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The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet

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Abstract

The Global energy system transition from fossil fuel to hydrogen utilization is described. Environmental benefits of the combustion of hydrogen are reported. World carbon emissions from fossil fuel are schematized in connection with the opportunities of using hydrogen. The atomic hydrogen/carbon ratio and chemical properties of hydrogen are described. Pollutants of the energy system in our planet and hydrogen production technologies are presented.
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1. Introduction

The production of hydrogen is an appropriate environmental solution. Hydrogen is the most abundant element in the universe. It cannot be destroyed unlike hydrocarbons, and it simply changes state from water to hydrogen and back to water—during consumption.

The pollutants emitted by fossil energy systems (e.g. CO, CO_2, CnHm, SO_x, NO_x, radioactivity, heavy metals, ashes, etc.) are greater and more damaging than those that might be produced by a renewable hydrogen energy system [1]. Worldwide reduction of CO_2 emission to reduce the risk of climate change (greenhouse effect) requires a major restructuring of the energy system. The use of hydrogen as an energy carrier is a long-term option to reduce CO_2 emissions.

Global utilization of fossil fuels for energy needs is rapidly resulting in critical environmental problems throuxghout the world.

In 1992, as a result of the Second World Renewable Energy Congress held in Reading, The world renewable energy network (WREN) has been formed. The first author of this paper is the founder member of WREN. This network is dedicated to promoting renewable energy throughout the world. The renewable energies are solar energy, wind power, hydro power, bio energy, hydrogen energy, geothermal energy, ocean energy, energy efficiency, education menu and others.

Energy, economic and political crises as well as the health of humans, animals and plant life are all critical concerns. There is an urgent need to expedite the process of implementing the hydrogen economy. A worldwide conversion from fossil fuels to hydrogen would eliminate many problems and their ramifications. The optimal endpoint for conversion to the hydrogen economy is the substitution of clean hydrogen for the present fossil fuels. The production of hydrogen from non polluting sources (such as solar energy) is the ideal way [2].

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2. The properties of hydrogen

Hydrogen is the simplest element, an atom consisting of only one proton and one electron. It is also the most plentiful element in the universe. Despite its simplicity and abundance, hydrogen does not occur naturally as a gas on the Earth—it is always combined with other elements. Water, for example, is a combination of hydrogen and oxygen (H·O). Hydrogen is also found in many organic compounds, notably the "hydrocarbons" that make up many of our fuels such as gasoline, natural gas, methanol and propane.

Hydrogen can be made by separating it from hydrocarbons by applying heat, a process known as "reforming" hydrogen. Currently, most hydrogen is made this way from natural gas. An electrical current can also be used to separate water into its components of oxygen and hydrogen. Some algae and bacteria, using sunlight as their energy source, even give off hydrogen under certain conditions.

Hydrogen is high in energy, an engine that burns pure hydrogen produces almost no pollution. NASA has used liquid hydrogen since the 1970s to propel the space shuttle and other rockets into orbit. Hydrogen fuel cells power the shuttle's electrical systems, producing a clean by-product—pure water, which the crew drinks. You can think of a fuel cell as a battery that is constantly replenished by adding fuel to it—it never loses its charge.

Fuel cells are a promising technology for use as a source of heat and electricity for buildings and as an electrical power source for electric vehicles. Although these applications would ideally run off pure hydrogen, in the near term they are likely to be fuelled with natural gas, methanol, or even gasoline. Reforming these fuels to create hydrogen will allow the use of much of our current energy infrastructure—gas stations, natural gas pipelines, etc.—while fuel cells are phased in.

In the future, hydrogen could also join electricity as an important energy carrier. An energy carrier stores, moves, and delivers energy in a usable form to consumers. Renewable energy sources, like the sun, cannot produce energy all the time. The sun does not always shine. But hydrogen can store this energy until it is needed and can be transported to where it is needed.

Some experts think that hydrogen will form the basic energy infrastructure that will power future societies, replacing today's natural gas, oil, coal, and electricity infrastructures. They see a new hydrogen economy to replace our current energy economies, although that vision probably will not be realised until far in the future.

Hydrogen has an excellent safety record and is as safe for transport, storage and uses as many other fuels. Nevertheless, safety remains a top priority in all aspects of hydrogen energy. The hydrogen community addresses safety through stringent design and testing of storage and transport concepts, and by developing codes and standards for all types of hydrogen-related equipment.

