# Toward a Hydrogen Transportation System:
# The Problem of Hydrogen Storage and Selecting an Energy Carrier

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## 1: Introduction

As far as energy sources are concerned, the 19th century was the age of coal, and the 20th the age of oil. As we enter the 21st century, oil's dominant position at the top is being challenged by a gas. In 1999 natural gas (predominantly methane, chemical formula $CH_4$) passed coal as the world's second most widely used energy source, and because of the relative ease with which natural gas can be transported, compared with gasoline, it may be the top energy source of the near future (see Figure 1). Natural gas is currently the fastest growing fossil fuel, and the fuel of choice for electricity generation, as it burns more efficiently than gasoline, and large, stationary power plants do not need to worry about the lower energy density of the gas, relative to a liquid fuel (Dunn, 2001, p.15).

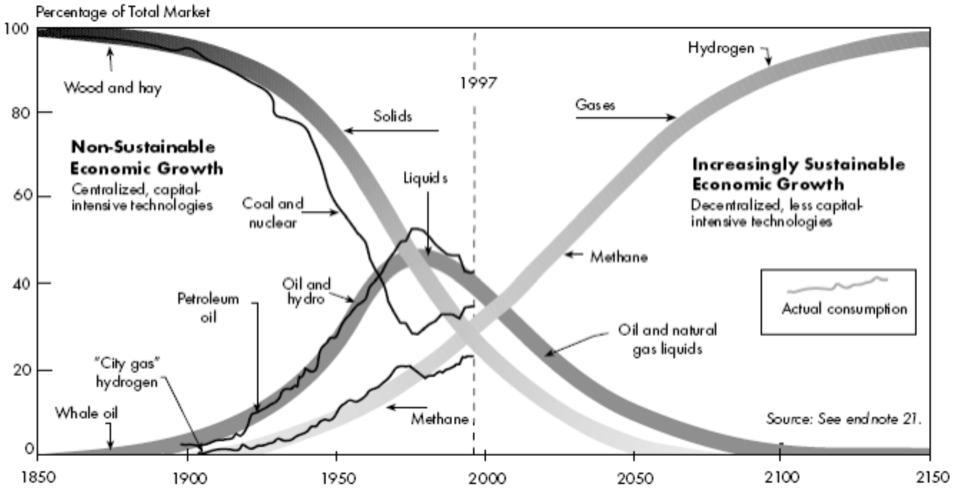


**Figure 1**: Energy consumption by type of fuel (gas, liquid, solid) until 1997, and a prediction based on the emergence of a hydrogen economy. (Dunn, 2001, p.15)

One major benefit to society that comes from the increasing use of natural gas is that it is a much cleaner burning fuel, in terms of carbon emissions, than gasoline and coal. Scientists are becoming more and more concerned as atmospheric $CO_2$ levels continue to increase and the threat of global warming increases. Classified as a greenhouse gas (GHG), $CO_2$ is thought to be the biggest contributor to the recent warming trend scientists have detected, and they warn that unless we greatly reduce GHG emissions in the near future, we could be facing severe climate changes. No one is certain exactly what will happen if GHG levels continue to increase, but many warn against it because of potentially drastic changes in worldwide climate, and, as Dr. Nathan Lewis put it: the industrialized nations would be "conducting the biggest scientific experiment mankind has ever attempted," one in which the outcome is unknown and could have an enormous worldwide impact (Lewis, 2004).

In light of these warnings, even natural gas may not be clean enough to rely on in the future. This concern is the basis for the push for a hydrogen economy. When burned, hydrogen gas combines with oxygen in the surroundings to create water. Even this, however, is not foolproof, as hydrogen burns at a very high temperature, and thus causes nitrogen in the surroundings to combine with oxygen to produce nitrous oxides ($NO_x$) which can be hazardous to human health. However, there is an alternate use for hydrogen, which could potentially be entirely clean: fuel cells. Fuel cells use a chemical process to separate the hydrogen electron from its proton, run it through an electrical circuit, and then recombine pairs of electrons and protons, plus one oxygen atom, to form water. Another benefit of hydrogen is that it can be produced from water using energy from renewable sources (water, wind, geothermal, solar) and can help the U.S. develop a sustainable, self-reliant energy economy by reducing our dependence on fossil fuels, most of which are imported from other countries.

