, Inc. is marketing a solar concentrator that will track the sun and collect heat energy. The heat is focused to power a free-piston Stirling engine that drives a linear alternator. This engine/alternator combination converts thermal energy into electrical energy.

While solar thermal collectors are typically twice as efficient as PV modules in collecting and converting the sun's energy (22% for solar thermal, 10% for PV)[25], some of this efficiency advantage is lost in the conversion from heat to electricity.

In California's sunny Mojave Desert, LUZ International is using solar thermal energy to produce commercial electricity in the world's largest solar facility at prices only slightly above those of a new coal-burning system. The LUZ system uses mirrors 17 feet high and 80 feet long in the shape of parabolic troughs to focus the sun's energy on stainless-steel tubes filled with oil. Heated to 390°C (734°F), the oil turns water to steam that drives conventional turbine generators. A natural gas boiler can be used to augment the solar heat as needed. In the future, plants like this could use a portion of daytime solar energy to produce hydrogen, which could be stored to fire boilers for steam turbines at night. LUZ plants being built today can produce electricity at a cost of 10 cents per kilowatt-hour. Former LUZ Vice President Paul Savoldelli predicts that within five years this will be the cheapest source of electricity in sunny areas "regardless of oil prices or environmental regulations."[26]

Central receiver systems, also called solar towers, consist of a large system of mirrors which track the sun and reflect the sunlight to a central collection point, typically a tower. This highly concentrated energy has generated temperatures of about 1,750°C (3,128°F) in early tests of a system in Albuquerque, New Mexico.[27] The ability to achieve such high temperatures may prove of value in thermochemical production of hydrogen.

### *Hydroelectricity*

Hydroelectric generating stations, which derive energy from the power of falling water, have long been regarded as one of the most reliable and inexpensive ways of generating electricity. In 1987, hydropower accounted for 17% of electricity production in industrialized countries and 31% in developing countries.[28] Significant potential for additional hydropower exists, though it is unlikely that all of this will be developed. Large scale hydro facilities have become targets of growing environmental concern, due to the large water impoundments that submerge vast areas of land and create major changes in rivers and associated ecosystems and communities. However, where properly responsive to environmental and social constraints, hydroelectric facilities are nearly ideal as sources of renewable energy.

In the Province of Quebec, Canada, which has enormous hydroelectric potential, energy analysts have been examining the possibilities for a long-term transition to increased production and use of hydrogen. In *Power From the North*, published in 1985, prime minister Robert Bourassa wrote:

> *There is no doubt that many of the ingredients for a successful hydrogen energy system are available in Quebec. The availability of multi-gigawatt hydroelectric power, the abundant natural water supply, and the leadership that has already been taken in electrolysis technology (sustained by major research and development programs*

*through a significant commitment from industry), put Quebec in a position to advance toward the hydrogen society of tomorrow?*[29]

Projections indicate that the initial markets for Quebec's hydrogen will be the northeastern United States or Europe. The hydrogen could be sent to the U.S. via pipeline and shipped to Europe, perhaps as liquid hydrogen. Hydro-Quebec and the European community are studying the feasibility of using hydrogen to replace gasoline, diesel oil, and other carbon-based fuels in Western Europe. Off-peak power from Hydro-Quebec would power a 100 megawatt electrolysis plant, producing hydrogen for export to Europe. The project, which began in 1989, hopes to have buses and airplanes running on hydrogen by 1997. The current phase of the effort is dedicated to determining the viability of the project and developing methods for storage of hydrogen. If the project gets the green light, expected sometime in 1991, future activities will involve: setting up a sample electrolysis plant in Quebec; developing appropriate ships to transport the hydrogen to Europe; and adapting vehicles and factories for operation on hydrogen. Hamburg, Germany will be the initial demonstration site. If the technologies perform well, the use of hydrogen would be expanded to other western European cities during the final stage. Proponents claim that this program could lead to a significant improvement in global air quality and demonstrate the feasibility of hydrogen as a fuel.[30]

Hydrogen technologies may also allow utilization of small dams and waterfalls considered uneconomical for large-scale hydroelectricity production. According to *Engineering News Record*, a study sponsored by the United States Department of Energy estimated that there are some 50,000 falling-water sites in the U. S. that could produce up to 240 trillion BTUs worth of hydrogen fuel annually.[31]

### *Wind-powered electric generators*

Wind-powered electric generators, when properly sited where wind velocities are consistently high, have proven to be reliable sources of electricity. Since 1981, the cost of wind-generated electricity has dropped dramatically, to less than seven cents per kilowatt-hour. (For comparison, electricity from a new coal-fired power plant in the U.S. sells for about five cents per kilowatt-hour. However this figure does not include environmental and social externalities.) The U.S. Department of Energy and industry analysts project that during the next 20 years the cost of wind electricity at sites with moderate wind resources could fall to 3.5 cents per kilowatt-hour.[32]

Wind generators have been considered somewhat problematic when connected to conventional electric utility grids because the availability of wind energy does not always coincide with the demand for electricity. (In general, this has not caused any difficulty when wind energy represents less than about 20% of the total generation capacity.) As part of a hydrogen-based system, a portion of the wind's energy could be "stored" -- surplus or off-peak electricity from wind generators would be supplied to electrolyzers that would generate hydrogen which could then be stored for later use. During periods of high electrical demand, this hydrogen could be supplied to a fuel cell to produce electricity.

### *Other renewables*

Renewable sources of energy that remain largely undeveloped but have potential for contributing to future energy systems are OTEC, wave power, and tidal power. These methods have attracted the attention of hydrogen proponents because of the availability of both energy and water.

Ocean Thermal Energy Conversion (OTEC) derives energy from the temperature difference between the ocean's warm surface waters and the cold water of the ocean's depths. A temperature difference of about 22°C (71.6°F) is typical of tropical waters.[33] This occurs because the energy of sunlight is trapped near the surface and there is little mixing of deep and surface waters. A working fluid, such as ammonia, which boils at low temperatures, is warmed by the surface waters. The liquid turns to vapor, expands and is used to drive a turbine (which could be used to generate electricity). The vapor is then cooled by water pumped up from the ocean depths; it condenses into liquid form and can be reused in a continuing closed cycle.