The vision of building an energy infrastructure that uses hydrogen as an energy carrier—a concept called the "hydrogen economy"—is considered the most likely path toward a full commercial application of hydrogen energy technologies.

3. Hydrogen research

3.1. Developing sustainable technologies for the 21st century

The vision is staggering: a society powered almost entirely by hydrogen, the most abundant element in the universe. In this vision, renewable resources such as biomass, wind, and solar energy are used to extract hydrogen from water. When the hydrogen is used as an energy source, it generates no emissions other than water, which is recycled to make more hydrogen.

3.2. Hydrogen and its uses

Hydrogen is a colorless, odorless gas that accounts for 75% of the universe mass. Hydrogen is found on Earth only in combination with other elements such as oxygen, carbon and nitrogen. To use hydrogen, it must be separated from these other elements.

Today, hydrogen is used primarily in ammonia manufacture, petroleum refinement and synthesis of methanol. It is also used in NASA's space program as fuel for the space shuttles, and in fuel cells that provide heat, electricity and drinking water for astronauts. Fuel cells are devices that directly convert hydrogen into electricity. In the future, hydrogen could be used to fuel vehicles and aircraft, and provide power for our homes and offices.

3.3. NREL's hydrogen research

The National Renewable Energy Laboratory (NREL, Denver, Colorado, USA).

As part of the US Department of Energy's Hydrogen Program, this laboratory conducts research on advanced technologies to produce, store and safely use hydrogen made from renewable resources. The goal is to help industry develop technologies to produce, store, transport and use hydrogen in quantities large enough, and at costs cheap enough to compete with traditional energy sources such as coal, oil and natural gas.

3.3.1. Production research

The researchers are exploring the use of renewable resources such as sunlight, biomass and biological organisms to produce hydrogen economically.

Photoconversion production: Researchers use either biological organisms (bacteria or algae) or semiconductors to absorb sunlight, split water and produce hydrogen. Through their normal metabolic function, some biological organisms naturally produce hydrogen; semiconductors produce hydrogen by generating an electric current that splits water.

NREL researchers have developed a device that splits water into hydrogen and oxygen with greater efficiency than most other methods using sunlight. Current systems link photovoltaic cells that generate electricity with an electrolyser to break down water. There is an advanced alternative to these less efficient photovoltaic/electrolyser systems. The new device converts about 12% of available sunlight into hydrogen, compared to 4–6% for the photovoltaic/electrolyser system. While not currently economical, the device has a potential for lower cost hydrogen and represents a breakthrough in hydrogen research.

Thermochemical production: This approach uses heat to produce hydrogen from biomass and solid waste. A developed pyrolysis technology uses heat to liquefy biomass. Steam is then used to make hydrogen from the resulting bio-oil in a process known as steam reforming.

3.3.2. Storage research

Hydrogen is currently stored as a compressed gas or a cryogenic liquid in physical storage systems. A solid-state storage system that is safer than physical storage systems and can potentially store more hydrogen per unit volume is being developed. Solid-state systems chemically or physically bind hydrogen to a solid material.

NREL's solid-state storage system uses microscopic carbon tubes to adsorb hydrogen. The technology can store high volumes of hydrogen at higher temperatures than other technologies and at near ambient pressure levels. The hydrogen attaches to the surface of the carbon and is released by changing temperature and pressure levels.

3.3.3. Hydrogen sensors

Since hydrogen can neither be seen nor smelled, as an added safety precaution for hydrogen-fuelled vehicles, the researchers are developing a hydrogen leak detector. To detect hydrogen, a very thin sensor that reacts to hydrogen by changing colors is applied to the end of a fiber optic cable. The sensors can be placed throughout the vehicle to relay information on leak detection to a central control panel.

3.3.4. Benefits of hydrogen

Hydrogen made from renewable energy resources is a virtually inexhaustible, environmentally benign energy source that could meet most of our future energy needs. It is more versatile and has more uses than electricity. These uses include providing energy for businesses, factories, electric utilities, homes, vehicles and airplanes. Hydrogen is also a domestically produced energy source that could help reduce our reliance on foreign oil.

3.3.5. Challenges

Researchers must overcome several obstacles if hydrogen is to become a major energy resource. Hydrogen is currently more expensive than traditional energy sources; the production efficiency (the amount of energy or feedstock used to produce hydrogen) must improve and an infrastructure to efficiently transport and distribute hydrogen must be developed.

