# Hydrogen Fuel—An Economically Viable Future for the Transportation Industry?

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# Abstract

This report assesses the potential of hydrogen fuel to serve as an economically viable fuel alternative to oil and natural gas. Hydrogen's physical properties are first reviewed with special attention to how they are advantageous and disadvantageous in hydrogen combustion and fuel cell propulsion systems. This analysis determines the primary shortcomings of the existing hydrogen economy, including limited, inefficient, and often environmentally detrimental production methods; insufficient delivery infrastructure; prohibitive costs; low energy density in storage applications; and problems associated with hydrogen vehicles themselves. These existing obstacles are weighed against new technologies and potential solutions to evaluate the future of hydrogen in the transportation sector.

With gasoline at the pump growing ever more expensive and greenhouse gas emissions an increasingly more worrisome environmental concern, finding a stable and environmentally friendly energy option has forced its way into the American and global agenda. Transportation, accounts for 29.2% of primary energy use and 33.9% of carbon dioxide emissions in the U.S. (according to 2001 figures), with the vast majority of emissions the result of the combustion of oil derivatives. The transportation sector represents not only a sizeable portion of energy consumption, but with technological advancement, a promising area for potential pollution reductions.[1] Current projections forecast that primary energy emissions of greenhouse gases and other air pollutants will continue to rise over the next 100 years from increased demand, especially from the developing world. Thus, in order to prevent potential environmental catastrophe without curbing demand, a viable fuel substitute is essential.

Numerous potential alternative fuels have been proposed, including reformulated gasoline, biodiesel, methanol, ethanol, synthetic liquids (such as dimethyl ether produced from coal and natural gas), compressed natural gas, and hydrogen.[2] Of these fuel sources, hydrogen appears to be on the forefront of the current administration's agenda, as made evident in a speech delivered by President Bush at the National Building Museum in Washington, D.C., in February 2003:

> "Cars that will run on hydrogen fuel produce only water, not exhaust fumes. Eliminating pollution from cars will obviously make our air healthier. Hydrogen power will dramatically reduce greenhouse gas emissions, helping this nation take the lead when it comes to tackling the long-term challenges of global climate change."[3]

This paper explores the economic feasibility and potential of hydrogen to serve as a competitive fuel option. We will first consider the advantages and disadvantages hydrogen offers as a fuel source based on its physical properties, and review how those properties may be employed to power a vehicle either in a hydrogen fuel cell or internal combustion engine. In order for hydrogen to be considered a viable option, there must be sufficient production and delivery infrastructure, and hydrogen must be supplied at a reasonable price so that the operating cost of a hydrogen vehicle on a cost per distance basis is competitive with the cost of operating a gasoline vehicle. Thus, it is necessary to assess the adequacy of current infrastructure, consider how this infrastructure must be expanded and at what investment cost, and estimate at what price this infrastructure will be able to deliver hydrogen to the consumer. Finally, existing and new vehicle and storage technologies will be evaluated focusing on propinquity to commercial availability, fuel economy, and operation cost in order to assess the capability of a hydrogen car to compete in the transportation sector.

## Hydrogen as a Fuel Source

As a fuel source, hydrogen is very similar to electricity, being considered a versatile energy carrier that can be produced from a variety of primary energy sources including (but not limited to) natural gas, coal, biomass products such as forestry residues and energy crops, sunlight, wastes, wind, and nuclear power. To provide energy, hydrogen can be either burned or reacted chemically at very high conversion efficiency and will produce virtually no emissions at the point of use.[4] Like any other fuel source, hydrogen has both strengths and weaknesses based on its chemical and physical properties (see **Table 1** for a summary of the physical properties of hydrogen, methane, and gasoline).

| | Hydrogen | Methane (H/C = 4) | Gasoline (H/C = 1.87) |
|---|---|---|---|
| Molecular weight (g/mol) | 2.016 | 16.04 | ~110 |
| Mass density (kg/$N_A$m$^3$) at P=1 atm=0.101 MPa, T=0ºC | 0.09 | 0.72 | 720-780 (liquid) |
| Mass density of liquid $H_2$ at 20 K (kg/$N_A$m$^3$) | 70.9 | - | - |
| Boiling point (K) | 20.2 | 111.6 | 310-478 |
| Higher heating value (MJ/kg) (assumes water is produced) | 142.0 | 55.5 | 47.3 |
| Lower heating value (MJ/kg) (assumes steam is produced) | 120.0 | 50.0 | 44.0 |
| Flammability limits (% volume) | 4.0-75.0 | 5.3-15.0 | 1.0-7.6 |
| Detonability limits (% volume) | 18.3-59.0 | 6.3-13.5 | 1.1-3.3 |
| Diffusion velocity in air (m/s) | 2.0 | 0.51 | 0.17 |
| Ignition energy (mJ) | | | |
| At stoichiometric mixture | 0.02 | 0.29 | 0.24 |
| At lower flammability limit | 10 | 20 | n/a |
| Flame velocity in air (cm/s) | 265-325 | 37-45 | 37-43 |
| Toxicity | Nontoxic | Nontoxic | Toxic above 50 ppm |

**Table 1:** Physical and Chemical Properties of Three Fuel Options (Hydrogen, Methane, and Gasoline)[5]

As a fuel option, and ignoring environmental concerns, hydrogen exhibits numerous advantageous properties including its high diffusion velocity, highest heating value of any fuel (per kilogram), wide range of flammability and detonability limits, low ignition energy, high flame speed, and nontoxicity. Because hydrogen diffuses very rapidly, it will disperse quickly from a leak, and doesn't form puddles that can explode. **Table 1** shows that the heating value of a fuel, or the amount of heat that is transferred from the complete combustion of the fuel in air, increases with the hydrogen to carbon ratio (H/C). Thus, gasoline has the lowest heating value and hydrogen the highest, and therefore a very high potential to do useful work in an engine. The broad range of flammability and detonability limits of hydrogen (the concentration of the fuel in air that can ignite or explode respectively) means that hydrogen does not have to be in stoichiometric ratios to be combusted – it can be burned in leaner concentrations leading to reduce fuel consumption. Additionally, the energy required to ignite a mixture of hydrogen in air (the ignition energy) is low and the flame speed of hydrogen is high, both factors which aid in the complete mixing and combustion of the fuel in a hydrogen combustion engine. The nontoxicity of hydrogen is also an added bonus when compared to gasoline. When combined with its environmental friendliness—except for very small levels of $NO_x$, hydrogen produces only water when burned or chemically reacted—its physical properties make it an intriguing fuel option.[6]