## 2. Hydrogen in the Transportation Sector

One of the key features of the hydrogen economy is the fuel cell car. The transportation sector is the fastest growing energy consumer, and currently uses more energy than any other sector. Approximately 95% of the energy for transportation comes from petroleum (EIA, 2006). Shifting to fuel cell powered transportation would reduce the nation's need of 70% of its current petroleum imports. If every part of the transportation sector switched to hydrogen, and the hydrogen was produced using renewable energy, carbon emissions could be reduced by up to 37%. Even if only personal vehicles are converted, the reduction in emissions could still be as much as 25% (Dunn, 2001, p.70).

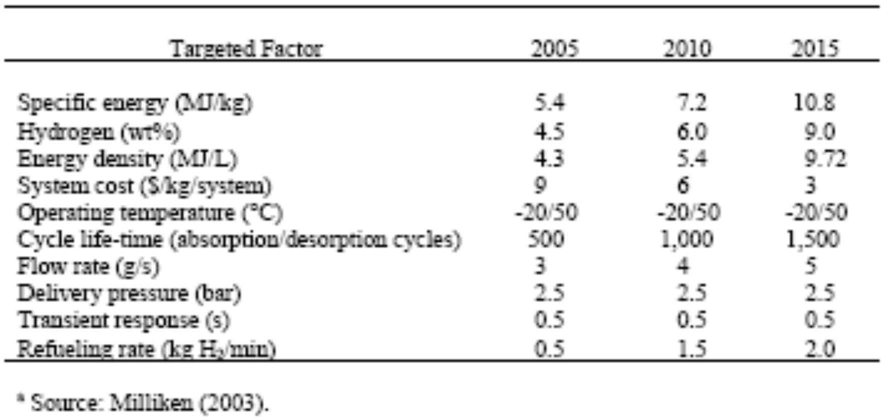
The transition to fuel cells is not without its problems, however, and will likely not even begin within the next decade. As fuel cells prepare for commercialization over then next couple of decades, the biggest question that must be answered is what kind of fuel will need to be provided at refueling stations? There are two key problems which must be solved (or proved too difficult to solve) in order to answer this question. First, there is the technical problem of storing hydrogen onboard a passenger vehicle. The U.S. Department of Energy (DOE) has identified this as the top technical barrier in the path toward hydrogen powered transportation (NREL, 2005). Most experts from government, industry, and research labs agree that the direct storage of hydrogen onboard is the best long-term solution, but current technology is not yet up to par, and it will take a significant technological breakthrough in the area before enough hydrogen can be stored to travel 300 miles on one tank, as we can today with gasoline (Dunn, 2001, p.45). The second problem is an economic one: how should hydrogen initially be produced and distributed, and what type of infrastructure should be built in order to provide enough hydrogen for every car in the country. This issue ties in with the storage problem, since if hydrogen cannot be stored effectively onboard in the short-term, a different fuel will have to be used with onboard reforming (chemically separating the hydrogen gas from the rest of the molecule) to get the desired performance.

In the following sections, the technical details of current hydrogen storage technologies will be presented, along with a look at some ideas for future storage, which have not been fully developed yet. Additionally, the economics of hydrogen production and distribution will be explored, including descriptions of different short-term solutions, such as on-board hydrogen reforming from gasoline. Lastly, the major social implications of moving to a hydrogen transportation system will be identified and discussed.

## 3: Hydrogen Storage

Most transportation fuel cell technologies have already been developed to the point where they now only need to follow the natural progression of development, as research continues to provide incremental improvements in performance. Once they reach the standards set for them and production begins, it is thought that prices will drop quickly as the components are produced in mass, creating economies of scale. Hopefully, this will lead to prices competitive with current internal combustion engine (ICE) vehicles, and fuel cells will begin replace the older, dirtier technology. However, hydrogen storage technology lags behind this development front. Most experts agree that it will take a major technological breakthrough, rather than simply improvements on an already developed technology, to solve the storage problem (NREL, 2005).