Theoretically, the energy potential of this sort of system is immense, although the technology has yet to be developed. Problems facing this approach include designing equipment sturdy enough to survive harsh ocean storms for extended periods and preventing the growth of biological organisms from fouling pipes and heat exchangers.

An energy source of significant potential lies in moving water in the form of waves and tides. Various approaches have been examined to take advantage of the horizontal and vertical motion of coastal waters. Buoys or vanes can be used to pump water or compress air, either of which may then be used to drive a turbine and generate electricity. Other strategies pump water to a reservoir and then generate electricity in much the same fashion as a hydroelectric facility.

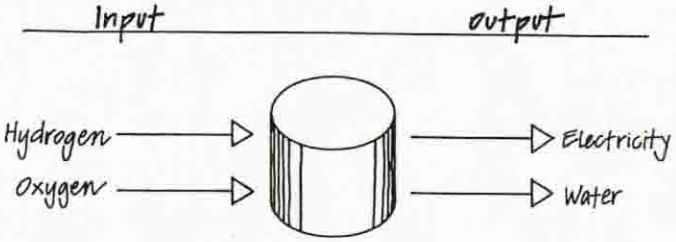
### *Nuclear power*

Some hydrogen advocates and nuclear power proponents argue that a new generation of advanced nuclear reactors will offer an excellent source of both heat and electricity for hydrogen production. Japan is investigating the use of high temperature gas-cooled reactors for thermochemical water splitting.[34] However, accidents at Chernobyl and Three Mile Island have reinforced the growing antinuclear sentiments of the last two decades. The costs and attendant risks of nuclear power plants, and the unresolved issues of safety and waste disposal, make this option unacceptable.

## Potential uses of hydrogen

*Fueling cars, trucks, and buses*

Fuel cells are electrochemical conversion devices in which hydrogen recombines with oxygen to produce electricity and water -- a reversal of electrolysis. A simple fuel cell consists of two porous electrodes connected by an electrolyte layer. The two electrodes, one positive and one negative are connected to an external electrical circuit. Hydrogen is supplied to the negative electrode and oxygen to the positive. As the reaction proceeds, hydrogen and oxygen pass through the porous electrodes, diffuse through the electrolyte, and combine to form water. This chemical reaction produces electricity in the circuit connecting the electrodes. Some heat is also produced in the process. As long as a fuel cell is supplied with hydrogen and oxygen, it will provide a steady source of electricity and water.

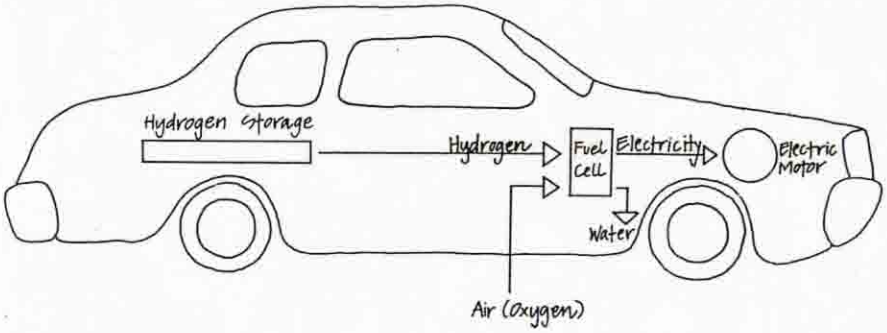


Fuel Cell

Though the principle of operation is relatively simple, the development of practical fuel cells has faced some technical challenges. Significant issues in fuel cell technology include the development of durable, inexpensive materials, reducing size and weight, removal of water and heat, and improvement in operating efficiency. The maximum theoretical efficiency of a hydrogen-oxygen fuel cell is 83%.[35] Typical efficiencies for existing fuel cells are in the range of 50 to 60%.[36]

A significant advance in fuel cell technology is the development of Solid Polymer Electrolyte (SPE), which provides a durable and safe electrolyte that has many advantages over liquids. SPE also allows for improvements in fuel cell geometry and electrode configurations. Fuel cells using SPE are referred to as Solid Polymer Fuel Cells (SPFC).

Early in the U.S. space program, fuel cells were chosen to provide electricity and water for on-board use in manned spacecraft. Fuel cells were a logical choice since the hydrogen and oxygen used as chemical rocket propellants could also supply the fuel cell.



Hydrogen / Electric Car

The Pennsylvania Energy Office and the American Academy of Science are in the early stages of a project which will power a vehicle using a fuel cell and an electric motor. The fuel cell is expected to have an efficiency of 55 to 60%. Electric motor efficiencies of 80 to 90% are not uncommon, so this vehicle could conceivably operate at an overall efficiency of 44 to 54% -- impressive compared to gasoline fueled internal combustion engines which are less than 30% efficient.[37] The fuel cell/electric motor drive system also produces no undesirable emissions such as carbon monoxide, reactive hydrocarbons, or nitrous oxides. Ballard Power Systems Inc. of Vancouver, British Columbia, was recently awarded funding by the B.C. government to test its solid polymer fuel cell in a small transit bus.[38]

Even using more conventional internal combustion engine technologies, hydrogen has significant potential for contributing to the development of more environmentally benign transportation systems. Hydrogen Consultants, Inc. of Littleton, Colorado operates a vehicle that burns *Hythane*. A mixture of approximately 5% hydrogen and 95% natural gas (principally methane), *Hythane* offers promise as a very clean-burning transportation fuel.[39] Tests on this vehicle are nearing completion and the results have been very encouraging. The underlying strategy in this approach is to enhance the existing supplies of natural gas with a clean, renewable component, hydrogen. As hydrogen technologies mature and hydrogen becomes more widely available, the hydrogen concentrations would be increased, thus providing an ongoing supply of an increasingly clean gaseous fuel.

Several experimental vehicles that run on pure hydrogen are now on the road. Mercedes-Benz, BMW, and researchers in Japan have been working on hydrogen cars for several years. Mercedes has used *metallic hydrides* for hydrogen storage while BMW has focused on using liquid hydrogen stored in vacuum superinsulated tanks. Japanese scientists, working with funds provided by Nissan Motor Co., unveiled a hydrogen car of their own in July, 1990 and Mazda plans to unveil a hydrogen car in the fall of 1991. Due in large measure to the weight and bulk of the hydrogen storage containers, these automobiles are still at some disadvantage in weight, performance, and fuel capacity when compared to gasoline vehicles. They are far superior in terms of their low emissions.