However, hydrogen also has several drawbacks. Compared to methane and gasoline, hydrogen is a very low-density diatomic gas, and thus must be compressed to very high pressures, liquefied at a temperature of about -252ºC, or stored in some other specialized fashion in order to condense a reasonable amount in a reasonable volume.[7] As a compressed gas, hydrogen exhibits rather low energy density, containing about one-third the energy as an equivalent volume of methane at the same pressure, and as a cryogenic liquid, about one-third the energy as an equivalent volume of gasoline. Hydrogen is also an extremely small molecule, diffusing more readily than other fuels, and is more likely to leak. Moreover, it can even diffuse into some metals and cause embrittlement (hydrogen systems thus necessitate special materials considerations). The lower flammability limit of hydrogen, above considered as a strength, also means that if hydrogen leaks and builds up in low concentrations in an enclosed space, accidental explosion can occur (in other words, if fuel and air mix outside the cylinder of an engine, backfiring can occur). Due to a high flame velocity, this explosion could also travel very rapidly. A potential solution to backfiring is direct injection of hydrogen gas into the cylinder prior to spark generation (which also increases engine efficiency by allowing the engine to run at higher compression ratios than if it ran on gasoline). Nonetheless, backfiring remains a potential risk of a hydrogen combustion engine.[8] Hydrogen clearly exhibits several attractive physical properties when it comes to fuel applications, but it is important to remember its potential risks when implementing it in a vehicle.

## Hydrogen Propulsion Options – Internal Combustion Engines and Fuel Cells

Based on its physical properties, an obvious means of generating energy using hydrogen is to burn it in air as you would a hydrocarbon. A hydrogen internal combustion engine is remarkably similar to more familiar engines that burn gasoline, diesel, or natural gas; in fact, with some modification an ordinary internal combustion engine could be made to run on hydrogen. If a standard gasoline internal combustion engine were run on hydrogen, employing stoichiometric ratios of fuel and oxygen to yield complete combustion, the hydrogen would occupy roughly 30% of the volume of the piston, compared to about 2% for gasoline vapor, and will generate 20% less power. However, hydrogen can be burned in lower fuel to air ratios, lowering the flame temperature and greatly enhancing the engine's energy efficiency. Estimations are that hydrogen combustion engines are already 20-25% more energy efficient than comparable gasoline engines.[9]

The second means of utilizing hydrogen in a vehicle is with a hydrogen fuel cell. Hydrogen fuel cells are extremely dissimilar to current internal combustion engines, but are potentially even more efficient than hydrogen combustion engines and produce no emissions besides water vapor at the point of use. Essentially a fuel cell is a device that produces electricity, water, and heat directly from the thermochemical reaction of a fuel source (hydrogen) and an oxidant (oxygen). While many combinations of fuels and oxidants may be used, hydrogen and oxygen are preferred due to the extremely high electrochemical activity of hydrogen, which allows dissociation of hydrogen gas at the anode of the fuel cell to proceed very rapidly compared to other fuels. The type of fuel cell that demonstrates the highest potential for automotive use is known as the proton exchange membrane (PEM) fuel cell. Essentially the PEM fuel cell operates like a battery. First, hydrogen molecules ($H_2$) enter the cell and dissociate at the anode into protons ($H^+$) and electrons ($e^-$). The anode is separated from the cathode by an electrolyte membrane, which permits the passage of protons, but not electrons. Electrons must travel through an external circuit, thus performing work, to reach the cathode, where they recombine with protons and oxygen molecules ($O_2$), producing waste heat and water. Theoretically, the hydrogen fuel cell has a conversion efficiency of 83%, although practically this figure is closer to 60% due to the production of waste heat. Still, compared to the efficiency of hydrogen combustion engines, which have approximately 45% conversion efficiency, and regular internal combustion engines with a range of 26-34% conversion efficiency, the hydrogen PEM fuel cell is potentially very attractive.[10]

## Hydrogen Production

Unfortunately, pure hydrogen needed for a combustion engine or fuel cell is not a naturally occurring resource. Hydrogen can be produced essentially one of two ways: via reforming or electrolysis. The global market for hydrogen is already greater than $40 billion per year, including hydrogen used in ammonia production, oil refineries, food processing, and chemical manufacturing, with 90% of commercially available hydrogen being produced through the process of reforming.[11] Reforming is a process whereby hydrocarbons react with steam or oxygen to produce carbon monoxide, carbon dioxide, water vapor, methane, and a synthetic gas (or "syngas") containing hydrogen (this occurs at very high temperatures of 800-1700ºC). The syngas can then be further processed to enhance its hydrogen composition and the pure hydrogen finally separated from the mixture using one of a variety of methods: using materials that can selectively absorb hydrogen from a pressurized mixture and release it when depressurized, via carbon dioxide absorption, or with membranes that are selectively permeable to hydrogen. Reforming is approximately 90% efficient, meaning that at the higher heating value (see **Table 1**), 90% of the energy content of the original hydrocarbon fuel is converted into energy stored in hydrogen. Currently, reforming technologies are only available on a very large scale; for applications such as fuel-cell cogeneration in buildings and stand-alone hydrogen refueling stations, smaller-scale hydrogen production facilities (approximately 0.1 to 1% of the current refinery scale) would be necessary.[12] While reforming is the cheapest means of producing hydrogen, it seems a rather futile exercise if the same fossil fuels are being burned to produce hydrogen as those being directly utilized currently in the transportation sector.

A second, more environmentally conscious means of producing hydrogen, is through water electrolysis. Electrolysis is a process by which water is split into hydrogen and oxygen gas using a combination of heat and electricity. Because electricity is the only necessary input for electrolysis, any technology that can produce electricity can drive the electrolysis reaction.[13] Thus, a huge advantage of electrolysis is that when an electrolyzer is powered by wind, solar, or nuclear energy sources, they can theoretically produce hydrogen gas from water with no emissions of carbon dioxide.[14] Commercial eletrolyzers range in efficiency from 60 to 73% with theoretical efficiency rising with increased temperature (because some of the work needed to split the water molecules is done by heat, less electrical energy is needed). At extremely high temperatures above 2000ºC water can be split directly; however, this process remains highly impractical with current technologies. Furthermore, because the total amount of energy required to split water remains relatively constant (whether it comes from heat or electricity), higher-temperature electrolysis is only sensible if the heat is free, a byproduct of another already established process (for example waste heat from a nuclear reaction).[15] Electrolysis offers by far the cleanest means of producing hydrogen, but as will be shown later it is significantly more expensive.