The compact storage of hydrogen could eventually be used in numerous applications, from stationary fuel cells to transportation to portable electronics. The driving force behind the technology, however, is mostly from the transportation sector, and goals have been established by the DOE to make onboard storage comparable to that of gasoline. The overarching goal is to provide enough fuel for a driving range of 300 miles, with enough space left over in the car for other needs. The primary DOE goals are broken down into three parts, gravimetric, volumetric, and cost. Gravimetric density is the amount of energy contained per unit mass of the tank, and the DOE goal for 2015 is 3.0 kWh/kg. A similar measure is the percentage of hydrogen mass relative to filled tank mass. When a tank with gravimetric density 3.0 kWh/kg is filled, 9% of its mass will be hydrogen. Volumetric density is the amount of energy stored per unit volume, and the 2015 goal is 2.7 kWh/L. Both of these values are approximately half of the respective densities of gasoline, meaning even at these target levels the hydrogen tank would have to be twice as large and twice as heavy to carry as much fuel energy as a simple gas tank can. However, since fuel cells are two to three times more efficient than ICEs in converting fuel energy into kinetic energy of the car, a storage system which meets these goals would be competitive with traditional gas tanks in terms of energy density. Other targets set by the DOE include system fill time, temperature and pressure of storage, flow rate out of the container, and length of life cycle, which must also be met by an acceptable storage system (BEES/TRB, 2005).



| Targeted Factor | 2005 | 2010 | 2015 |
|---|---|---|---|
| Specific energy (MJ/kg) | 5.4 | 7.2 | 10.8 |
| Hydrogen (wt%) | 4.5 | 6.0 | 9.0 |
| Energy density (MJ/L) | 4.3 | 5.4 | 9.72 |
| System cost ($/kg/system) | 9 | 6 | 3 |
| Operating temperature (°C) | -20/50 | -20/50 | -20/50 |
| Cycle life-time (absorption/desorption cycles) | 500 | 1,000 | 1,500 |
| Flow rate (g/s) | 3 | 4 | 5 |
| Delivery pressure (bar) | 2.5 | 2.5 | 2.5 |
| Transient response (s) | 0.5 | 0.5 | 0.5 |
| Refueling rate (kg $H_2$/min) | 0.5 | 1.5 | 2.0 |

[a] Source: Milliken (2003).

**Figure 2**: Goals for hydrogen storage set by the U.S. Department of Energy. Note: 3.6 MJ = 1.0 kWh.

No current technology can meet the DOE energy density goals. The three current directions of research are physical storage as pressurized or liquefied hydrogen, reversible chemical storage with metal hydrides or adsorption to carbon surfaces, and irreversible chemical storage in complex metal hydrides (NREL, 2005). Each of these technologies is described below.

### *3.1: Physical Storage*

Pure hydrogen has an energy content of 33.3 kWh/kg, but unfortunately a single gram of hydrogen at atmospheric pressure takes up about 11 L of space (Becker, 2006). This is equivalent to about 0.003 kWh/L, or 1/1000 of the desired volumetric density goal. Physical storage refers to storing pure hydrogen under physical constraints to reduce its volume. One such constraint is to pressurize the gas. At 700 times atmospheric pressure (about 10,000 psi) the volumetric density is still only about 1.3 kWh/L (Crabtree et.al, 2004). Storing hydrogen at such a high pressure has its problems, as well. First, the tank required to hold a gas at such high pressure would weigh far more than the gas contained within it, so the gravimetric density is actually no better than other methods (about 1.5 kWh/kg maximum) (Crabtree, 2004). Also, any sort of leak in the fuel line could vent the pressurized gas quickly, and there are safety concerns for high-pressure gases, as the tanks could rupture explosively upon impact, potentially worsening a crash. Additionally, pressurizing the gas takes a significant input of energy, as much as 10% of the energy contained within the gas being pressurized, so this storage system loses efficiency there.