The reality of an eventual transition from oil to hydrogen becomes more evident when one takes an atomic view of energy history. Since the mid-nineteenth century, the world has been slowly shifting from one form of energy to another from solids to liquids to gases, as Robert Hefner has illustrated (GHK Company) [3] (Fig. 1).

3.3.6. Potential

The first widespread use of hydrogen as an energy source is likely to be in the transportation sector, where it will help reduce pollution. Internal combustion engines can be fueled with pure hydrogen, or hydrogen blended with natural gas. Vehicles can also be powered with hydrogen fuel cells, which are three times more efficient than a gasoline-powered engine. Fuel cells can also supply heat and electricity for homes and buildings.

The overall goal of DOE's hydrogen program is to replace two to four quads of conventional energy with hydrogen by the year 2010, and replace 10 quads per year by 2030. A quad is the amount of energy consumed by 1 million households.

Hydrogen is everywhere, but it is hard to find on Earth as a separate element. Instead, it is primarily found in combination with oxygen in water, in combination with carbon in a range of hydrocarbon fuels, and in combination with carbon in plants, animals, and other forms of life. Hydrogen bound in water and organic forms accounts for more than 70% of the Earth's surface. Once it is extracted, this colorless, odorless, and tasteless element becomes a useful “feedstock”, or input, to a variety of industrial activities and a potentially ubiquitous fuel sufficient to energize virtually all aspects of society, from homes to electric utilities to business and industry [4]. (Fig. 2).

It was agreed that the hydrogen energy system was an idea whose time had arrived. It was a permanent solution to the depletion of conventional fuels and global environmental problems. [5] (Fig. 3).

The combustion of hydrogen does not produce CO_2, CO, SO_2, VOC and particles, but entails emission of vapor and NO_x. The formation of NO_x is a function of flame temperature and duration. Considering the wide flammability range of hydrogen its combustion can be influenced by the design of the engine so that the NO_x emission can be reduced. Recent research regarding air pollution effects on human health describes serious lung damage sustained from fossil fuel combustion. Substituting hydrogen for fossil fuel will result in improved physical health [6].

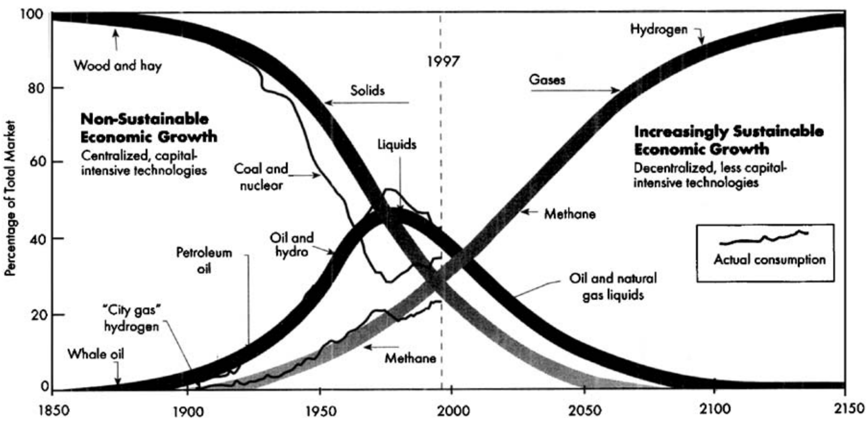

Fig. 1. Global energy system transition, 1850–2150.

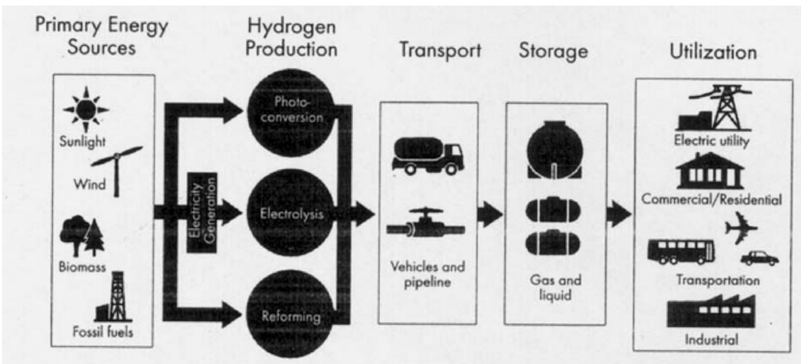

Fig. 2. A hydrogen energy system.