## Current Obstacles

Widespread use of hydrogen for automotive applications necessitates the establishment of a sizeable hydrogen infrastructure. Commercial methods of hydrogen production, storage, and transmission already exist, but there are major barriers (both engineering and cost) associated with implementing these technologies on a large scale. Worldwide consumption of hydrogen is at about 103 million kilograms per day. Demand for gasoline on the other hand is almost 400 million gallons per day in the U.S. alone (as of November 2006).[16] Considering a kilogram of hydrogen has roughly the same energy content as a gallon of gas, it is apparent that the market for hydrogen is diminutive. Due to these huge discrepancies in demand, compared to the well-established natural gas and gasoline infrastructure, the present day hydrogen distribution infrastructure is extremely modest at best, about 1% of the size of the current gasoline distribution network. The existing hydrogen infrastructure is utilized to produce two types of hydrogen. About 7.1 million kilograms of what is known as captive hydrogen are produced daily for on-site use, while about 4.0 million kilograms of hydrogen are produced for commercial sale each day (this is known as merchant hydrogen). Merchant hydrogen is transported via railcars, barges, liquid hydrogen trucks, compressed gas trucks, and gas pipelines to where it will eventually be used. If all of this current hydrogen capacity were used in transportation, there would only be enough fuel for about 20 million vehicles (as of 2002 there were about 140 million personal vehicles in the U.S.).[17] To support the needs of a new U.S. hydrogen vehicle fleet the market for hydrogen clearly has a long way to go.

The small size of hydrogen markets can be attributed to a lack of demand, which is understandable—how many appliances in the average U.S. household run on hydrogen? U.S. demand for merchant hydrogen has, however, been growing at a steady pace of about 10% per year since 1997 (see **Figure 1**). Over this period the price of merchant hydrogen has been highly variable, depending on the type of delivery, the consumption demand, the primary resources used in production (for instance the price of hydrogen produced from natural gas is heavily dependent on unpredictable natural gas markets), the location, and the contract length of the hydrogen provider. Price figures for hydrogen on a per kilogram basis as of February of 2003 are provided in **Table 2**.[18] For the most part, these prices only capture hydrogen produced through reforming. Currently, electrolysis is not economically feasible with a minimum cost of about $8 per kilogram including energy, capital, and operating costs (delivery costs would even further expand this estimate).[19]

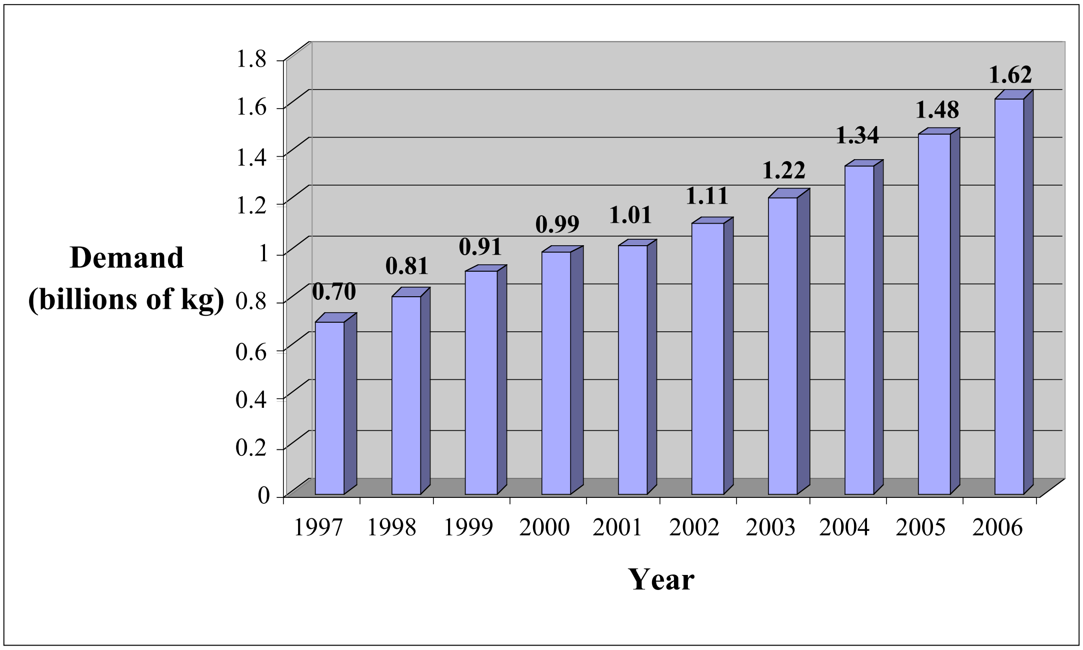

**Figure 1**: Estimated U.S. demand for merchant hydrogen (excluding production of captive hydrogen, production via ammonia dissociation, and hydrogen used as fuel)[2][20]

| Delivery Method | Price ($/kg) | |
|---|---|---|
| | Low | High |
| Compressed gas pipeline | 0.75 | 3.32 |
| Compressed gas trailer | 7.06 | 10.79 |
| Cryogenic liquid tanker | 4.77 | 7.47 |
| Compressed gas trailer (Historical price 1997-2002) | 1.25 | 2.60 |

**Table 2**: Price estimates for hydrogen as of February 2003[21]

Hydrogen delivered via a compressed gas pipeline is undoubtedly the cheapest, but this is only economical for very large, industrial consumers and is dependent on the very limited existence of such pipelines. These price estimates help to shed light on another of the major obstacles associated with the widespread implementation of hydrogen as a fuel source in transportation: the price of hydrogen is not only generally

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[2] Demand figures were taken from the February 24, 2003 issue of the *Chemical Market Reporter*. The 1997-2002 figures are actual, while the 2003-2006 figures are estimates assuming a constant 10% growth rate. For the purpose of clarity, billions of SCF (standard cubic feet, defined as a cubic foot at 15.7ºC and 1 bar) were converted into kilograms assuming the ideal gas law PV=nRT and a molecular weight of hydrogen gas of 2.01588 g/mol.

too high compared to a gallon of gas, but also extremely variable.[22] It should also be noted that if hydrogen is ever to be employed for extensive automotive use, production and delivery of hydrogen will have to be increased by orders of magnitude to meet demand and the subsequent price will be very different from these estimations. This obstacle will be revisited and new price figures developed based on the construction of a pervasive hydrogen infrastructure in order to assess the cost of operating a hydrogen vehicle on a cost-per-distance basis.