The second, and more dense, option for physical storage is liquefaction. Currently, liquefaction is actually the closest to reaching the proposed DOE goals for 2015, with gravimetric and volumetric densities of 2.4 kWh/kg and 2.2 kWh/L, respectively (Crabtree, 2004). Though the numbers seem promising, a key problem with liquefaction is that the hydrogen must be cooled to 20K, or about -253°C, to condense, and then must be kept at this temperature so that it does not simply boil off again. Designing a cryogenic tank to go on a passenger car would be difficult in itself, plus nearly 40% of the energy content in the hydrogen is required for liquefaction, so this option is not terribly efficient, nor is it easy to implement, though we do have the technology for it today (NRC/NAE, 2004, p.40).

### *3.2: Reversible Chemical Storage*

The primary method of reversible chemical storage uses conventional hydrides, which are metal alloys that display the interesting and useful property of absorbing certain gases when exposed to them, and releasing the gases when heated sufficiently. The absorption of hydrogen is of particular interest to fuel cell research. The absorption process begins when the hydrogen molecule comes in contact with the alloy, at which point the molecule dissociates into two atoms, which then chemically bond to interstitial sites on the metal alloy. An interstitial site is a void space between the atoms in the crystal lattice structure of the metal alloy. The bond is created when the electron from the hydrogen atom enters an electron band of the metal atom, and the metal's valence electrons concentrate around the positive nucleus of the hydrogen atom. This is considered a weak chemical bond, and is thus more reversible than a covalent bond, a desirable property for hydrogen storage purposes (Oriani, 1994). In most cases, when the hydrogen is absorbed into the alloy's lattice, the combination is in a lower energy state than when the two components are separate (hence the spontaneous absorption). This drop in energy state is accompanied by a net loss of heat to the surroundings as the hydrogen is absorbed. If that heat is later returned to the system, the hydrogen can be released from its bond and can flow back out of the metal hydride fuel tank. Both chemical equation and visual representations of the process are given below: (M represents the metal alloy, H is a hydrogen atom after the gas molecule has dissociated, and MH is the metal hydride).

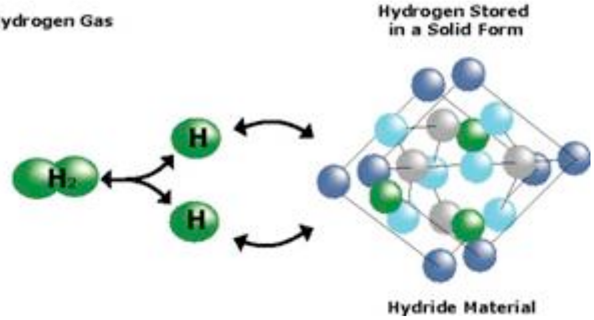


**Figure 3**: The diatomic hydrogen gas molecule dissociate upon contact with the alloy surface and the hydrogen atoms are loosely bonded by within the crystal lattice structure of the alloy, producing a hydride. (http://www.herahydrogen.com/en/about.html)

In addition to conventional hydrides, alloys called metal hydrides exhibit similar hydrogen absorbing behavior. The major difference between the two types of hydrides is the type of bond formed between hydrogen and the metal. In advanced hydrides the hydrogen is bonded by non-interstitial bonds, which are far more complex than those of conventional hydrides, and will not be described in more detail here. An example of a type of hydride is the group of nickel-metal hydrides, such as Ni-MH, which are used in the batteries of many portable electronic devices today (Becker, 2001). Unfortunately, the density of hydrogen in any battery is extremely low, less than one tenth of the DOE goal for 2015. This means that traditional battery hydrides cannot be used on fuel cell cars, as they cannot store enough energy. Most current research in metal hydrides focuses on the alanate chemical structure, which has a tetrahedral geometry, much like methanol gas, and can hold four hydrogen atoms. The figure on the next page shows the density characteristics of some of these compounds. Those in boxes are of the alanate structure.