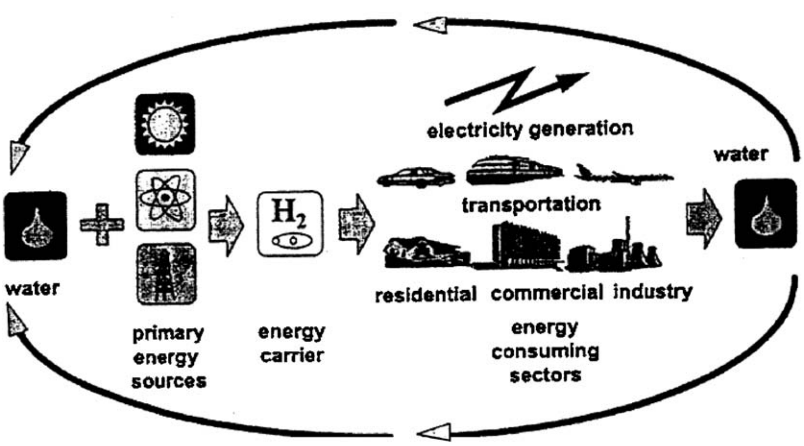

Fig. 3. A hydrogen economy for sustainability.

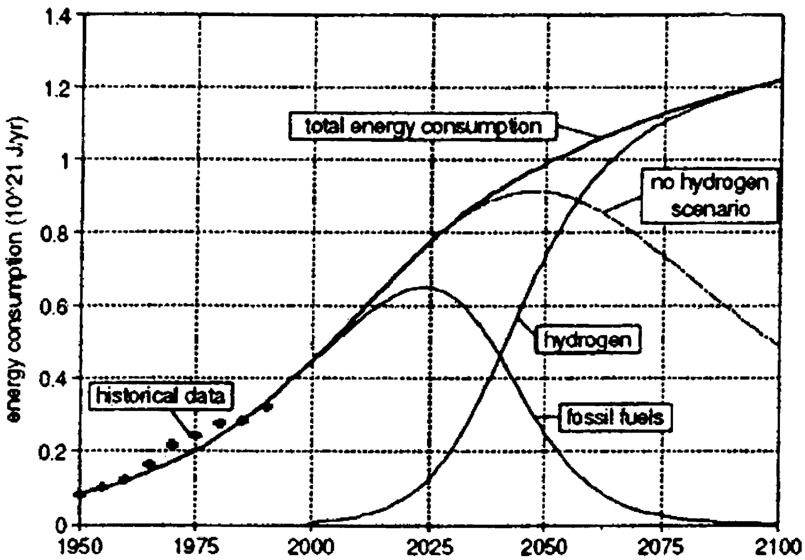

Fig. 4. Energy consumption.

It is a major option to slow down the rate of atmospheric CO_2 emissions or level out the CO_2 concentration in the atmosphere. A unique system has been devised which offers a method of actually reducing the CO_2 concentration in the atmosphere while still generating energy from fossil fuels. The only economically and technically reasonable method for removal of CO_2 from the atmosphere is by the process of solar photosynthesis which extracts carbon from atmospheric CO_2 by formation of biomass, e.g., lignocelluloses. The biomass is then thermochemically converted by the HYDROCARB technology with fossil fuel, gas oil or coal to produce carbon black and methanol. The carbon is returned to the Earth, for long-term storage, while biomass results in a net removal of CO_2 from the atmosphere of about 33.49 g CO_2 per million J of methanol-generated energy. There is also large energy enhancement in utilizing gas and oil for producing methanol compared to conventional methanol process using these fuels. Coprocessing with bituminous coal results in no net CO_2 emitted or removed per unit of methanol energy generated [7].

There is a new important development in automotive technology in recent years, which is aimed toward more efficient and less polluting vehicles.

The analysis of full cycles shows that the fuel cell drive for city buses offers significant environmental improvements compared to diesel internal combustion engines. This refers to emissions of greenhouse gases as well as to local emissions of trace gases. The main improvement with regard to the global warming problem can nonetheless only be achieved if renewable fuels are introduced [8].