Infrastructure development notwithstanding, cost barriers persist with respect to the hydrogen propulsion technologies themselves. While hydrogen combustion engines, which are very similar to a standard internal combustion engine, may in the near future be produced for little to no additional cost, the economics of PEM fuel cells are a stumbling block. Currently, the cost of a PEM fuel cell is approximately $1500-$10,000 per kilowatt, with the majority of the cost coming from the expensive membrane electrolyte. In order for a PEM fuel-cell vehicle to be competitive in the automotive industry this price needs to drop to about $50-$100 per kilowatt. Because fuel cells are so dissimilar to combustion engines, the technology is simply not developed to the point of realizing significant cost reductions. Presently, very few fuel cells are produced, but costs are expected to decline with mass production and with the establishment of economies of scale. The high cost of hydrogen end use technologies such as the fuel cell compared to the costs associated with end use products of other energy substitutes explains why the demand for hydrogen is so much lower than for other conventional fuels.[23]

A final barrier to the development of a hydrogen economy relates to the safety concerns associated with hydrogen and hydrogen-powered vehicles. In addition to the inherent material dangers discussed previously, employing hydrogen as a vehicle fuel imposes several additional distinct risks. Vehicular dangers associated with any type of fuel can essentially be divided into three categories: fire, explosion, and toxicity. The latter category can be ignored for hydrogen as it is nontoxic. With respect to the first two risks, a fire or explosion could occur in the fuel storage compartment, the fuel supply lines, or in a fuel cell. In the fuel cell, there is an extremely thin membrane separating the hydrogen and oxygen gas (on the order of 20 to 30 micrometers). There is a slight possibility of this membrane rupturing, allowing hydrogen and oxygen to mix in a potentially explosive ratio; however, if this were to occur, the cell would immediately lose its potential, an easily detectable event, and the fuel lines could be automatically disconnected and therefore isolated from any sparks made by the fuel cell. Additionally, a fuel cell's operating temperature is sufficiently low so as to make explosion unlikely.[24]

At the fuel tank there are also potential risks of catastrophic rupture, or the formation of a massive or very slow leak. A study performed by the Ford Motor Company and Directed Technologies concluded that catastrophic failure was extremely unlikely and while failure modes existed for the other two dangers, they could be easily avoided through conscientious system design, leak detection systems (or adding an odorant to the fuel), and ignition prevention (automatic disconnection of the battery where sparks are produced, physical separation of the fuel lines from electrical components, ventilation, etc.). Based on computer simulations, this study concluded that a hydrogen vehicle can be engineered to be safer than a natural gas or gasoline vehicle in an open space collision, and as safe as natural gas and still safer than gasoline in a tunnel collision. If the hydrogen fuel is stored as a liquid, there is also some additional risk of cold burns as well as the possibility of an explosion from rapidly expanding vapors in the fuel tank caused by a malfunctioning pressure relief valve. Liquid hydrogen spills behave very similarly to gasoline spills, but with a much faster dissipation time. Further testing will be necessary to quantify and address the safety risks associated with specific new hydrogen technologies, but current research has at least shown that a hydrogen vehicle can potentially be as safe as existing automotive technologies, perhaps even safer.[25]

## Overcoming Infrastructure and Production Challenges—Looking Towards a Viable Hydrogen Economy

In order for hydrogen to be considered an economically viable fuel alternative it must be delivered to consumers at a stable price that is competitive with the current price of gasoline. Furthermore, the cost associated with hydrogen infrastructure development must be considered, as the increased availability of hydrogen and cost reductions of the fuel on a per kilogram basis will not be realized without the development of new production and distribution capacity. It is possible that a network of hydrogen pipelines could be built similar to existing natural gas pipelines; indeed, some existing pipelines could even be modified with new seals, meters, and end-use equipment to support hydrogen. A long-distance distribution network may not even be necessary if hydrogen is produced regionally where it is needed. One major advantage of hydrogen is that it can be produced from a variety of primary resources, one of which will most likely be readily accessible almost anywhere in the world. Energy sources such as natural gas, coal, and oil, on the other hand, are unevenly distributed geographically. Still, the infrastructure cost will not be entirely avoided, as even regional distribution networks are not currently pervasive.[26]

Several attempts have been made by companies to estimate the infrastructure development costs, and a wide range of results have been produced. To expand hydrogen capacity by about 27,000 kilograms per day, SFA Pacific, a consulting firm that specializes in fuel, power, and chemical companies, estimated an investment ranging from $71 to $102 million. For a smaller increase in capacity of only 2,700 kilograms per day, the investment figures ranged from $6 to $6.2 million. Air Products, a major supplier of industrial gases and equipment, estimated the necessary investment at $63 to $82 million and $6.8 to $9.6 million for the 27,000 and 2,700 kilogram per day capacity increases, respectively.[27] These cost estimates for building an adequate hydrogen infrastructure to support the needs of a new U.S. hydrogen vehicle fleet break down to anywhere from several hundred to several thousand dollars per new vehicle, depending on such factors as production and delivery method and demand (this includes the cost of establishing a production, delivery, and refueling network, but not the capital cost of the vehicle itself). While these costs may seem high, they are comparable to the cost of implementing large-scale infrastructures for other alternative fuels (such as methanol).[28]

The next major cost category is the price of the delivered hydrogen itself. The price of delivered hydrogen on a per kilogram basis is important, because when combined with data on the mass of hydrogen a vehicle consumes for every mile traveled, operation cost estimates can be produced for that vehicle on a cost-per-distance basis (how far will a hydrogen vehicle be able to travel for each dollar spent?). Based on the primary energy source used as an input in production, and the type of delivery, cost estimates for hydrogen produced from a central plant with a capacity of 150,000 kilograms per day are shown in **Figure 2** (in dollars per kilogram). This chart shows that after new infrastructure is built, reforming (especially from natural gas) remains the cheapest option ($3.75 to $5.00 per kilogram), while hydrogen produced from water through electrolysis continues to be the most expensive ($7.75 to $9.25 per kilogram). Reforming is a less expensive hydrogen production option, but will inevitably not help to significantly reduce carbon emissions, while electrolysis is pricey, but much more environmentally sound. Therefore, in order, for hydrogen to have a competitive chance as a fuel alternative and still cut down on carbon emissions, reforming must be made cleaner or electrolysis cheaper.