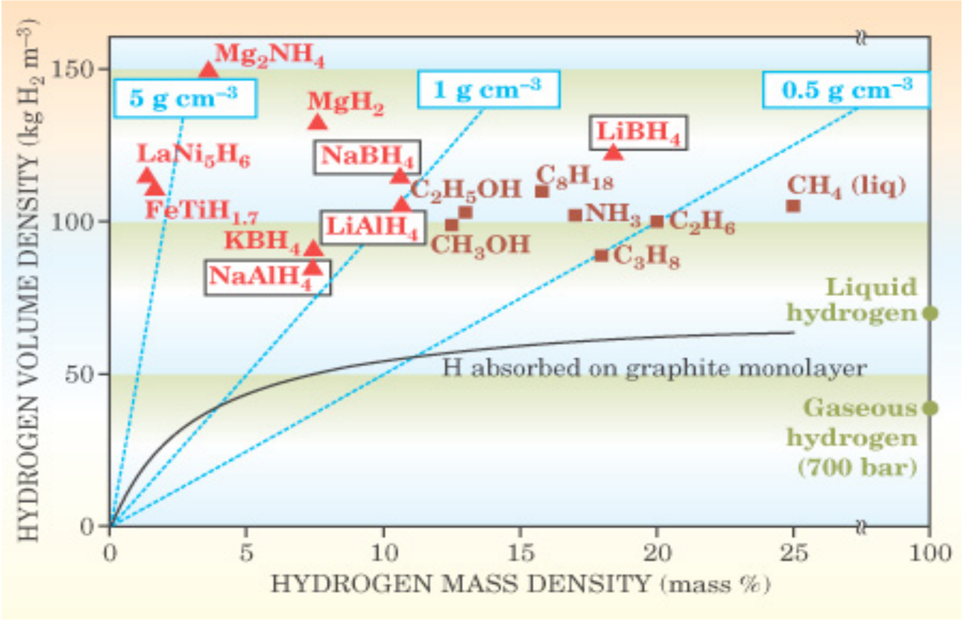


**Figure 4**: Volumetric and Gravimentric (mass) densities of various metal hydrides. Pressurized and liquefied hydrogen are also included for comparison (without considering the tank, these are 100% hydrogen by mass). Note: 30 kg/m³ = 1 kWh/L and 3% (mass $H_2$) = 1 kWh/kg. See discussion below for clarification regarding the differences between these values and the true, useable values. (Crabtree, 2004)

$$M + H \rightleftharpoons MH + \text{heat}$$

The values in the figure can be misleading. The densities reported represent the total density of all of the hydrogen in the compound. For some hydrides, the release of all of the hydrogen atoms requires temperatures outside of the range of normal vehicle fuel cell operation (some as high as 300°C), so the values in the figure are not necessarily the values for the densities of the hydrogen that is useable within standard operating temperatures. An additional challenge for hydride storage is the balancing of two competing characteristics. To achieve high storage density, the hydrogen-metal bonds should be stronger, such as in $LiBH_4$. However, to achieve fast cycling (fuel entering and exiting) at ambient temperatures, weak chemical bonds are better. Thus a balance must be reached between the two, or priority given to one goal over the other. No metal hydride currently meets the DOE standards, so there is still work to be done in all aspects of the technology. If the solution is a metal hydride, it will likely require a new approach to find and utilize, as it appears that incremental improvements will not be enough.

### *3.3: Irreversible Chemical Storage*

Irreversible chemical storage also relies on hydrides, though the bonding behaviors are so different from conventional hydrides that an irreversible chemical reaction is required to remove the hydrogen from the hydride. The reaction takes place as shown in the figure below. (The byproduct is made up of parts of the original metal alloy, though they are no longer in the original lattice structure, which is why the process is irreversible).

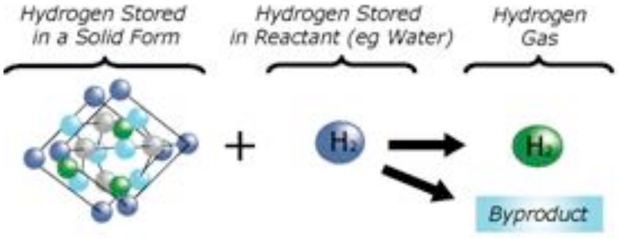


**Figure 5**: The complex hydride is mixed with a hydrogen containing reactant. The hydrogen from both the hydride and the reactant is converted into hydrogen gas (diatomic) and the byproduct is composed of the remains of the hydride and reactant. (http://www.herahydrogen.com/en/about.html)

