THE HYDROGEN ECONOMY

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INTRODUCTION

Figure 1. Hydrogen automobile fuel cell refueling station at Burlington, Vermont. Electrolysis is used to dissociate water into hydrogen and oxygen. Source: USDOE.

An initiative exists to replace fossil fuels used in passenger cars by 2040. This would need 150 x 10^6 tons of hydrogen per year. Several technologies can provide this supply of hydrogen.

A straight-forward approach is to burn hydrogen in an adapted model of an Internal Combustion Engine (ICE). With little modification, these engines are relatively cheap, and 25 percent more efficient than gasoline powered engines. The German Bayerische Motor Werken (BMW) car company built its first hydrogen ICE back in the 1970s. The USA Ford Company produced of a hydrogen ICE shuttle bus.

A better alternative is the use of fuel cells. First invented in 1839, a fuel cell combines hydrogen and oxygen to generate electricity without any moving parts.

The Proton Exchange Membrane (PEM) fuel cell is lightweight and responsive enough to be practical for vehicle use. Though twice as efficient as ICEs, PEM fuel cells are still highly priced at about $30,000 each. Technical hurdles need to be surmounted.

An analysis by the Department of Energy projected that a supply network adequate for 40 percent of the light-duty fleet could cost more than $500 billion.

A classic chicken-and-egg problem exists: How to get consumers to buy hydrogen-powered vehicles before there is an infrastructure in place to refuel them, and how do you get the energy companies to build that infrastructure before there is a potential market demand.

Awaiting the establishment of a basic infrastructure, hydrogen fuel cells is expected to replace chemical batteries in niche equipment, such as TV cameras and forklifts, and provide power at remote locations, such as at cellular phone towers.

HYDROGEN AS AN ENERGY CARRIER

Figure 2. Four 250 kW hydrogen fuel cells units power a plant at Chico, California, with natural gas as a source of hydrogen.

Hydrogen stores 3 times as much energy per unit mass as natural gas. When consumed its only emission is water in the form of steam.

It is strictly an energy carrier and not an energy source by itself. It stores the energy generated from other sources such as nuclear, wind, solar, geothermal, biomass or fossil petroleum, natural gas or coal.

Unlike petroleum and natural gas, hydrogen is not a fuel. It is a way of storing or transporting energy.

While petroleum and natural gas are easy to transport in pipelines and fuel tanks since they contain energy into a dense, stable form, hydrogen presents a host of technical and economic challenges.

Skeptics say that hydrogen promises to be a needlessly expensive solution for applications for which simpler, cheaper and cleaner alternatives already exist.

On the other hand, advocates promote hydrogen as a panacea for energy needs ranging from consumer electronics to home power.

Its real impact will likely occur as a transportation fuel; which represents 2/3 of the USA petroleum consumption consumption. This would be in competition with biofuels, ethanol, biodiesel and other technologies.

Hydrogen, ultimately, over the long term, can delink light duty transportation from petroleum entirely. The USA automakers General Motors (GM), Ford and Chrysler, as well as the Japanese Toyota, Honda, and Nissan, and German BMW have all been preparing for that day.

Fuel cell vehicles can travel 300 miles on 17.6 pounds of hydrogen and achieve speeds of up to 132 mph. A critical infrastructure is needed for a hydrogen economy. The practical employment of hydrogen power involves challenges in production, storage, distribution and use [1].

HYDROGEN PRODUCTION SOURCES

The USA uses some 10 x 10^6 tons /year of hydrogen for industrial purposes, such as making fertilizer and refining petroleum. If hydrogen powered vehicles are to come into use the need would increase to 10 times the current usage.

Several methods of hydrogen production are under consideration:

1. Steam Reformation of Fossil Fuels

Fossil fuels are also considered as “hydrocarbons” and hence contain hydrogen in addition to carbon.

About 95 percent of the USAs hydrogen is produced from natural gas through a process called steam methane reformation.

High temperature and pressure break the hydrocarbon into hydrogen and carbon oxides including carbon dioxide, which is released into the atmosphere as a greenhouse gas.

Over the next 10 or 20 years, fossil fuels are expected to continue to be the main feedstock for the hydrogen economy. Using fossil fuels energy to make clean energy does not solve the CO_2, SO_x and NO_x, mercury, arsenic, cadmium and even radioactive pollution problems associated with fossil fuels.