A system of photovoltaic panels and advanced water electrolysis equipment will be used to supply the fuel needs of two hydrogen-powered vehicles at Riverside Community College in Riverside, California. The photovoltaic hydrogen production facility will be supplied by The Electrolyser Corporation Ltd. of Toronto, Canada. This project, which has the support of the South Coast Air Quality Management District and the Ontario Ministry of Energy, will provide valuable experience in hydrogen production, vehicle conversion, and safe handling of hydrogen.

### *Aviation fuel*

Hydrogen is the undisputed choice as a fuel for space propulsion. Its light weight and desirable fuel properties have also attracted some interest in the world of aviation. In 1956, NASA converted one of the engines of a B-57 to run on hydrogen for brief periods while the plane was aloft. The Soviets modified the right outboard engine of a triple-engine commercial jet airliner and successfully ran that engine on hydrogen during its entire 21-minute maiden flight in 1988. An agreement signed by the Soviet Union and Germany's Deutsche Airbus at the 1990 Hanover Air Show called for the joint development of hydrogen propulsion technology for civilian aircraft. In the U.S., Lockheed Corp. has shown the most interest among airframe manufacturers in investigating hydrogen-powered aircraft. In the early 1980s, Lockheed tried, unsuccessfully, to interest some

Western governments in building a hydrogen-fueled commercial airliner.[40]

*Domestic heating and cooking uses*

With appropriate appliances, hydrogen readily lends itself to domestic space heating, water heating or cooking. Hydrogen appliances are designed so that the hydrogen streams into the burner directly rather than being premixed with air as is done with natural gas. The gas flow rate is also about three times that of a natural gas burner. A catalyst such as platinum or stainless steel is used to lower the combustion temperature. Catalytic combustion of hydrogen increases efficiency and reduces nitrous oxide emissions to negligible levels. The combustion products, mainly water vapor, can be discharged directly into living spaces without endangering health. For space and water heating applications, hydrogen burners approach 100% efficiency! (Catalytic natural gas heaters must be vented to the outside to avoid the buildup of combustion products such as carbon monoxide and nitrous oxides. Since some heat is lost with the vented air, natural gas heaters are only 80 to 90% efficient.) The water vapor produced by a catalytic hydrogen heater can also act to improve comfort by raising indoor relative humidity. If additional humidity is undesirable, the steam from combustion could be condensed and collected as potable water.[41]

**"For space and water heating applications, hydrogen burners approach 100% efficiency."**

*Integrating hydrogen and electric systems*

Peter Lehman, Professor of Environmental Engineering at Humboldt State University (CA), is piloting a project in its initial stages that integrates photovoltaic panels, an electrolyzer, and a fuel cell. The installation, at Humboldt's Telonicher Marine Laboratory uses photovoltaic panels which produce about 8 kilowatts of power in bright sunlight. These panels provide electricity for the lab. Surplus electricity is supplied to an electrolyzer which splits water into hydrogen and oxygen. The hydrogen and oxygen are stored in tanks behind the lab, effectively acting as stored solar energy. At night or when the clouds are thick, the system automatically shifts to fuel cell operation. The stored hydrogen and oxygen are fed into the fuel cell, which produces electricity for the laboratory -- energy from the sun, even while the sun is temporarily unavailable![42]

*Utility load management*

Hydrogen is also seen as a potential energy storage medium for use in utility load management. Since electrical generating capacity is installed to meet peak demand, during off-peak periods surplus power is available and could be used to electrolytically produce hydrogen. This hydrogen could be supplied as fuel, or stored and then converted back to electricity during peak demand periods.

Hydrogen technology must necessarily compete with other energy storage methods. One highly developed, though not widely used, form of large scale energy storage is pumped hydroelectric storage. This approach uses off-peak power to pump water uphill to a reservoir; then during periods of peak demand, the water is released allowing it to flow back down and its energy is harnessed to generate electricity. This process has a net, round trip efficiency of about 66%. The best hydrogen technologies for energy storage have efficiencies of about 40 to 50% for an equivalent process. This points to a need for improvement in the efficiency of both electrolyzers and fuel cells if hydrogen is to prove viable for large scale energy storage.[43]

## Hydrogen storage

The properties of hydrogen necessitate some special storage considerations. For example, hydrogen's high chemical activity can result in embrittlement of metal pipes and storage containers. Hydrogen embrittlement, which reduces the strength and durability of metals and can lead to fracturing, depends largely on the nature of the metal, the system pressure, the temperature, and the purity of the hydrogen. Embrittlement can be minimized by: reducing operating temperatures and pressures; selecting non-metallic materials or metal alloys that are less affected by hydrogen; lining or coating metal vessels; or mixing an additive with the hydrogen. Another factor affecting hydrogen storage is that the volumetric energy density (energy per unit volume) of natural gas is over three times that of hydrogen. So for equivalent amounts of energy, hydrogen requires over three times the storage volume of natural gas stored at the same pressure.

**"...hydrogen requires over three times the volume of natural gas for the equivalent amount of energy stored at the same pressure."**

Storing gases at high pressures is an obvious way to minimize the cost of a storage facility -- more gas can be stored in a container of fixed volume if the gas is compressed. It requires some additional input of energy to compress the gas, but gases are commonly distributed under pressure in pipelines so pressurization would be necessary, independent of the storage technique.

### *Pressure vessels*

Pressure vessels of conventional design could be used for stationary storage as long as the problem of hydrogen embrittlement is adequately considered. Pressure storage is problematic for use in vehicles because of the substantial bulk, weight, and expense of the storage tanks. A steel tank full of *gaseous* hydrogen at a typical pressure of 136 atmospheres (2,000 PSI) would occupy 24 times the volume and weigh 30 times as much as a fuel tank containing an energy equivalent amount of gasoline. Ninety-nine percent of this weight is in the hydrogen container.[44]

### *Underground cavities*

A relatively low cost method is to store compressed hydrogen in natural or constructed cavities underground. These could include depleted oil and gas reservoirs, aquifers, salt caverns, or coal mines. The technology of underground gas storage is fairly complex and the specific process depends on the geology of a particular site. Some of the common technical considerations for evaluating the suitability of a site include proximity of geological faults, gas containment characteristics, capacity, reactivity of hydrogen with the cavity materials, tendency for hydrogen to diffuse into ground water, potential for contamination of stored hydrogen, and accessibility of the site.