Irreversible hydrides have a huge advantage over conventional hydrides because the hydrogen in the water also reacts and becomes a part of the hydrogen output, so only half of the generated hydrogen is actually derived from the hydride. This leads to staggering energy densities of more than 10%, well above the DOE goals for 2015. In fact, the research group that developed LiH (which has an energy density of 25% hydrogen by mass) as in irreversible hydride recently created a small company, Safe Hydrogen, LLC., to market the product as an energy storage material. Their product is a mixture of mineral oil and LiH powder, which results in a fluid that can be easily stored onboard, has a hydrogen density of 13% by mass, and releases $H_2$ and LiOH when mixed with water. The reaction is irreversible under standard conditions, but the byproduct can be returned to the company, where it is recharged with hydrogen and prepared for reuse. They call the substance a slurry, and claim that it is easily distributed by tanker trucks or pipelines, the current infrastructure of gasoline, and could provide the supply of pure hydrogen needed to move toward a hydrogen economy (SafeHydrogen, 2000). The key problems with irreversible hydrides are that water must be carried onboard as a reactant, which increases the weight of the car, and the need to rely on central stations where the spent liquid can be recharged and new slurry obtained. Possibly with a better distribution system, this technology could be used widely for convenient and clean hydrogen production, though it will probably not be the common solution for passenger vehicles because it requires the hassle of returning and reprocessing the spent fuel.

### *3.4: Novel Solutions and Future Research*

A few researchers have developed new and unique methods of storing hydrogen which do not rely on metal hydrides. Though they show potential, these technologies remain under scrutiny because of inconsistent results or unproved theories involved, and are not likely to be used in the final storage solution, though they may help to develop that technology. One of these methods is the physisorption, or physical adsorption, of hydrogen onto carbon surfaces. The reversible process relies on intermolecular forces—specifically van der Waals forces—between the hydrogen and carbon. The bonds made are extremely weak and do not alter the electron configurations of either carbon or hydrogen (IUPAC 1976), but the forces can be sufficient to store hydrogen at many times its normal density. The two carbon structures being researched the most aggressively are nanotubes and graphite layering, though numerous more have been studies as well. Carbon nanotubes are tiny cylinders, about 6 nm across, made entirely of carbon, which draw hydrogen in just as water is drawn up a straw. Bundles of these nanotubes essentially create sponges which may be able to store up to 8% hydrogen by weight. This is on the verge of meeting the DOE goals for 2015 (NREL, 2005). One problem most carbon structure methods face, however, is that high storage densities can only be achieved at either very low temperatures, approximately 80K, or at high pressures, well over 300 times atmospheric pressure. Thus, these storage methods face many of the same obstacles that make pressurized and liquefied hydrogen impractical.

Canadian and German researchers have proposed a second carbon structure that was previously overlooked. Graphite was shown by initial research to be unable to store sufficient quantities of hydrogen, but a new study has concluded that the original research did not account for all quantum behaviors of graphite. Taking these effects into consideration, it is calculated that, when stacked with a separation of 0.6 to 0.7 nm between graphite layers, storage densities of 62 kg/m$^3$—approximately 2 kWh/L, equivalent to 7% hydrogen by weight for a carbon structure—could be reached at room temperatures and moderate pressures (the value is unspecified in the news release, but moderate pressure is generally below 200 times atmospheric pressure). This is a significant step up from previous research, as it does not require such extreme pressures or temperatures. However, this study only conceived of the model, and further research must be done to develop and test such finely spaced graphite layers (RSC, 2005).

While the results achieved with carbon nanostructures remain to be proved, and researchers continue to search for new, innovative structures, some scientists have found that ammonia may be the ultimate storage medium. Researchers at the Technical University of Denmark invented a new technology, where ammonia (chemical formula $NH_3$) is absorbed into a small tablet, and can be released through a catalyst, releasing the hydrogen and nitrogen separately as gases. The tablets have energy densities of 3.0 kWh/kg gravimetric, and 3.6 kWh/L volumetric, high enough that 300 miles worth of hydrogen could be stored in a traditional gas tank. This storage technique meets the DOE goals for 2015, and is also extremely safe (researchers boast that the tablets could be carried in a pocket), has fast kinetics, and is inexpensive. The lead scientists have started a new company, Amminex, to produce these tablets for use in hydrogen systems (Science Daily, 2005). The key problem with the technology is the use of ammonia, rather than pure hydrogen, as the energy carrier. Ammonia is hazardous to the environment, particularly aquatic life (Environment Canada, 2005). The conversion from pure hydrogen to ammonia and back to hydrogen again is also undesirable, as the ultimate goal for a hydrogen transportation system is to produce, distribute, store, and use pure hydrogen without any intermediate conversions.