A partial remedy is Carbon Capture and sequestration (CCS) which involves capturing that CO_2 and sequestering it underground to make the process more environmentally friendly.

The General Electric Company (GE) and British petroleum (BP) announced plans to develop as many as 15 power plants over the next 10 years that will strip hydrogen from natural gas to generate electricity. The waste CO_2 would be pumped into depleted oil and gas fields.

The USA Department of Energy (USDOE) is considering funding a 10-year, $950 million project to build a coal-fed plant that will produce hydrogen to make electricity, and likewise lock away CO_2 to achieve what it bills as "the world's first zero-emissions fossil fuel plant."

Uncertainties exist about the CO_2 containment in large scale operations. Natural gas is a limited resource whose price fluctuation would affect the cost of the produced hydrogen.

2. Water Electrolysis

Hydrogen can be generated by electrically splitting water into its constituent parts, hydrogen and oxygen.

Since fossil fuels generate 70 percent of the nation's electrical power, hydrogen produced from the grid would still be a significant source of greenhouse gases. If nuclear, wind, solar, geothermal or other renewable resources generate the electricity, hydrogen could be produced without carbon emissions.

The data suggest that no single energy source would be able to satisfy the need for hydrogen as a transportation energy carrier. An optimal combination of different energy sources would be called for to satisfy the need.

3. Nuclear Fission

Next-generation nuclear power plants will reach temperatures high enough to produce hydrogen as well as electricity, either by adding steam and heat to the electrolysis process, or by adding heat to a series of chemical reactions that split the hydrogen from water.

Very High Temperature Reactors (VHTRs) would provide process heat for High Temperature Electrolysis (HTE) of water or thermochemical processes.

This would need 240,000 tons of natural uranium, an increase of the current world production by 5 times.

Although 103 nuclear power plants operate in the USA today, 2,000 600 MWe nuclear power plants would be required. The first VHTR will be built in the USA at the Idaho National Engineering and Environmental Laboratory (INEEL) by 2021.

4. Wind Power

Wind turbines operate at a typical 20-40 percent intermittence factor. The produced electricity can be used in electrolysis to produce hydrogen from water.

At 7 meters/sec average wind speed, a number of 1 million 2 MW rated power wind turbines would be required covering 5 percent of 120 million acres of land; an area larger than the state of California.

5. Solar Power

Operating at 10 percent efficiency, Photo Voltaic (PV) systems can provide electricity for water electrolysis. Concentrated Solar Power (CSP) is developing at a rate as fast as wind power introduction will help fill the gap.

For PV alone, 2,500 kW.hr / (m^2.year) of solar insolation is available in south-western part of the USA sun-belt. There would be a need for 113 million 40 kW systems covering 50 percent of more than 300 million acres of land, an area 3 times the size of the state of Nevada.

6. Natural Gas

Hydrogen gas can be produced in gas station-size facilities using steam reformation. There would be a need for 15.9 million ft3 / year, which is a fraction of the current USA annual natural gas consumption.

A number of 777,000 small distribution facilities would be needed with a number of large central production plants.

7. Biomass

Hydrogen could be produced by biomass gasification plants using steam reforming.

There would be a need for 1.5 billion tons per year of dry biomass products. Initially waste products such as wood chips, corn cobs and peanut shells can be used, to be followed by concentrated specialized crops such as switchgrass or the Miscanthus ornamental grass.

About 3,300 gasification plants would be constructed, and 113.4 million acres of lands used to grow the biomass crops. This is 11 percent of the USA's farmland to be dedicated to energy crops.

8. Coal gasification

Hydrogen can be produced from coal gasification plants followed by steam reforming. The Carbon Capture and segregation (CCS) technology has to be used.

Doubling the USA domestic production of coal to 1 billion tons / year would be required.

About 1,000 275 MW plants would have to be constructed. Twelve sites were chosen for a demonstration plant. Not all sites met the required criteria.

Table 1. Comparison of different sources of hydrogen as transportation fuel. Hydrogen production: 150 x 10^6 tons /year.

	Nuclear Fission	Wind Power	Solar Power	Natural Gas	Biomass	Coal
Total cost [$ trillion]	0.84	3.0	22.0	1.0	0.565	0.500
Price per gallon of gasoline equivalent [$ /gce]	2.5	3.0	9.5	3.0	1.9	1.0
CO_2 emissions [million tons]	0	0	0	300	600*	600**

* Zero net emissions.