### *Glass microballoons*

Another potential pressure storage technology utilizes glass microballoons, tiny spheres made from fly ash and similar in appearance to powdered sugar. These spheres are heated to about 900°C (1,652°F) to increase their gas permeability. Hydrogen is introduced under pressure and diffuses into the heated microballoons. The spheres are then cooled, their permeability decreases and the hydrogen is safely trapped. To release the hydrogen, the spheres are heated to a temperature that will allow the gas to escape. This system offers potential for stable, light, and safe hydrogen storage that may prove applicable in vehicles or homes.[45]

### *Cryogenic*

Cryogenic, or very low temperature, storage of *liquid* hydrogen ($LH_2$) has a number of advantages. $LH_2$ occupies about one fifth the volume of *gaseous* hydrogen (at 2,000 PSI) of equivalent energy content. It has the highest energy density by weight of any liquid fuel (2.8 times that of gasoline).[46] Unfortunately, compared to an energy equivalent amount of gasoline, $LH_2$ still requires storage containers that are nearly four times the volume and far more expensive. $LH_2$ in storage must be maintained at a temperature of -253°C (-423°F), which is the boiling point of hydrogen at atmospheric pressure.[47] Liquefaction of hydrogen is energy intensive, requiring an energy input equal to roughly 39% of the energy content of the hydrogen gas. Most of this energy is not retrievable upon reconversion to gas, so liquefaction of hydrogen produces a net energy conversion loss of 25-30%.[48]

### *Metal hydrides*

Metal hydride storage is considered a promising prospect for hydrogen-powered vehicles. This storage technology takes advantage of the well known tendency for hydrogen to combine with certain metals. When exposed to hydrogen under moderate pressures, these metals will absorb hydrogen and form metal hydrides, giving off heat in the process. To retrieve the stored hydrogen, the metal hydrides are heated (40 to 100°C, 104-212°F) and the hydrogen is released. In applications that burn hydrogen, the heat required to release the hydrogen can easily be obtained as part of the combustion cycle, often using heat that might otherwise be wasted.

Hydrides have attracted interest primarily because they accommodate an extremely high density of hydrogen. Curiously enough, it is possible to pack more hydrogen into a metal hydride than into the same volume of liquid hydrogen. This is possible because metal crystals have numerous interstitial sites -- spaces in the molecular structure that can accommodate large amounts of hydrogen in a relatively compact manner.[49] Hydride storage is still at a disadvantage to gasoline. A hydride storage tank would occupy 4 times the volume and weigh 4.6 times as much as a fuel tank containing an energy equivalent amount of gasoline.[50]

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**"Curiously enough, it is possible to pack more hydrogen into a metal hydride than into the same volume of liquid hydrogen.**

---

The hydrides of most interest are those which are reasonably stable and operate at convenient temperatures and pressures. Of particular interest are the hydrides of intermetallic compounds such as iron-titanium hydride ($FeTiH_X$) or lanthanum-pentanickel hydride ($LaNi_5H_X$). Some of these compounds can be mixed with other materials to produce desired temperature/pressure characteristics. While these hydrides can store hydrogen compactly, they add a considerable weight penalty because they can only store about 1 to 2% of their weight in hydrogen. As compared to gaseous storage of hydrogen, hydride storage would weigh about the same, would occupy one-third the volume, and would cost about half to two-thirds as much.[51]

Hydride storage faces some technical difficulties that could limit the applicability of this technology. The heat of the reactions for absorption and desorption of hydrogen need to be managed carefully to assure safe and efficient operation. The container must be able to withstand the temperatures and pressures of operation as well as the minimal swelling and shrinking of the hydrides as they absorb and desorb hydrogen. The hydrides are reusable and should endure many cycles of use. However, the hydrides may suffer some degradation in storage effectiveness as a result of contamination by impurities in the hydrogen gas or due to intrinsic degradation of hydrides after extensive cycling.

### *Activated carbon*

At Syracuse University's Laboratory for Advanced Storage Systems for Hydrogen, James Schwarz is experimenting with a process for storage of hydrogen using specially treated activated carbon.[52] The activated carbon is a highly porous material -- so porous that a gram of it, or about a thimble full, contains 2,000 square meters (nearly a half an acre) of interior surface area. The carbon's ability to store hydrogen is enhanced by chemical processing and by applying catalytic metal particles to its surface. Storage under pressure at low temperatures also increases storage capacity.

A prototype storage system is currently being developed. The storage vessel will be vacuum-jacketed (like a thermos bottle) to provide good thermal insulation. The hydrogen is pressurized and cooled prior to flowing into the carbon bed, where it is stored at a pressure of 55 atmospheres (800 PSI) and a temperature of minus 125°C (minus 193°F). Applying heat to the carbon and opening a valve to reduce the pressure in the tank allows the hydrogen gas to be released from the surface of the activated carbon. The goal is to store 160 grams of hydrogen (5 oz.) in 1,700 grams (60 oz.) of the modified carbon (9.4% by weight as compared to 1 to 2% in metal hydride storage).

Prof. Schwarz hopes that the properties of the carbon can be modified to allow storage at normal refrigeration temperatures which would make the system more energy efficient and commercially attractive. Although still in the early stages of development, activated carbon offers promise for a safe, cost-efficient, and relatively compact form of hydrogen storage.[53]

## Transportation and distribution of hydrogen

In both gaseous and liquid forms, hydrogen has been transported by rail and road for over 20 years. The safety record is commendable and this approach continues to be viable on a small scale. A better option for *large* scale transportation of hydrogen is transmission through pipes. The low temperatures (-253°C, -423°F) required by liquid hydrogen limit the applicability of piping $LH_2$ to very short distances, but pipeline transmission of gaseous hydrogen appears to be technically and economically feasible.

*Using natural gas pipelines*

While not ideal, the vast network of existing natural gas pipelines could be adapted for hydrogen transmission as part of a transition strategy. At modest pressures, hydrogen embrittlement is not expected to be severe for pipes. One study indicates that the fracture toughness of pipeline steel is reduced by about 60% in 1000 PSI hydrogen but that hydrogen can be transported in natural gas pipelines if working pressures are reduced.[54] Pumps, valves and other flow-modifying parts would have to be evaluated for susceptibility to embrittlement and suitability to the different fluid characteristics of hydrogen.

