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Hydrogen Pure & Simple

Hydrogen is the simplest element in the universe. It is also the most abundant element, constituting more that 90% of the atoms of the universe and 75% of its mass. It is the third most abundant element in the Earth's surface and is found mostly in combination with oxygen as water (H_2O). As a gas (H_2), it is colorless, odorless, tasteless, and non-poisonous.

Hydrogen also may be one of the best bets to fuel the future economy of America and the world. Why? First, it is widely distributed in many resources. Hydrogen is not only present in water, but is in fossil fuels, like petroleum, coal, and natural gas, and it is in plants and organic waste. Hydrogen can be produced from these resources using electrolytic, thermochemical, or photolytic processes.

NASA's space shuttle (top) uses liquid hydrogen and oxygen for propulsion and hydrogen-powered fuel cells to provide onboard electricity and water. Car manufacturers (bottom) are beginning to produce vehicles powered by fuel cells. (Shuttle photo and Eagle Nebula photo in the background and on the front cover are courtesy of NASA.)

Second, as a fuel, hydrogen is clean. Solar energy can provide the electricity to split water into its constituent elements of hydrogen and oxygen (see sidebar "Solid-State Water Splitting"). The hydrogen then can be used in a

Harvesting Hydrogen from Microalgae

A scientist scrutinizes a flask containing microalgae for hydrogen production.

Scientists have known for decades that green algae can produce hydrogen. Researchers at NREL, ORNL, and the University of California at Berkeley have unlocked the secret to increasing the hydrogen yield of a certain type of green microalgae—*Chlamydomonas reinhardtii*—which shows promise of producing hydrogen cheaply, easily, and cleanly.

The process they've developed involves interrupting the algae's normal photosynthesis process. These algae, like all green plants, use photosynthesis—i.e., in the presence of light they "inhale" carbon dioxide and "exhale" oxygen. But hydrogenase—an enzyme that produces hydrogen—shuts down in the presence of oxygen, in the daylight, during prime photosynthesis time. This confines the algae's production of hydrogen to nighttime when photosynthesis does not occur, limiting the amount of hydrogen produced.

To overcome this limitation, the scientists developed a two-step method that allows the algae to make hydrogen while the sun shines. First they grow out ("fatten") the algae under normal photosynthetic conditions. Second, they withhold sulfur which, the scientists discovered, is essential for this green algae to maintain normal photosynthesis. Without sulfur, the algae stop emitting oxygen and stop storing energy. Instead, they switch to a new metabolic pathway—one that exploits stored energy reserves in the absence of net oxygen production. This kicks the hydrogenase into high gear to release large amounts of hydrogen.

This process induces the algae to produce 100,000 times more hydrogen than they do under normal conditions. Plus, the researchers have developed a process to fatten the algae again on a diet of sunshine and sulfur, and then to starve the algae of sulfur again to produce hydrogen. This cycle can be repeated several times. Still, much work remains to be done to make the process feasible on a larger scale.

fuel cell, where hydrogen and oxygen from air recombine to generate electricity, heat, and water (see sidebar “Fuel Cells”). Deriving and using hydrogen in this manner produces no particulates, carbon dioxide, or pollution.

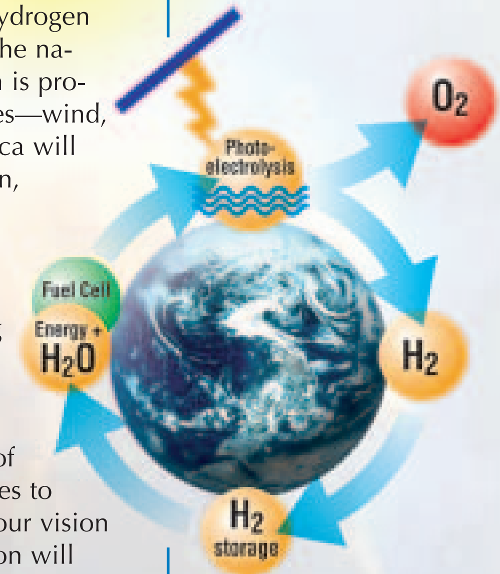
Third, hydrogen is versatile. We can produce hydrogen at one location or time to store energy and then distribute it to release the energy at another time or place. Hydrogen can be used to generate electricity, through the use of fuel cells, turbines, or microturbines. It can supply us with heat, warm our buildings, or power industrial processes. It can be used in internal combustion engines to power our cars, trucks, and buses, or in fuel cells for the same purpose. It can provide power for our jetliners and ocean fleets. Because fuel cells are modular, hydrogen can be used for both small- and large-scale applications—to provide heat and electricity for single homes or to supply the energy to run an entire large commercial building; to provide a small amount of electricity to a community grid, or a large amount of electricity to a large grid network.