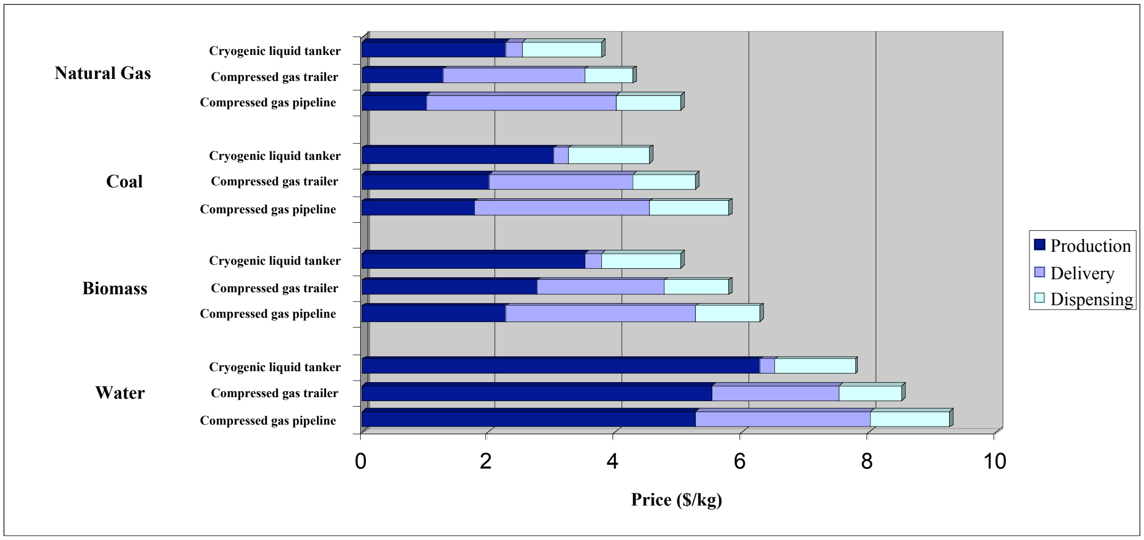

**Figure 2**: Estimated cost of delivered hydrogen produced from a central plant with capacity of 150,000 kilograms per day (based on production input and delivery method)[29]

With respect to the first possibility, the prospect of environmentally conscious reforming is not altogether unreasonable. As is the case with gasoline, fossil fuels are still being burned; however, as opposed to being burned in a constantly moving vehicle, the fossil fuels in the case of reforming are all being burned in one place. This fundamental difference means that carbon dioxide separation and sequestration is a much more workable option. As reforming proceeds, carbon dioxide can be separated from the emissions and then piped into deep saline aquifers or exhausted hydrocarbon reservoirs. Preliminary figures estimate that deep saline aquifers alone could potentially hold trillions of tons of carbon, the equivalent of more than 100 years of carbon production (as of 2002 worldwide anthropogenic emissions were about 6 billion tons per year, and left unchecked will rise to 20 billion tons per year by 2100). This process would inevitably necessitate considerable capital costs, but the technology for carbon sequestration does at least exist.[30]

Significant progress has also been made towards achieving the second goal—reducing the cost of electrolysis. Just last year, General Electric unveiled a new water electrolyzer, which received *Popular Mechanics* magazine's 2006 Breakthrough Award. Developed by a team in GE's Global Research Division led by Richard Bourgeois, this new electrolyzer ostensibly has the potential to produce hydrogen in an economically feasible manner so as to make electrolysis competitive with other hydrogen production methods and hydrogen itself competitive with current gasoline prices. The U.S. Department of Energy has identified very high capital costs as the primary barrier to the competitiveness of hydrogen fuel in the transportation sector, and through a partnership with GE, hopes to be able to reduce the price of hydrogen produced by electrolysis from its current price of more than $8 per kilogram to under $3 per kilogram (in 2005, the Department of Energy announced a price target by 2015 of $2.00 to $3.00, untaxed in 2005 dollars, for a gallon of gas equivalent amount of delivered hydrogen independent of the production and delivery pathway).[31] The new electrolyzer is a significant step towards this end. The design employs a GE invented plastic known as Noryl as a replacement for many of the complex and expensive metal parts. Noryl exhibits the physical properties needed in an electrolyzer, notably resistance to the strong alkaline solution used as an electrolyte, and more importantly, is very cheap to manufacture. The design also uses high performance electrodes built using metal coating techniques from GE's aircraft engine and power generation products. Essentially, GE is able to achieve cost reductions by using technologies they have already invented and exploiting their ability to mass-produce. Nonetheless, GE and the Department of Energy still have some work to do, as the current prototype can only produce 1 kilogram of hydrogen per hour, far below a useful level of production for the amount of fuel a hydrogen vehicle fleet would demand.[32]

Though not economically feasible at present, there are also a handful of other "green" methods of hydrogen production. The National Renewable Energy Laboratory in Golden, Colorado, successfully employed a photoelectrochemical cell to produce hydrogen directly from sunlight (with an energy conversion efficiency of about 12%). Alternatively, there is some possibility of producing hydrogen from algae, bacteria, and other biological systems. Hydrogen can also be derived from biomass—approximately two-thirds of currently idle cropland could produce enough hydrogen to fuel all cars in the U.S. if they were all fuel-cell vehicles. Gasification of municipal solid waste could potentially produce 25 to 50% of fuel for cars in metropolitan areas in the U.S. Solar and wind power could be used indirectly to produce hydrogen by driving electrolysis. All of these possibilities are, however, quite theoretical as they are prohibitively expensive (for instance, using wind or solar power to power electrolytic hydrogen production would cost two to three times more than hydrogen from reforming with current technologies) and make unreasonable assumptions about the existence of the specialized infrastructure necessary to produce hydrogen through each respective process.[33]

## Hydrogen Storage—Surmounting the Energy Density Problem

Regardless of how it is derived, hydrogen is not easy to store. The hydrogen storage issue remains one of the largest technological barriers that must be resolved in order for a hydrogen vehicle to be able to offer comparable performance characteristics and travel distance as a gasoline-powered vehicle. Logical requirements of any vehicular fuel storage system are that it is lightweight, compact, safe, and affordable. A hydrogen storage system, in particular, must be able to overcome the low energy density of hydrogen and be able to store a sufficient amount of fuel to provide for a reasonable travel range (in the case of fuel-cell propulsion, high efficiency means this does not necessarily have to be an enormous amount of hydrogen). Dealing in averages, a modern commercially available car with a range of about 250 miles that was built with mobility and efficiency considerations in mind burns about 8.6 gallons of gas in a typical combustion engine, which means a fuel economy of about 29 miles per gallon (this is notably higher than the industry average for automobiles driven in the U.S.); a hydrogen combustion vehicle by comparison would require about 8 kilograms of hydrogen and a fuel-cell vehicle about 4 kilograms. At room temperature, 4 kilograms of hydrogen occupies about 45 cubic meters, which is obviously not practical for a consumer uninterested in attaching a semi-trailer to the back of their car. Thus, for hydrogen to be a useful automotive fuel, its volume must be substantially reduced in some way.[34]

There are essentially three conventional methods of hydrogen storage to achieve these necessary volume reductions: storing hydrogen as a compressed gas, a cryogenic liquid, or chemically bonded in metal hydrides. There are several methods of conventional compressed-gas storage. Hydrogen can be stored in relatively cheap, high-pressure steel tanks. Such tanks are usually tested at about 300 bar (about 4350 psi) and filled to about 200 bar (or about 2900 psi). Under these conditions an internal volume of 225 liters (about 60 gallons) would be needed to store the 4 kilograms hydrogen to power the before mentioned fuel-cell vehicle. Hydrogen can also be stored as a compressed gas in stronger tanks made out of composite materials and reinforced with carbon fiber. These tanks are usually tested at about 600 bar (8700 psi) and filled to about 450 bar (6500 psi). The higher pressure allows the tank volume to be reduced, but also introduces several notable disadvantages. Higher compression correlates to greater risk of explosion and necessitates additional pressure controls. High compression tanks also need inert inner coatings so that the pressurized hydrogen doesn't react with the tank itself.[35]