Since hydrogen has less than one-third the energy of an equal volume of natural gas, at least three times as much hydrogen must be delivered to provide the equivalent energy of natural gas. This is partially offset because hydrogen has a lower viscosity (resistance to flow) than natural gas, thereby allowing hydrogen to move faster than natural gas through pipes of the same diameter and pressure.

Estimates of the cost of pipeline transmission of hydrogen vary. Using existing natural gas pipelines, at pressures of 750 PSI, hydrogen transmission might cost two and a half times as much as natural gas transmission. In a system optimized for hydrogen, costs may be only 30 to 50% more than those of current natural gas transmission.[55]

*Comparative economics of hydrogen and electricity*

It's more difficult to directly compare the energy transmission costs of hydrogen and electricity because these two energy carriers have fundamentally different properties. One study argues that for distances greater than 300 to 1,000 km (186-621 miles), depending on specific circumstances, transmission of gaseous hydrogen becomes cheaper than electrical transmission.[56] For short distances, the relationship between the primary energy source and the desired energy end use is more of a factor than transmission costs. If, for example, electrolytically produced hydrogen has to be reconverted to electricity at the receiving end, the conversion losses would more than offset higher efficiencies of hydrogen transmission.

## Safety issues

The mention of using hydrogen as a fuel frequently conjures up visions of the Hindenburg disaster, or images of an exploding Hydrogen-bomb, or even the Challenger space shuttle disaster. While such associations excite fear and suspicion, they are often coupled with a large degree of ignorance about the real or imagined dangers of hydrogen.

The Hindenburg dirigible, which caught fire and crashed while mooring in 1937, did not explode, as is commonly believed. In fact, it burned, sinking rapidly toward the ground. Of the 100 persons involved, 65 survived, partly because the lightweight gas rose clear of the craft as it burned. This is a remarkable survival rate compared to contemporary air disasters. While sabotage has been suggested as the cause, it is considered more likely that electrical charges produced in the atmosphere in the midst of a thunderstorm ignited the hydrogen that was being vented in an effort to lower the big ship to its mooring tower. It should also be noted that the Hindenburg was designed to be filled with nonflammable helium gas to provide buoyancy, but was instead inflated with hydrogen after the United States refused to sell helium to the Germans.[57]

In the case of the Hydrogen-bomb, the only technical connection between the bomb and hydrogen fuel is the word itself. The H-bomb explodes as a result of precisely controlled conditions and materials which produce very high temperatures and pressures. This creates extreme conditions which are sufficient to alter the *atomic* structure of the materials involved, and tremendous amounts of energy are released. In marked contrast, the production and use of hydrogen as a fuel are essentially confined to the realm of *chemical* reactions, in which bonds between atoms change, but fundamental atomic structures remain unchanged.

The tragic explosion of the space shuttle Challenger, moments after its launch in January, 1986, is sometimes mistakenly attributed to hydrogen. A presidential commission reported that there was no evidence to support speculation that a hydrogen leak contributed to the accident.[58] Analysis of this disaster revealed a failure of the O-ring seal in the joints that hold together segments of the solid-fuel rocket boosters. This allowed hot, pressurized gases from the burning fuel to escape out the side and melt the outer casing of the booster, which led to the breakup of the booster tank and the ensuing explosion. According to subsequent investigations, the launch was allowed to proceed in spite of explicit recommendations by engineers that the launch be postponed because the cold temperatures at the launch site would prevent the O-rings from sealing properly.[59]

The nature of fluid fuels, in that they are concentrated stores of readily accessible energy, makes them at once very useful and potentially hazardous. The widespread perception that hydrogen is far more dangerous than natural gas or gasoline does not provide a fair assessment of the properties of hydrogen. Studies of the relative safety of hydrogen, methane (natural gas is typically 96% methane), and gasoline have concluded that no one of these fuels is inherently safer than the others in every respect (see page 34).[60] Each of these fuels pose very real dangers that demand appropriate precautions.

Hydrogen will burn over a much wider range of concentrations than gasoline or methane, but gasoline will burn at significantly lower concentrations. Hydrogen will also detonate over a fairly wide range of fuel to air ratios, but the lower limit is significantly higher than methane or gasoline. If present in the proper concentrations, all of these fuels will ignite with very little energy -- sparks from static electricity, friction, impact, open flames, or hot surfaces. Obviously, with all three fuels, detection of leaks and adequate ventilation in enclosed spaces are necessary to prevent the accumulation of dangerous levels.

If a leak were to occur, hydrogen and methane will rise and disperse rather quickly in open air or properly vented enclosures. In an unvented area, hydrogen's high diffusion velocity will allow for fairly rapid development of combustible hydrogen/air mixtures. Gasoline vapors are heavier than air and will linger in enclosed spaces or outside in still air, potentially reaching dangerous concentrations. The diffusion rate for all of these fuels is high enough to be hazardous in enclosed, unvented areas.

Hydrogen has a volumetric leakage rate about three times that of methane, but the volumetric energy density of hydrogen is one-third that of methane, so the *energy* leakage is the same. Hydrogen is odorless and colorless, so an odorant added to the hydrogen, as is done with natural gas, would aid detection of leaks. Gasoline also leaks more rapidly than methane, and would not disperse as rapidly as hydrogen. With proper care and appropriate containers, all three fuels can be safely stored and distributed with minimal leakage.

## *Safety related properties*

| | hydrogen | methane | gasoline |
|---|---|---|---|
| **Limits of flammability in air** (% volume) | 4.0-75.0 | 5.3-15.0 | 1.0-7.6 |
| **Limits of detonability in air** (% volume) | 18.3-59.0 | 6.3-13.5 | 1.1-3.3 |
| **Min. ignition energy in air** (millijoules) | 0.02 | 0.29 | 0.24 |
| **Diffusion velocity in air**(meters/second) | 2.0 | 0.51 | 0.17 |
| **Buoyant velocity in air** (meters per second) | 1.2-9.0 | 0.8-6.0 | non-buoyant |
| **Relative leak rate in air** (by volume) | 2.8 | 1 | 1.7-3.6 (vapors) |

**Limits of flammability in air** is the range of fuel/air mixtures which will sustain a fire.

**Limits of detonability in air** is the range of fuel/air mixtures which will sustain an explosion.

**Minimum energy for ignition in air** is the amount of energy required to induce flame in a flammable mixture.

**Diffusion velocity in air** is the rate at which fuels diffuse through air. It indicates both how rapidly a fuel will disperse and how rapidly it will mix with air.