A major advantage of fuel cell vehicles (and all fuel cells) is that they represent an inherently clean, efficient and quiet technology and can optimize use of fuels from environmentally benign energy sources and feed stocks such as solar, wind, geothermal and biomass. One must emphasize these attributes to the maximum extent possible because there is increasing competition from conventional technologies [9].

In the case where utilization of solar energy and hydrogen is introduced in the energy market, energy consumption continues to increase, although at a lower rate than between 1950 and 1990 (Fig. 4).

The move from solid to liquid to gas fuels involves another sort of transition: the less visible process of "decarburization". From wood to coal to oil to natural gas, the ratio of hydrogen (H) to carbon (C) in the molecule of each successive source has increased. Roughly speaking, the ratio is between 1 to 3 and 1 to 10 for wood: 1 to 2 for coal; 2 to 1 for oil and 4 to 1 for natural gas [10] (Fig. 5).

A major problem in using fossil fuels is the pollution. The pollutants of energy systems in comparison with hydrogen are presented in Fig. 6.

Several solar hydrogen demonstration plants have been built. Other major hydrogen projects are moving ahead. The development of the international standards for hydrogen energy is moving ahead. Hydrogen production, storage and utilization technologies are continually improving. It is only a matter of time before hydrogen will start replacing fossil fuels on a large scale. Once this is known, the transition to our new economy will progress rapidly. The future for our planet is bright because hydrogen provides the solution to environmental pollution and dwindling fossil fuels [11]. On the transition path from fossil fuels to hydrogen, the economy will prosper. The fossil fuel infrastructure will remain in place without loss of jobs, but a change only in job

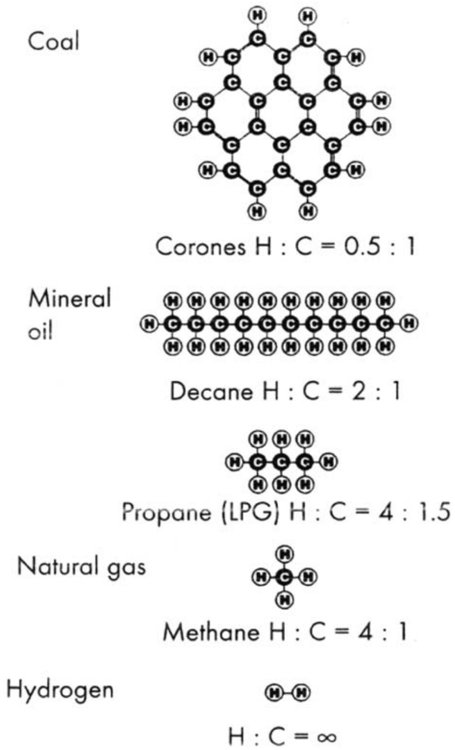

Fig. 5. The atomic hydrogen/carbon ratio.

descriptions, as this infrastructure becomes the hydrogen infrastructure. Energy investors will prosper [12].

In September 2002, a demonstration of running a public bus with hydrogen was made in Brussels. On 10 October 2002, the new high-level group for hydrogen and fuel cells was launched in Brussels by the EU Commission. The group, comprising representatives from industry, research and national governments, is charged with assessing the potential benefits of using hydrogen and fuel cells in EU transport, energy production and other areas and preparing the way for more focused EU action in this field.

In the United States and Japan, we see clear developments toward programs and strategic alliances around hydrogen and fuel cells. These movements are seeking to bring hydrogen to the market, pushing it toward commercialization [13].

4. Developing hydrogen and fuel cell products

4.1. Hydrogen production

Hydrogen is already being produced in huge volumes and is used in a variety of industries. Current worldwide production is around 500 billion Nm^3 per year. Most of the hydrogen produced today is consumed on-site, such as at oil refineries, and is not sold on the market. From large-scale production, hydrogen costs around \$0.70/kg if it is consumed on-site. When hydrogen is sold on the market, the cost of liquefying the hydrogen and transporting it to the user adds considerably to the production cost.