** With 90 percent CO_2 capture and underground storage.

HYDROGEN STORAGE

At room temperature and pressure, the hydrogen gas density is so low that it contains less than 1 / 300 the energy in an equivalent volume of gasoline. To fit it into a reasonably sized storage tank, hydrogen has to be stored in a denser state squeezed into a denser form. Three approaches are contemplated.

1. Cryogenic liquefaction:

Cooled to near absolute zero, the hydrogen gas turns into a liquid containing 1/4 the energy in an equivalent volume of gasoline. The technology is proven in aerospace applications. The National Aeronautics and Space Administration, NASA has used liquid hydrogen to power space vehicles and rockets such as the space shuttle. The cooling process requires a significant amount of energy input, 1/3 of it remains held in the hydrogen. There is a need for heavy, bulky, and expensive insulated storage tanks.

2. Compression:

Some hydrogen powered vehicles use tanks of room-temperature hydrogen compressed to an astounding 10,000 psi. The Sequel design by GM carries 8 kgs of compressed hydrogen, sufficient to power the vehicle for 300 miles.

Refueling with compressed hydrogen is relatively fast and simple. Compressed hydrogen requires large volume tanks that take up to 4-5 four times as much space as a gasoline tank with an equivalent mileage range.

Fuel cell cars can yet accommodate larger tanks since they contain fewer mechanical parts.

3. Solid State Storage:

Several compounds can trap hydrogen at room temperature and pressure, then release it upon demand. The most promising ones are metal hydrides. They are stable, but heavy. A 700 lbs tank could hold enough fuel for a few hours of operation.

More exotic compounds could provide a breakthrough to make hydrogen storage truly practical. High pressure tanks remain as a stopgap until materials that will allow efficient solid-state storage.

HYDROGEN DISTRIBUTION SYSTEM

Hydrogen is a reactive substance reacting with oxygen in air explosively. It is a difficult substance to move from place to place. It can embrittle steel and other metals, weakening them to the point of fracture, causing explosion in containers.

Special provisions are needed to move hydrogen from the production to the consumption centers.

1. Railroad Cars and Tanker Trucks

Most hydrogen is transported either in liquid form by tankers or as a compressed gas in cylinders by trailers.

Both approaches are inefficient. Trucking compressed hydrogen for a 150 miles distance consumes diesel fuel that is equivalent to 11 percent of the energy the hydrogen stores.

Multiple round trips are required. A 44 ton vehicle that can carry enough gasoline to refuel 800 cars could only carry enough hydrogen to fuel 80 vehicles.

2. **Pipelines Conveyance**

About 700 miles of hydrogen pipelines now operate in the USA near large users such as oil refineries.

The longest hydrogen pipeline in the world is a 250 mile line between Belgium and France.

To protect them from embrittlement and high pressure requires special treatment of the piping. This makes cost about $1 million per mile. Once built, they are the cheapest way to deliver high volumes of hydrogen.

3. Localized production

Considering the difficulties encountered in transporting hydrogen, about half the hydrogen refueling stations currently operating in the USA produce hydrogen locally. Four of these rely on natural gas; the rest use water electrolysis.

The Japanese car manufacturer Honda introduced a Home Energy Station that performs steam reforming right in an owner's garage. Because natural gas is the feedstock, it still releases carbon dioxide to the atmosphere.

A greenhouse gas free approach would use onsite wind or solar power to produce hydrogen through electrolysis from water.

The car manufacturer Honda designed a solar-powered hydrogen refueling station at its California laboratory since 2001.

The hydrogen national power supply could become more ecologically friendly by using water electrolysis with electricity from the power grid.

4. On-Board Hydrogen Production

Prototype vehicles make their own hydrogen from stored hydrocarbons, eliminating the issue of distribution. The Mercedes NECAR 3 vehicle produces hydrogen from methanol.

Other on-board production technologies combine ordinary water with reagents like boron or aluminum to produce hydrogen, oxygen and a metal oxide residue.

DISCUSSION

Hydrogen will be one part of a number of future energy alternatives. Any one of them will involve the investment in new infrastructure.

With a steep price tag, the age of hydrocarbons fuels is being replaced by sustainable, environmentally favorable, and economic alternatives.

REFERENCE

1. Jeff Wise, "The Truth about Hydrogen," Popular Mechanics, November 1, 2006.