**Buoyant velocity in air** is the rate at which fuels rise in air.

**Relative leak rate in air** is the propensity of materials to leak (for example, from a cracked weld or defective seal).

In enclosed, unvented spaces gaseous hydrogen is more likely to pose a hazard than gasoline. It diffuses rapidly, ignites easily, and burns over a wide range of fuel/air mixtures. Out in the open, or in properly vented areas, it would seem to be far safer than gasoline. Its high buoyancy and rapid diffusion would normally preclude the accumulation of dangerous concentrations.

There are some safety-related properties which are less easy to quantify, but bear mentioning. Methane and hydrogen are non-toxic, while gasoline and gasoline fumes are somewhat toxic. All three gases will cause asphyxiation at high concentrations. Combustion of any of these fuels contributes to atmospheric pollution -- a long term safety hazard. Gasoline is by far the most polluting, methane is considerably cleaner, and hydrogen is cleanest of all -- nearly pollution-free when combustion is carefully controlled.

Hydrogen flames, though readily apparent in darkness, are almost invisible in daylight, thus making them somewhat difficult to detect. Hydrogen fires are relatively short-lived. A gasoline fire would last 5 to 10 times longer than a liquid hydrogen fire for the same amount of fuel spilled. Petroleum spills are also more likely to contaminate soil and water. When gasoline spills occur, heavier than air vapors spread in a wide layer near the ground, greatly extending the hazardous areas.

Since the physical and chemical properties of hydrogen are quite different from conventional fuels, direct safety comparisons are inconclusive. The hazards associated with hydrogen are very much influenced by circumstances. Blanket statements about the safety of hydrogen relative to other fuels are generally misleading. This is particularly true in light of the fact that safe practices and technologies for routine handling and use of hydrogen have not been demonstrated on a widespread basis in the residential and automotive sectors. There is simply insufficient evidence to support empirical claims for or against hydrogen safety. The available safety data is largely inadequate for making decisions concerning a hydrogen energy economy.

Extensive experience with both gasoline and methane have demonstrated that these potentially hazardous fuels are reasonably safe if appropriate precautions are taken. Though our experience with hydrogen is more limited, there is sufficient aerospace and industrial experience to *suggest* that hydrogen can be produced, stored, distributed, and utilized safely.

## Hydrogen's role in the sustainable energy future

For the modern comforts and conveniences we enjoy, most of us living in industrialized nations depend on a global system of energy resource extraction, conversion, storage, distribution, and consumption. While energy is derived from a variety of sources, the principal energy system that currently serves most of our needs is based on burning fossil fuels. This system is often described as a *carbon-combustion energy economy*.

Historically, carbon compounds have been widely available in the form of wood, peat, coal, oil, and natural gas. These are primary energy sources that must be burned to convert the carbon compounds into usable forms of energy. The conversion may be direct, natural gas is burned in a furnace to provide heat or petroleum is used as fuel in an engine to provide transportation, or it may be indirect, coal is burned to produce heat to produce steam to generate electricity. While the carbon-based energy system has proven quite versatile in providing energy services, it is now facing the crippling issues of intolerable pollution (at all points from extraction to combustion) and basic resource scarcity.

Although it does not appear that hydrogen technologies are sufficiently mature to initiate any significant short-term displacement of fossil fuels, the future potential to do so is very real, and the opportunity to rigorously explore the promise of hydrogen ought not be squandered as we languish in the availability of artificially cheap fossil fuels. We need research to improve the performance of *renewable* hydrogen production technologies, and we need to encourage efforts to demonstrate the viability of hydrogen energy for various end uses.

Hydrogen can provide a very important component for the energy future, as an appropriately produced, effectively stored, transported, and utilized fuel. Hydrogen produced with renewable energy sources

-- and coupled with an overriding ethic of energy efficiency and sufficiency -- can play a pivotal role in moving beyond the carbon-combustion economy and into the sustainable *solar energy economy*.

**"Hydrogen can play a pivotal role in moving beyond the carbon-combustion economy and into the sustainable solar energy economy."**

The scope of this fundamental energy transition is clearly beyond the resources of market-driven businesses. Additional government support for hydrogen research is critical and highly warranted given its potentials. The U.S. currently spends a paltry $3 million a year on hydrogen research (compared to billions for nuclear and "clean coal") plus nominal sums for fuel cell development. Japan and Germany are both far more committed to hydrogen research. Germany, which is considered to be a leader in hydrogen research and development, spent $12 million U.S. on hydrogen in 1990.[61] When both public and private investments are counted, Germany probably spends at least twice that amount annually, *eight times* the U.S. government funding level.

It is unlikely that hydrogen will ever replace electricity as an energy carrier. Electricity has established itself as an incredibly versatile energy carrier, both in generation and use. Like hydrogen, it can be produced using various renewable energy sources. Electricity is clearly better suited to some applications, hydrogen to others. Thus electricity and hydrogen will make excellent partners. The choice of which energy carrier to use is likely to be determined by both the primary energy source, the desired end use, and the distance between the two.

Hydrogen has a certain elegance. It is abundant, can be produced by a variety of methods and is readily converted for use. If the technologies for production and use are carefully chosen and properly developed, hydrogen can be an integral part of the sustainable energy future.