## 4: Hydrogen Production and Distribution: Economics

Fuel cell vehicles (FCVs) cannot be commercialized immediately because of their prohibitively high costs. Only a few years ago, the drive train of a new FCV would have cost as much as $200,000, and without large-scale production, that price is not much lower today. In comparison, the price of a drive train for a new ICE hybrid-electric vehicle (HEV) is on the order of $5,000 and declining, as hybrids take to the roads (Dunn, 2001, p.60). To be competitive, a market must be created for FCVs and economies of scale and mass production techniques must bring production costs down more than an order of magnitude. Most experts are confident that this price reduction will occur given time and a large enough market. The major road block, then, is the creation of such a market. This is where the problem of hydrogen production comes in. Without the hydrogen to run these FCVs, there will be no such market.

The key question that needs to be answered before fuel cell vehicles enter production is what fuel will be used to introduce the vehicles. The fuel cells powering the vehicles will run on pure hydrogen gas, but that gas does not necessarily need to be stored onboard as pure hydrogen. Indeed, the distribution and storage problems associated with hydrogen may make it an impractical introductory fuel. Instead, the hydrogen gas could come from liquid fuels which would be "reformed" onboard, producing hydrogen and a byproduct, usually $CO_2$. The three major contenders for onboard fuel are gasoline, methanol, and hydrogen. Each has its advantages and disadvantages, in terms of economics and practicality, and it is likely that any one of the three would create the FCV market and eventually lead to a pure hydrogen transportation economy, which most experts agree is the best long-term solution to the two problems of dependence on foreign oil and carbon emissions (Ogden et.al, 2001, p.12).

### *4.1: Gasoline as the Initial Fuel*

For those interested in the simplest commercialization of FCVs, onboard gasoline processing may be the answer. The infrastructure is already in place, and the improved efficiency of a fuel cell over an ICE means that, even though reforming gasoline produces the same $CO_2$ as burning it, the FCV could cut carbon dioxide emissions in half while reducing hydrocarbon and NOx emissions. Much of the energy in a hydrocarbon is maintained in the hydrogen produced through the reforming process and FCVs are better than 60% efficient at converting hydrogen energy to kinetic energy (approximately 70% hydrogen to electricity in the fuel cell and 90% electricity to kinetic energy in the electric motors) (Ogden, 2004, p.13). ICEs, on the other hand, can only convert 25% of the chemical energy in gasoline into kinetic energy of the car. The rest is radiated away as heat.

Nearly all energy companies—including BP, ExxonMobil, and Royal Dutch/Shell to name a few—along with General Motors are strong proponents of the gasoline reforming path. Advantages this group point out include the existing infrastructure, customers' familiarity with the fuel, and the ability to store enough fuel onboard to drive 300 miles or more. They claim this path will be the most acceptable to the general public and will thus create a popular market for the new vehicles (Dunn, 2001, p.46). The increased cost in the FCV over a traditional ICE vehicle (estimated to be about $5,100 when the market settles) will be offset by the doubled fuel economy (Ogden, 2004, p.13). GM and ExxonMobil are so confident in this approach that they have planned a multi-billion-dollar project to begin mass production of the FCVs by 2010 and be the first company with 1 million of the vehicles on the road (Dunn, 2001, p.50).