The fundamental research in hydrogen field is also important. A thermal process for hydrogen generation has been developed using water in the presence of zeolites

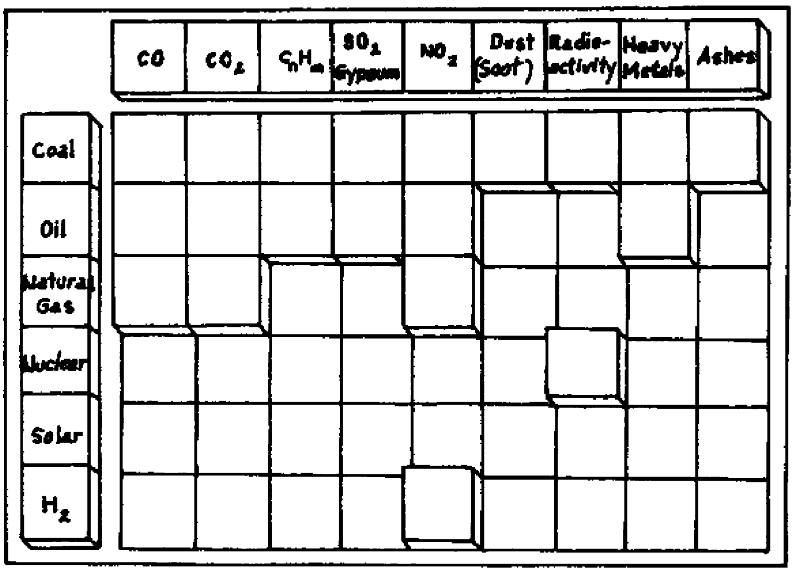

Fig. 6. Pollutants of energy systems.

impregnated with non-noble metals of variable valences and activated in a vacuum [14–25].

4.2. Hydrogen storage

Hydrogen is now beginning to be accepted as a useful form for storing energy for reuse on, or for export off, the grid. Clean electrical power harvested from wind and wave power projects can be used to produce hydrogen by electrolysis of water—splitting this into its constituent parts of hydrogen and oxygen.

Hydrogen can be stored in a variety of forms:

- cryogenic, this has the highest gravimetric energy density,
- high-pressure cylinders; pressures of 690 bar are quite normal,
- metal hydride absorbs hydrogen, providing a very low pressure and extremely safe mechanism, but is heavy and more expensive than cylinders;
- chemical carriers offer an alternative, with anhydrous ammonia offering similar gravimetric and volumetric energy densities to ethanol and methanol.

4.3. Consumption of hydrogen

Current thinking suggests that fuel cells are the path for the use of hydrogen and that the fuel cell industry is driving the hydrogen economy. This may be true but it loses sight of other, less costly opportunities.

Hydrogen can also be used in internal combustion engines, fuel cells, turbines, cookers and gas boilers.

In many towns of the world, lamplighters once lit gas street lights at dusk. Inside middle class homes, gas lamps provided light while gas heaters provided warmth. The gas that fuelled the lights and furnaces was a hydrogen-rich mixture called "town gas", which was manufactured from coal and consisted mainly of raw hydrogen, some methane and small amounts of CO and CO_2. Town gas or hydrogen is still used in many parts of the world such as China and other Asian countries. The traditional internal combustion engine can be converted to run-on hydrogen.

The BMW Clean Energy World Tour 2002 presented the hydrogen technology and the hydrogen internal combustion engine to leading opinion leaders and decision makers from politics, industry and science. The goal was to establish a hydrogen infrastructure through global partnerships in order to cause the breakthrough of the fuel of the future [26].

5. New hydrogen cars and fueling stations in the US

The new Toyota Motor is powered by a 90-kW fuel cell in combination with a nickel–metal hydride battery and regenerative braking, which uses the energy of braking to recharge the battery. Running on high-pressure hydrogen, the vehicle achieves a top speed of nearly 153 km per hour, has a range of more than 250 km and achieves triple the fuel efficiency of a regular gasoline-powered car. Toyota is road-testing the vehicle in Japan and the US, with the US tests being carried out through the California Fuel Cell Partnership.

Ford believes that the vehicle can help lead to a hydrogen infrastructure while fuel cells continue to be developed.

Hydrogen-fueled vehicles became a step more feasible as both the American Honda Motor Company and BMW have opened hydrogen fuelling stations in California for their fuel cell-powered vehicles.

Located at its research and development center in Torrance, California, Honda's station uses solar power to extract hydrogen from water. Solar panels on the station generate enough hydrogen to power one fuel cell vehicle, but additional electrical power from the power grid is used to increase the hydrogen production capacity.

BMW's new liquid hydrogen fuel station is located at its engineering and emissions control test center in Oxnard, California, where the company is taking a different approach to most car companies by burning hydrogen directly in advanced internal engines [27].

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