To avoid the dangers associated with higher compression and even further increase mass-volume density at ambient pressures, hydrogen can be stored on a vehicle in the from of a liquid (the density of liquid hydrogen is 0.07 kg/liter compared to $8.9\_10^{-5}$ kg/liter for hydrogen gas). Cryogenic cooling techniques and insulation systems (of adequate but limited performance) already exist for storing liquid hydrogen. Such systems have been successfully employed in the Space Shuttle as well as in military aircraft designed by Lockheed. In conjunction with introducing its new hydrogen vehicle technology, BMW has also built and tested an effective automated liquid hydrogen refueling station, and claims to have significantly improved insulation and reduced evaporative fuel loses. Unfortunately, liquefying hydrogen ultimately introduces more problems than it solves. The condensation temperature of liquid hydrogen is -252ºC at atmospheric pressure and therefore it must be kept in an extremely cold, well-insulated container, the technology for which, despite claims, is currently imperfect. Liquid hydrogen containers must also be kept as open systems to prevent explosions from over pressure when the liquid inevitably evaporates and therefore heat transfer to the storage tank leads directly to hydrogen loss.[36]

Storing hydrogen chemically bonded to other materials can further increase mass-volume density. It is possible to store hydrogen at room temperature in liquid hydrocarbons with a molecular weight greater than 60 g/mol if the hydrocarbon is able to quickly hydrogenate and dehydrogenate (adjust the number of hydrogen atoms in its structure); however, this is still not a well-developed process for vehicular applications.[37] A more promising form of chemical hydrogen storage is using metal hydrides. Various types of metals and alloys are capable of reversibly binding and storing large quantities of hydrogen—essentially the molecular hydrogen gas disassociates at the surface of the metal and is absorbed, the individual hydrogen atoms being stored within the metal's lattice structure. The individual atoms can then be released, or desorbed, the atoms recombining at the metal's surface to again produce hydrogen gas. **Table 3** lists the hydrogen storage properties of several promising intermetallic compounds.[38]

| Metal | Hydride | % Hydrogen by Mass | Equilibrium Pressure (bar) | Equilibrium Temperature (ºC) |
|---|---|---|---|---|
| Pd | $PdH_{0.6}$ | 0.56 | 0.020 | 25 |
| $LaNi_5$ | $LaNi_5H_6$ | 1.37 | 2 | 25 |
| $ZrV_2$ | $ZrV_2H_{5.5}$ | 3.01 | $10^{-8}$ | 50 |
| FeTi | $FeTiH_2$ | 1.89 | 5 | 30 |
| $Mg_2Ni$ | $Mg_2NiH_4$ | 3.59 | 1 | 282 |
| $TiV_2$ | $TiV_2H_4$ | 2.6 | 10 | 40 |

**Table 3**: Hydrogen-storage properties of several intermetallic compounds[39]

Of the numerous metals and alloys capable of storing hydrogen, several are worthy of note. Alloys derived from $LaNi_5$ have the advantage of rapidly and reversibly absorbing and desorbing hydrogen at reasonable pressure values. The alloys themselves also exhibit long material lives through repeated cycles of absorption and desorption and are capable of storing high volumetric densities of hydrogen. Nevertheless, lanthanum and nickel are quite large elements with large atomic weights compared to hydrogen and thus metal hydroxides of the two elements have a low mass density of hydrogen. Other intermetallic compounds such as $Li_3Be_2H_7$ and $BaReH_9$ can store up to 9% hydrogen by mass, but the binding reactions are not reversible in reasonable temperature and pressure ranges. Some lighter elements such as magnesium and calcium can also form hydrides, thus conferring the advantage of high mass percentage of hydrogen. These hydrides, however, exhibit very slow absorption and desorption and frequently only under conditions of unreasonably high or low temperatures and pressures. Extremely light hydrides can also be formed using some of the lightest elements in the periodic table such as lithium, boron, sodium, and aluminum. These ionic compounds may be able to store a very high mass percentage of hydrogen (for example $LiBH_4$ is 18% hydrogen by mass), but they only release hydrogen at very high temperatures (between 80ºC and 600ºC), and the reversibility of their binding reactions is not well understood. Composite materials, which combine the attractive properties of two different materials in order to overcome their individual weaknesses, may also be able to provide a solution to the low mass density problem, but also are not well understood. While hydrides are certainly capable of storing an adequate amount of hydrogen in a reasonable volume, it is safe to say that more research is necessary for them to achieve sufficiently lightweight hydrogen storage volume.[40]

The Ford Motor Company performed a study to compare the weight and volume of these three primary hydrogen fuel storage systems: compression, liquification, and in a metal-hydride. The study considered fuel storage systems capable of powering a lightweight, efficient, four or five-person vehicle. A compressed gas system based on a carbon-fiber-wrapped compressed gas cylinder storing 12% hydrogen by weight at a pressure of 340 bar weighed 32.5 kilograms, and had a volume of 186 liters. A liquid hydrogen storage system for the same vehicle weighed 28.5 kilograms and had a volume of 116 liters, while the metal hydride system weighed an enormous 325 kilograms, but had a much smaller volume of only 100 liters. For the purpose of comparison, a similar lightweight gas vehicle of comparable size, performance, and travel range has a fuel storage system that weighs only 25 kilograms and occupies only 25 liters, while a purely electric battery powered system is several times larger and heavier.[41]

A great deal of research is now being done into a fourth possible means of hydrogen storage using carbon, a readily available, lightweight, and cheap resource. Depending on the applied pressure and temperature, hydrogen gas molecules are known to aggregate on the surface of many solid materials (as opposed to dissolved inside the lattice structure as in the case of metal hydrides), a fact that can be exploited to store potentially large amounts of hydrogen for fuel purposes.[42] In order for such a carbon-based hydrogen storage system to be practical —i.e. allow for a reasonable driving range while being suitably lightweight for automotive applications—the U.S. Department of Energy set a target that it be able to store hydrogen at 6.5% by weight.[43] Graphene, a single planar sheet of carbon, can store 3.3% hydrogen by mass and a sheet of active carbon is capable of 2% hydrogen storage by mass (with reversible binding at -196ºC). It turns out that at low temperatures hydrogen molecules condense in a monolayer on a carbon surface and thus the hydrogen storage capacity of a carbon solid is directly proportional to its specific surface area.[44] So the question arises—why not increase the surface area of a solid by building nanostructures and therefore increase its hydrogen storage capacity?