The Road to the Hydrogen Economy

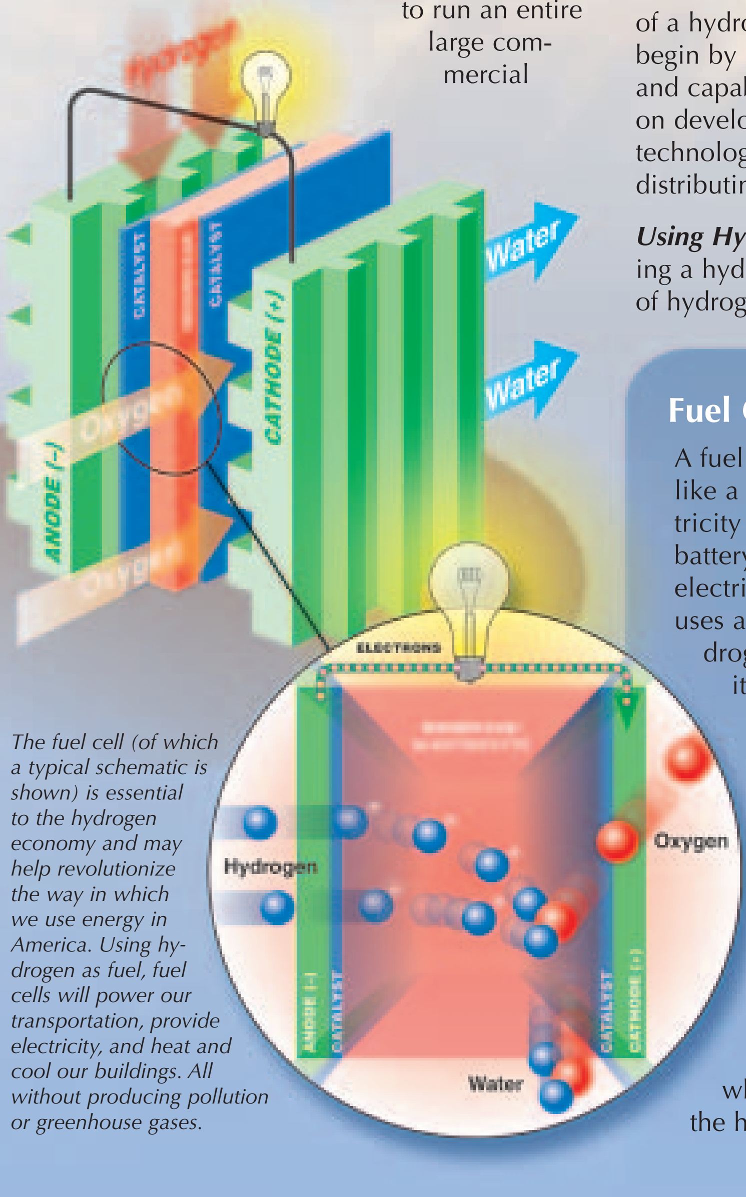
In the coming *hydrogen economy*, hydrogen will serve, along with electricity, as the nation’s energy carrier. When hydrogen is produced from renewable energy sources—wind, solar energy, biomass, water—America will have an inexhaustible supply of clean, domestically produced energy.

Although making the transition to a renewable hydrogen economy will take decades, we are already starting down the road toward an energy economy based on hydrogen and electricity. NREL is working with industry, universities, the Department of Energy, and other national laboratories to outline the steps required to realize our vision of a hydrogen economy. The transition will begin by building on current infrastructures and capabilities; future progress will depend on developing and commercializing a range of technologies for using, producing, storing, and distributing hydrogen.

Using Hydrogen. An essential driver for reaching a hydrogen economy is to increase the use of hydrogen. Today, the United States uses



The hydrogen cycle: When generated from renewable sources, hydrogen production and use is part of a clean, cyclic process.



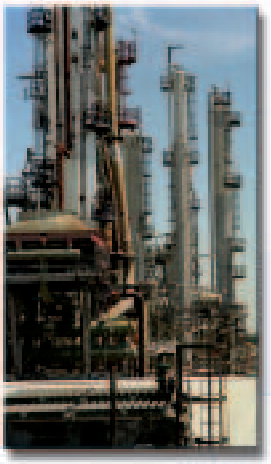
The fuel cell (of which a typical schematic is shown) is essential to the hydrogen economy and may help revolutionize the way in which we use energy in America. Using hydrogen as fuel, fuel cells will power our transportation, provide electricity, and heat and cool our buildings. All without producing pollution or greenhouse gases.