## Appendix A

## Hydrogen resource list

American Academy of Science
26900 East Pink Hill Road
Independence, MO 64057
(816) 229-3800

American Hydrogen Association
P.O. Box 15075
Phoenix, AZ 85060
or:
219 South Siesta Lane, Suite 101
Tempe, AZ 85281
(602) 921-0433
FAX (602) 967-6601

Center for Electrochemical Systems
and Hydrogen Research
Texas A & M University
Mail Stop 3402
College Station, TX 77843-3577
(409) 845-0424

Citizens for Clean Energy
P.O. Box 17147
Boulder, CO 80308
(303) 443-6181
Attn: Stephen J. Clark

Clean Energy Research Institute
University of Miami
P.O. Box 248294
Coral Gables, FL 33124

Electric Power Research Institute,
Generation and Storage Division
3412 Hillview Avenue
Palo Alto, CA 94304
(415) 855-2000

Hydrogen Consultants, Incorporated
12420 North Dumont Way
Littleton, CO 80125
(303) 791-7972

Hydrogen Industry Council
(Head Office, Eastern Office)
1801 McGill College Avenue
Suite 920
Montreal, Quebec
Canada H3A 2N4
(514) 288-5139
FAX (514) 843-6079
or:
(Western Office)
700 Fourth Avenue S.W.
17th Floor - McFarlane Tower
Calgary, Alberta
Canada T2P 3J4
(403) 233-2163
FAX (403) 233-2165

The Hydrogen Letter
(monthly newsletter, $120/yr.
consulting services)
Peter Hoffmann, ed.
4104 Jefferson St.
Hyattsville, MD 20781
(301) 779-1561
FAX (301) 927-6345

National Hydrogen Association
Suite 910
1101 Connecticut Avenue, N.W.
Washington, DC 20036
(202) 223-5547
FAX (202) 223-5537

International Association
for Hydrogen Energy
P.O. Box 248266
Coral Gables, FL 33124

International Journal of Hydrogen Energy
T. Nejat Veziroglu, ed.
Pergamon Press Ltd.
Headington Hill Hall
Oxford OX3 0BW, U.K.
(A publication of International Association
for Hydrogen Energy)

Schatz Solar Hydrogen Project
Environmental Resources Engineering Dept.
Humboldt State University
Arcata, CA 95521
(707) 677-0306
FAX (707) 826-3616

Solar Hydrogen Research Program
Solar Energy Research Institute
Denver West Office Park
Building 17, 4th Floor
1617 Cole Blvd.
Golden, CO 80401-3393

# Appendix B *Technical properties of hydrogen*[62]

| | |
|---|---|
| Density (gas) | 0.89 x $10^{-4}$ grams/$cm^3$ |
| (liquid) | 0.71 x $10^{-1}$ grams/$cm^3$ |
| Boiling point | -253°C, -423°F |
| Energy release upon combustion | 2.9 x $10^4$ calories/gram<br>1.21 x $10^5$ Joules/gram |
| Flame temperature in air | 2210°C, 4010°F |
| Auto-ignition temperature | 585°C, 1085°F |

## Appendix C

### *Notes*

1. Further technical properties of hydrogen are presented in tabular form in appendix B.

2. Uncontrolled burning of hydrogen in air produces unnecessarily high levels of nitrogen oxide. When burned in air at high flame temperatures, the presence of nitrogen and oxygen in the atmosphere leads to the formation of nitrous oxides (NOx), an air pollutant. With carefully controlled combustion, however, these levels can be dramatically reduced.

3. Ogden, J.M. and R.H. Williams, *Solar Hydrogen,* 1989, World Resources Institute, pp. 71, 85.

4. Electrolytes are substances that when dissolved can serve as ionic conductors.

5. Siegert, R., "Industrial Overview," *Hydrogen Conference: Workshop Proceedings,* EPRI GS-6563, Electric Power Research Institute, 1989, p. 86.

6. The thermal conductivity of hydrogen is 6.7 times that of air and the fluid friction losses of hydrogen are one-tenth those of air. *Van Nostrand's Scientific Encyclopedia*, D.M. Considine ed., 7th edition, 1989, p. 1493.

7. U.S. Hydrogen Uses chart adapted from Escher, W. J. D. "Hydrogen: Aerospace Fuel Par Excellence," Electric Power Research Institute, *Hydrogen Conference: Workshop Proceedings,* EPRI GS-6563, 1989, p. 119. For other estimates see p. 86.

8. U.S. Liquid Hydrogen Uses chart adapted from Escher, W. J. D. "Hydrogen: Aerospace Fuel Par Excellence," Electric Power Research Institute, *Hydrogen Conference: Workshop Proceedings,* EPRI GS-6563, 1989, p. 120. See also pp. 3, 85.

9. Hoffmann, P., *The Forever Fuel*, 1981, Westview Press, Boulder, CO, p. 56.

10. Siegert, R., "Industrial Overview," *Hydrogen Conference: Workshop Proceedings,* EPRI GS-6563, Electric Power Research Institute, 1989, p. 90.

11. Bockris, J. O'M, *Energy Options*, 1980, Australia and New Zealand Book Co., p. 336; *Van Nostrand's Scientific Encyclopedia*, D.M. Considine ed., 7th edition, 1989, p. 1496.

12. Bockris, J. O'M, *Energy Options*, 1980, Australia and New Zealand Book Co., p. 329.

13. Hoffmann, P., *The Forever Fuel*, 1981, Westview Press, Boulder, CO, pp. 67-68.

14. Ogden, J.M. and R.H. Williams, *Solar Hydrogen*, 1989, World Resources Institute, pp. 45, 48.

15. Staff: "Tailored Photosynthesis," *Scientific American*, pp. 69-70, Jan. 1986.

16. Hoffmann, P., et al, "The Fuel of the Future is Making a Comeback," *Business Week*, 28 Nov. 1988, pp. 130-131.

17. Ogden, J.M. and R.H. Williams, *Solar Hydrogen*, 1989, World Resources Institute, p. 13.

18. Ibid, p. 17.

19. Ibid, pp. 17, 36, 39.

20. Ibid, pp. 44-48.

21. Cook, W. J., "The Future of Power," *U.S. News & World Report*, April 23, 1990.

22. Ogden, J.M. and R.H. Williams, *Solar Hydrogen*, 1989, World Resources Institute, p. 48.

23. *Hydrogen Today*, American Hydrogen Association, Nov.-Dec. 1990, p. 2.

24. Skelton, L.W., *The Solar-Hydrogen Energy Economy*, 1984, Van Nostrand Reinhold Company, pp. 69-70.

25. Flavin, C. and Lenssen, N., *Beyond the Petroleum Age: Designing a Solar Economy*, Worldwatch Paper 100, Worldwatch Institute, Dec. 1990, p. 47.

26. Cook, W. J., "The Future of Power," *U.S. News & World Report*, April 23, 1990; Weinberg, C.J., and R.H. Williams, "Energy from the Sun," *Scientific American*, Sept. 1990, pp. 146-155.