Potential nanostructured carbon materials include carbon nanofibers, carbon nanohorns, multi-walled carbon nanotubes, single-walled carbon nanotubes (SWNTs), alkali-doped graphite, fullerenes, and active carbon. SWNTs are probably the best understood of these nanostructures. Numerous publications have reported very high hydrogen storage capacities; indeed, chemisorption models (which look at chemical interactions on the quantum level) predict a theoretical storage capacity for SWNTs of 14% by weight. This high level of storage capacity has not, however, been achieved experimentally, with results scattered from about 0.01 to 8% hydrogen storage by mass. Individual experiments of hydrogen storage capacity have also never been reproduced. Graphitic nanofibers may have even more potential for hydrogen storage, but also have an even higher spread (from 0.1 to 67% hydrogen by weight).[45] These discrepancies can likely be attributed to the limited quantity and purity of nanotubes that have thus far been tested; in truth, storage in carbon nanostructures has really only been studied on the microgram level and the mechanism of injection and release from the nanostructure is not well understood experimentally or theoretically.[46]

Despite their theoretically promising properties, carbon nanostructures currently still have numerous inadequacies when it comes to hydrogen storage in vehicles. While they may become more promising in the future, at their present stage of development, there is not a sufficient level of dependable research on their behavior and they are not understood well enough to meet the requirements for vehicular hydrogen storage. For the time being, compressed gas remains the preferred and most realistic onboard storage system. Liquification simply is overly energy demanding and complicates refueling and distribution, metal hydride storage prohibitively heavy, and carbon nanostructures too immature as a technology. The weight and volume characteristics of such a compressed-gas system may not be ideal, but they are at least acceptable.

## The Hydrogen Vehicle – Prototypes and New Technology

In the last decade, several automakers have made significant progress in fuel-cell and hydrogen combustion vehicles and several currently have prototypes. Some of these new hydrogen prototype vehicles are the BMW 760hL and H2R super car; the DaimlerChrysler F-Cell; the Ford Motors Focus FCV; the General Motors AUTOnomy, Hy-wire, HydroGen3, and Sequel; the Honda FCX; the Hyundai Tuscon FCEV; the Mazda RX-8; the Nissan X-TRAIL FCV; and the Toyota Highlander FCHV.[47] These vehicles range in size, type of hydrogen deployment (fuel cell or combustion), performance, fuel efficiency, and development (from pure concept to close to commercial availability). To assess the viability of current hydrogen vehicular technology as a whole, this study will consider two of the most advanced vehicles, both of which are nearing the point of commercial availability, one powered by a hydrogen combustion engine and the other by a hydrogen fuel cell.

Much of the research done into modern hydrogen combustion engines has been done by BMW. BMW first began research into hydrogen vehicles in 1986. By 2004, the company had developed a high-performance hydrogen combustion prototype car, which was titled the H2R at its unveiling at the Paris auto show.[48] The H2R, built on a 6-liter V12 engine (a hydrogen modified version of the engine used in the 760i) was itself a feat in engineering, setting nine international performance records for hydrogen vehicles, demonstrating a top speed of 186.52 mph, and with a 0 to 60 mph split of about 6 seconds.[49] The H2R, designed strictly as a prototype super car, was never meant for commercial availability; however, its technologies would become the basis for the BMW 760hL, also known as the "Hydrogen 7," a dual mode 7 series capable of running on either liquid hydrogen or gasoline and intended for commercial release.[50]

With the majority of hydrogen vehicle research focusing on the more efficient fuel cell, the Hydrogen 7 is one of few, and likely the most advanced, hydrogen combustion vehicle. It is scheduled to begin serial production in April of this year (only a few hundred will be produced initially) and if all goes as planned, will be the first widespread-released hydrogen vehicle.[51] The primary difference between the Hydrogen 7 and an ordinary 7 series is the specially designed 170-liter (45 gallon) tank in its trunk, which can hold both hydrogen fuel and gasoline.[52] The Hydrogen 7 also runs on a 6-liter V12, which outputs 260 horsepower, goes 0 to 60 mph in 9.5 seconds, and has an electronically limited top speed of 140 mph—all of these figures are independent of whether hydrogen or gasoline fuel is being used.[53] These performance characteristics can be directly compared to those of the non-hydrogen powered 760Li, a luxury sedan which runs on a 6-liter V12 which outputs 438 horsepower, and has a 0 to 60 mph time of 5.4 seconds.[54] While the Hydrogen 7 is noticeably less powerful than its gasoline equivalent, it should be noted that it does outperform many alternative fuel vehicles currently on the market.

Diminished performance characteristics, however, should be the least of BMW's concerns. Technological and production obstacles alone may be sufficient to prevent the Hydrogen 7 from being successful. As discussed above, hydrogen has a very low energy volume and as a consequence the fuel tank of the Hydrogen 7 is so large that it actually takes up half of the trunk space. Also, due to the open system requirements of a liquid hydrogen fuel system and BMW's imperfect cryogenic insulation system half of the fuel tank will evaporate after only nine days without even starting the engine.[55]

Assuming these technological barriers can be overcome, the Hydrogen 7 still must meet the before-mentioned cost criteria to be considered a viable and competitive transportation option: its capital costs must be on a level comparable to its gasoline equivalent (in this instance say the 760Li) and its engine efficiency must be such that when the delivered price of hydrogen is considered, it is economically competitive on a cost per mile basis. Addressing the first criteria, BMW has been unable to lower its costs of production to a reasonable level so as to make the Hydrogen 7 affordable to the average consumer. Indeed, the cost to purchase a Hydrogen 7 would be so high that BMW is not willing to even quote a price and the vehicle will only be available for lease.