Fuel Cells

A fuel cell is a device somewhat like a battery—it produces electricity electrochemically. Unlike a battery, it does not need to be electrically recharged because it uses an external fuel source, hydrogen gas, to generate electricity as long as hydrogen fuel is supplied.

A typical fuel cell employs a catalyzed membrane sandwiched between a negative electrode (anode) and a positive electrode (cathode). Oxygen flows into the fuel cell on the cathode side. Hydrogen flows into the cell on the anode side, where the catalyst separates the hydrogen atoms into protons (hydrogen ions) and electrons. The electrons are attracted to the cathode, but they are blocked by the membrane. Consequently, they flow to the cathode through an external circuit, creating a current of electricity. The protons are attracted by the oxygen at the cathode and flow through the membrane, where they combine with the electrons and the oxygen to produce heat and water.

Individual fuel cells can be combined into a fuel-cell stack. This modular design capability allows fuel-cell stacks to produce enough electric power or heat for almost any size application. In addition, by putting both the heat and electricity to effective use, a fuel cell could be 80% to 90% efficient.

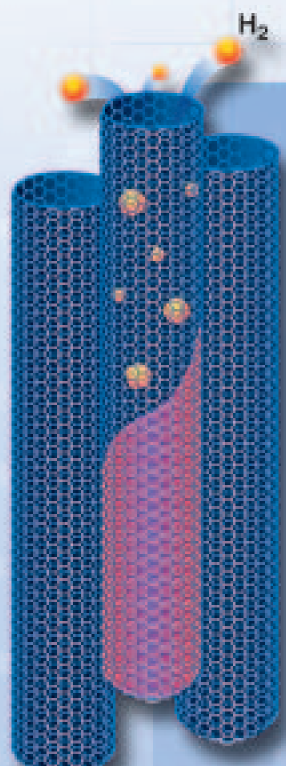


Today, most all hydrogen is produced via steam reformation of natural gas at oil refineries. The great majority of that hydrogen is used by oil refineries and petrochemical plants to refine fuel and to make industrial commodities.

more than 90 billion cubic meters (3.2 trillion cubic feet) of hydrogen annually. The great majority of this is used for refining petroleum, making plastics, and producing fertilizers. Demonstrations are now under way to prove hydrogen's potential for transportation, for producing electricity, and for providing heat and electricity to buildings—all of which will help spur the growth of the hydrogen economy. Take transportation as an example. Initially we may witness the growth of hydrogen-fueled internal combustion engines—building on current transportation technologies and infrastructure. Ultimately, however, fuel cells will be integral to transportation (as well as to buildings, industry, and utilities). We will see fuel cells being incorporated into hybrid electric vehicles (which use both fuel-cell electricity and internal combustion), in which they will replace the engine. And eventually, fuel cells will provide the power for advanced fuel-cell vehicles (see also "Transportation Technologies" on pages 6-9).

Producing Hydrogen. Almost all of the hydrogen produced today is made by steam reformation of natural gas. For the near term, this method of production will continue to dominate. Hydrogen can also be produced by the gasification of coal or the partial oxidation of oil. Near-term improvements in these fossil-fuel-based processes will allow for the capture of the carbon dioxide byproduct, which can then be sequestered (stored or locked away). In the mid term, we'll see renewable energy technologies taking a larger role—via gasification or pyrolysis of biomass (see "Biorefineries" on pages 2-5) or via electrolysis of water with electricity produced by wind energy or other renewable electric technologies. Eventually, through long-term R&D, hydrogen will be produced directly using photobiological or photolytic processes (see sidebars "Harvesting Hydrogen from Microalgae" and "Solid-State Water Splitting"), in which hydrogen will be derived directly from sunlight and water.

Storing Hydrogen. Today, we store hydrogen as a compressed gas under high pressure or as a liquid at cryogenic temperatures. These will continue to be the primary means of storage for quite some time. There is also a possibility that we soon may be able to store hydrogen onboard vehicles or at the point of use as gasoline, methanol, or some other hydrogen-rich material, from which it could be extracted using a reformer (which breaks down hydrogen-carbon bonds to produce a gas from which hydrogen



Carbon nanotubes carry the promise of being able to store high volumes of hydrogen and to release the hydrogen on demand.