27. Hoffmann, P., *The Forever Fuel*, 1981, Westview Press, Boulder, CO, p. 85.

28. Weinberg, C.J., and R.H. Williams, "Energy from the Sun," *Scientific American*, Sept. 1990, pp. 146-155.

29. Bourassa, Robert, *Power from the North*, 1985, Prentice-Hall, p. 158.

30. Staff, "Canadian Companies Develop Hydrogen Fuels," *Engineering Dimensions*, Jan./Feb. 1991, p. 21.

31. Hoffmann, Peter, *The Forever Fuel*, 1981, Westview Press,Boulder, CO, p. 103.

32. Weinberg, C.J., and R.H. Williams, "Energy from the Sun,"*Scientific American*, Sept. 1990, pp. 146-155.

33. Bockris, J. O'M, *Energy Options*, 1980, Australia and New Zealand Book Co., p. 149.

34. Personal communication with Peter Hoffmann, *The Hydrogen Letter*, Hyattsville, Maryland.

35. Skelton, L. W., *The Solar-Hydrogen Energy Economy*, 1984, Van Nostrand Reinhold Company, p. 112.

36. Fulkerson, W., et al., "Energy from Fossil Fuels," *Scientific American*, V. 263, No. 3, Sept. 1990, pp. 129-135.

37. Personal communication with Daniel J. Desmond, Pennsylvania Energy Office, 7 February 1991, and *Hydrogen Today*, American Hydrogen Association, Nov.-Dec. 1990, p. 5.

38. Staff, "Canadian Companies Develop Hydrogen Fuels," *Engineering Dimensions*, Jan./Feb. 1991, p. 21.

39. Lynch, F.E. and G.J. Eagan, "An Introduction Strategy for Hythane, an Alternative Fuel Blend of Hydrogen and Natural Gas," July 1990.

40. Hoffmann, P., et al, "The Fuel of the Future is Making a Comeback," *Business Week*, 28 Nov. 1988, pp. 130-131; Staff, "The Hydrogen Age," *Popular Mechanics*, pp. 21-23, 92.

41. Ogden, J.M. and R.H. Williams, *Solar Hydrogen*, 1989, World Resources Institute, pp. 70-71.

42. See "Schatz Solar Hydrogen Project" in appendix.

43. Bourassa, Robert, *Power from the North*, 1985, Prentice-Hall, pp. 167-168.

44. Reilly, J.J. and G. D. Sandrock, "Hydrogen Storage in Metal Hydrides," *Scientific American*, pp. 118-129, Feb. 1980.

45. S.L Robinson and J.J. Iannucci, *Technologies and Economics of Small-Scale Hydrogen Storage* (Sandia Laboratories: US DOE, Dec. 1979), p. 10, cited in Skelton, L.W., *The Solar-Hydrogen Energy Economy*, 1984, Van Nostrand Reinhold Company pp. 140-141.

46. Bockris, J. O'M, *Energy Options*, 1980, Australia and New Zealand Book Co., p. 251, *Van Nostrand's Scientific Encyclopedia*, D.M. Considine ed., 7th edition, 1989, p. 1494.

47. *Van Nostrand's Scientific Encyclopedia*, D.M. Considine ed., 7th edition, 1989, p. 1494.

48. Bockris, J. O'M, *Energy Options*, 1980, Australia and New Zealand Book Co., pp. 250-251; Cohen, R.L. and J.H. Wernick, "Hydrogen Storage Materials: Properties and Possibilities," *Science*, 4 Dec. 1981, p. 1081.

49. Reilly, J.J. and G. D. Sandrock, "Hydrogen Storage in Metal Hydrides," *Scientific American*, p. 118, Feb. 1980.

50. *Van Nostrand's Scientific Encyclopedia*, D.M. Considine ed., 7th edition, 1989, p. 1494

51. Ogden, J.M. and R.H. Williams, *Solar Hydrogen*, 1989, World Resources Institute, pp. 62, 113.

52. C. Carpetis and W. Peschka from the Institute for Energy Conversion of DFVLR in Stuttgart presented the concept of cyrogenic adsorption of hydrogen at the 1976 Miami Beach hydrogen conference. See Hoffmann P., *The Forever Fuel*, 1981, Westview Press, Boulder, CO, pp. 177-178.

53. Stevens, C.W., "Practical Way to Store Hydrogen is Found," *Wall Street Journal*, March 8, 1989, p. B4; Staff, "Schwarz Explores Hydrogen Storage Methods," *Technologist*, Dec. 1990, Syracuse, NY.

54. Hoover, W.R., et al., *Hydrogen Compatibility of Structural Materials for Energy Storage and Transmission*, Materials Development Division 8312, (Sandia Laboratories, Livermore, Annual Report, 1978, 1979), cited in Skelton, L.W., *The Solar-Hydrogen Energy Economy*, 1984, p. 151.

55. Hoffmann P., *The Forever Fuel*, 1981, Westview Press, Boulder, CO, pp. 185-186; *Van Nostrand's Scientific Encyclopedia*, D.M. Considine ed., 7th edition, 1989, p. 1496; Bockris, J. O'M, *Energy Options*, 1980, Australia and New Zealand Book Co., p. 224.

56. Bockris, J. O'M, *Energy Options*, 1980, Australia and New Zealand Book Co., pp. 214-232.

57. Hoffmann, P., *The Forever Fuel*, 1981, Westview Press, Boulder, CO, pp. 210-211.

58. Hoffmann, P., *The Hydrogen Letter*, June 1986, Hyattsville, Maryland.

59. Adler, J., et al., "After the Challenger," *Newsweek*, Oct. 10, 1988, pp. 28-36.

60. Ogden, J.M. and R.H. Williams, *Solar Hydrogen*, 1989, World Resources Institute, pp. 50-54; Bockris, J. O'M, *Energy Options*, 1980, Australia and New Zealand Book Co., pp. 228, 379-391; Hoffmann P., *The Forever Fuel*, 1981, Westview Press, Boulder, CO, pp. 209-218. For an excellent discussion of hydrogen safety issues, see: Hord, J., "Is Hydrogen a Safe Fuel?," *International Journal of Hydrogen Energy*, v. 3, pp. 157-176, 1978.

61. Fax from Dr. H-J Pfriem, DLR, Cologne.

62. *Van Nostrand's Scientific Encyclopedia*, D.M. Considine ed., 7th edition, 1989, p. 1493.