The leasing price, though not official, will purportedly be around that of leasing the top-of-the-line 760Li with a full service package. While BMW hopes to expand the hydrogen power option to all its vehicles, due to large fuel requirements of a hydrogen combustion engine and limits to the size reductions possible in a liquid hydrogen storage system, the 7 series is the only BMW currently capable of running on hydrogen. Other models are simply not large enough to fit the fuel tank, which is just as well because the huge cost barriers involved in producing the Hydrogen 7 would price all but the richest consumers out of the market even if it were made available in one of their lower-end vehicles.[56]

In terms of operating cost, the Hydrogen 7's practicality is largely dependent on the delivered price of hydrogen. The Hydrogen 7 has a driving range of 125 miles when running on hydrogen, and 300 miles when running on regular gasoline.[57] Based on this range and the size of its fuel tank, the vehicle gets about 16.9 miles per gallon of gasoline or 4.7 miles per gallon of hydrogen (with a mass density for liquid hydrogen of 0.07 kg/liter, this figure is about 17.8 miles per kilogram of hydrogen consumed (remember a kilogram of hydrogen stores about as much energy as a gallon of gas).[58] Combining these fuel mileage figures with the previously established estimates for the price of hydrogen after the establishment of large-scale infrastructure, the Hydrogen 7 operates at a cost of about \$0.21 to \$0.28 per mile on hydrogen produced using reforming technologies and \$0.44 to \$0.52 per mile on hydrogen produced by electrolysis. The before mentioned average mid-sized, reasonably efficient combustion engine (with a fuel economy of about 29 miles per gallon), on the other hand, has an operation cost of about \$0.086 per mile to \$0.12 per mile assuming gas prices at the pump fluctuating between

$2.50 and $3.50 per gallon. The Hydrogen 7 could just be run on gas with an operation cost between $0.15 and $0.21 per mile, but then why even pay extra for a hydrogen engine at all? This comparison makes it very clear that the average cost-sensitive consumer would not choose to drive the Hydrogen 7, (in fact even a gas-guzzling SUV that gets 15 miles per gallon only has an operation cost between $0.17 and $0.23 per mile, and with a lower upfront vehicle cost, would be a wiser choice).

The fuel-cell vehicle, touted as considerably more energy efficient, is potentially a more economically viable option. General Motors is currently making considerable efforts to develop their own fuel-cell vehicle. Their first prototype was the somewhat ridiculous looking, purely concept vehicle based on first generation hydrogen technologies called the AUTOnomy. Their next concept, the Hy-wire, a five-passenger, luxury sedan, is a somewhat more reasonable model, running on compressed hydrogen fuel and having a range of 80 miles with a gasoline equivalent fuel economy of 41 miles per gallon. The Chevrolet Sequel further developed these technologies and is the most feasible of their fuel-cell vehicle prototypes. The Sequel is a four to five-passenger small SUV, which runs on compressed hydrogen fuel out of three carbon-composite, high-pressure tanks with a service pressure of 10,000 psi (700 bar).[59] About the size of a Cadillac SRX, the Sequel, unlike its predecessors, actually looks like a real car and has reasonable performance specifications including a 0 to 60 mph time of about 10 seconds.[60]

The Sequel incorporates several new innovations, but nonetheless still has its drawbacks. Unlike current vehicle technologies, the Sequel employs “by-wire” controls, meaning it operates using electrical signals instead of mechanical links and hydraulics for steering, braking, and acceleration, so there is no engine, steering column, brakes, or gas pedals and thus fewer parts to wear out (and also a shorter braking distance than a comparable gasoline vehicle of equal size). The Sequel has also overcome the fuel-cell freezing problem (fuel cells have traditionally suffered problems at very low temperatures, often freezing up and ceasing to function). The start up time of 15 seconds to achieve 100% power at -20ºC is quite good compared to other fuel-cell vehicles. Unfortunately, the Sequel remains held back by cost barriers, the current model sufficiently expensive to eliminate any chance of industry competitiveness. For this reason, the Sequel is still only a concept vehicle and GM does not project to have a commercially available fuel-cell car for a few years (which is still sooner than most of its competitors).[61]

If the Sequel or a similar model were made commercially available, it potentially would have a considerable operating cost advantage over BMW's Hydrogen 7. The Sequel has an estimated driving range of 300 miles and a hydrogen storage capacity of 17.6 lbs or 8 kilograms. This corresponds to a fuel mileage of approximately 37.5 miles per kilogram of hydrogen consumed.[62] Again, these fuel economies can be combined with estimates for the price of hydrogen post infrastructural development to develop an operating cost for the Sequel on a cost-per-distance basis. Using hydrogen produced through reforming, the Sequel operates at a cost of about $0.10 to $0.13 per mile and $0.21 to $0.25 when the hydrogen is produced by electrolysis. Compared to the benchmark 29 miles to the gallon combustion vehicle (with an operating cost of about $0.086 per mile to $0.12 per mile), the Sequel may still not be quite as cheap in terms of operating cost, but is at least a much more cost-effective option when compared to the Hydrogen 7.

## Conclusions

Judging from these analyses hydrogen is not yet at a point of technical or economic viability. It is unlikely that consumers will be eager to pay more for a hydrogen vehicle that is ultimately more expensive to operate than a gasoline vehicle on a per-mile basis. Without demand for hydrogen end-use technologies, there will be no infrastructure development, and without increases in the production and delivery capacity of hydrogen, there will be no cost reductions and therefore no further increases in demand. Moreover, a hydrogen vehicle would only be in the realm of commercial practicality when powered by hydrogen produced through reforming; hydrogen produced from electrolysis pushes the hydrogen vehicle even farther from pecuniary sensibility. Thus, at present switching the transportation sector to hydrogen may not even help to reduce emissions of carbon and other pollutants. With all of these setbacks, is hydrogen doomed to fail as an alternative fuel?

Not necessarily. Economics alone is unlikely to lead to a switch to hydrogen, but a not altogether unreasonable mix of progressive actions and uncontrollable global developments could. As the availability of energy sources becomes increasingly squeezed, the price of gasoline could rise to a point where paying five, six, even seven dollars for a kilogram of hydrogen may not be unreasonable. After all, gasoline prices only ten years ago were half of what they are now.[63] Further development of hydrogen sequestration may potentially be able to make hydrogen reformation cheaper and if the Department of Energy is successful in its endeavors, the cost of electrolysis may be considerably reduced.  Technologically, fuel efficient hydrogen vehicles exist, and despite negligible demand, car manufacturers continue to produce increasingly more innovative and efficient fuel cells.  While continued research is still necessary the obstacles once posed by hydrogen safety and storage also do not seem insurmountable.

Because tailpipe emissions are virtually zero when hydrogen is burned or chemically reacted, it certainly has enormous potential to effect substantial and indispensable environmental benefits and improve air quality if it is produced with an environmental conscience.  The success of hydrogen fuel is dependent on such a wide variety of factors, including the size, type, and geographic density of demand; local energy prices and availability; the cost of primary resources needed as production inputs; the price of fuel substitutes; and the availability of hydrogen vehicles, that for now it is important to focus on short-term goals including the continued development of vehicle and production technologies, and increasing cost reductions.  It is possible that hydrogen may have faster growth in developing countries that have little existing energy infrastructure or in isolated areas of the globe that are entirely dependent on the price of imported oil.  For the time being, however, it is safe to say that hydrogen's development as a mainstream alternative fuel in the U.S. will be slow and its ultimate success reliant on a strong political will.

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