Storing Hydrogen in Nanotubes

The energy density (energy per mass) of hydrogen is more than three times that of gasoline. The problem is, because hydrogen is so light, it requires a large volume to store an appropriate amount of hydrogen energy onboard a vehicle. To overcome this, we can store the hydrogen at very low temperatures, under high pressure as a compressed gas, in chemical or metal hydrides (materials that reversibly absorb hydrogen), or even in liquid hydrocarbons that can be reformed to hydrogen on demand.

A team of NREL scientists is pursuing a novel and promising long-term solution: storage of hydrogen in carbon nanotubes—hollow tubes of carbon 1-2 nanometers in diameter. The walls of the tubes are made of a single layer of carbon atoms arranged in hexagonal patterns. These tubes can absorb and safely store high volumes of hydrogen in a small space at normal operating conditions. The stored hydrogen can be released on demand through small changes in temperature and pressure.

Researchers have been able to make some very pure carbon nanotubes that appear to be able to store up to 67 kilograms of hydrogen per cubic meter (kg/m^3). At such a capacity—which surpasses the goal of 62 kg/m^3 set by the Department of Energy—it would take only about 0.075 cubic meters to store 5 kilograms of hydrogen, which is about the size of gas tanks used in some cars and small trucks today. With this amount of stored hydrogen, an advanced fuel-cell car should be able to travel farther on a tank than today's typical car or small truck.

This photovoltaic system at SunLine Transit Agency in Thousand Palms, California, provides electricity for the Stuart Energy electrolysis unit (on the right).

is obtained). In the meantime, research will continue to explore ways in which to store hydrogen in chemical or metal hydrides or in carbon nanotubes. These long-term options could provide safe and high-density storage, reducing storage space and providing a range that could be greater than that provided by conventional vehicles (see sidebar "Storing Hydrogen in Nanotubes").

Distributing Hydrogen. America has an extensive distribution network for its energy. There are more than 3 million miles of pipelines for transporting natural gas and petroleum, 160,000 miles of high-voltage transmission lines, and thousands of tankers and trucks. And there are tens of thousands of gas stations for dispensing gasoline. This network is characterized by centralized production with distribution to regional and local markets. Hydrogen itself is transported primarily by truck, but also by tankers and pipeline. In the near term, hydrogen for energy will use the existing distribution systems. But as demand grows in the future, we could see natural gas piped to regional locations, where it will be reformed to hydrogen for regional distribution. Farther into the future, as production from renewable energy sources and technologies becomes less expensive, we may see hydrogen produced both regionally and locally, and distributed locally. Thus, the emerging hydrogen economy will not only provide secure and clean energy for the nation, but also will provide local communities with an important economic base from which to grow.

Hydrogen-powered vehicles, which are becoming more popular, include SUVs and fleets of buses. The SunLine Transit Agency, for example, uses two buses powered by a mixture of hydrogen and natural gas, and one bus powered by hydrogen fuel cells.

Solid-State Water Splitting

The cleanest way to produce hydrogen is by using sunlight to directly split water into hydrogen and oxygen. All you need is sunlight and water, and an appropriate system to split the water.

NREL scientists have devised such a system, in which a multijunction solar cell is immersed in an aqueous electrolytic solution. The top cell in the structure (made of gallium indium phosphide—$GaInP_2$) absorbs the high-energy photons in the solar spectrum to produce electron-hole pairs. The bottom cell (made of gallium arsenide—GaAs) does likewise with the lower-energy photons that pass through the top cell. The electrons flow toward the illuminated surface and the electrolytic-$GaInP_2$ interface, which serves as a cathode for the system. Holes travel to the GaAs bottom surface, which is coated with platinum to provide an ohmic contact. The tandem cell provides a sufficient voltage to drive an oxidation-reduction reaction that produces hydrogen at the cathode and oxygen at a platinum anode.

An NREL scientist holds a beaker containing a photolytic device submerged in an alkaline aqueous solution. This configuration produces hydrogen from water with greater than 12% efficiency.

This NREL system produces electricity from sunlight without the expense and complication of electrolyzers—and at 12.4% solar-to-hydrogen efficiency, does so more efficiently than other photolytic approaches. This approach represents one possible long-term solution for the sustainable production of hydrogen. In the meantime, there remains much to be explored, including non-aqueous electrolytes, alternate semiconductor systems, and lower-cost materials that may lead to the commercial production of hydrogen from sunlight and water.