There are three key problems with this path, however, which may outweigh its advantages. First, although gasoline reforming is significantly better than burning, in a well-to-wheels comparison of total carbon emissions over the lifecycle of the three fuels, this method is the biggest polluter. It also may delay the conversion to direct hydrogen storage by creating an intermediate market which could compete with the ultimate goal of direct hydrogen fuel. Second, gasoline reformers that run at temperatures safe for onboard reforming and are small enough to fit comfortably in the vehicle have not yet been developed. The technology has been researched since the mid-1990s, but most automakers believe the products are still 5-10 years away (Ogden, 2004, p.13). The third, and potentially largest, problem, is the recent introduction of ICE hybrid-electric vehicles (HEVs). These vehicles would directly compete with the gasoline reforming FCVs, using the same fuel and getting approximately the same mileage, and as they have been introduced already, HEVs have some popular familiarity, along with lower costs of production. The hybrid can match the FCV in both fuel economy and well-to-wheels carbon emissions, and the HEV boasts superior performance over fuel cell vehicles (Dunn, 2001, p.49). The FCV will have no clear advantages, and might not be able to force its way into the market enough to produce the "buy down" effect (lowering of costs by increasing scale of production) required to compete (Ogden, 2004, p.14).

### *4.2 Methanol as the Initial Fuel*

The quickest and most effective market penetration FCVs can make may be through the methanol reforming path. Methanol is backed by a number of automotive companies (many of which are also testing direct hydrogen vehicles) and boasts some of the same advantages as gasoline while avoiding most of its drawbacks. As a liquid, methanol is much denser than $H_2$ gas and is far easier to reform onboard than gasoline. The technology has already been demonstrated in working prototype vehicles. Methanol is cleaner than gasoline and offers an additional reduction in emissions, bringing it well below the level of an HEV. Additionally, there is currently an excess in methanol production worldwide, and since the fuel is only meant to be a temporary energy carrier along the path to $H_2$, demand may never require additional production plants to be built, keeping costs low. If the methanol reforming FCVs are able to establish themselves, there will be natural market pressure toward direct $H_2$, since direct FCVs are cheaper to produce, and $H_2$ can be produced at prices comparable to gasoline (Ogden, 2004, p.14). Thus, methanol could be an ideal transition technology.

Like gasoline, methanol has its own problems, too. Though the vehicle will be able to easily handle the fuel, methanol is toxic to humans, and some of the automotive and energy companies are hesitant to pursue methanol because of possible liability issues (Ogden, 2004, p.14). Again, though methanol is slightly superior in terms of emissions when compared with HEVs, methanol FCVs will have trouble in the market, as the vehicle price is higher, and the only benefit to owning the FCV is the lower emissions, which is not, at the moment, a strong enough market force to overcome the added costs. However, this problem could be mitigated by a carbon tax, as this could give a significant financial benefit to the FCV, making it comparable in price to an HEV. The issue of product familiarity may still cause problems in this situation, however, as HEVs are more like current vehicles, and people are, in general, more comfortable with technology they are used to. This is especially applicable to people who prefer to maintain their own vehicles, rather than taking them to a mechanic, as FEVs would require specially trained mechanics, and this entails a loss of self-reliance that people may be unwilling to give up.

### *4.3: Direct Hydrogen as the Initial Fuel*

The ultimate benefit to using hydrogen as the initial energy carrier is that a potentially costly transition between fuels could be avoided. There would be no need to spend resources on the development of a gasoline reformer, and FCVs could be designed from the beginning without the extra liquid fuel lines and other added components, which could ultimately help keep vehicle costs down. Market penetration could also occur sooner without the added fuel type transition. Additionally, the stigma that hydrogen carries in popular culture—mostly in regard to safety—could be addressed earlier, potentially leading to quicker acceptance by the public. As the fastest method to the ultimate goal of clean and sustainable transportation energy, this path is advocated by most environmental groups, and could achieve the fastest reduction in emissions, which could prove vital in slowing the current exponential rise in $CO_2$ levels in the atmosphere.

The key concerns that the direct hydrogen strategy must address are the $H_2$ storage problem, the question of how hydrogen will be produced and distributed, and the fear that it will not likely be accepted as readily as the gasoline hybrid because of safety concerns—well-founded or not—the public has regarding hydrogen. Additionally, hydrogen faces the daunting challenge of entering the market without any existing infrastructure. Without efficient storage of the gas, the best method of transport is either at extremely high pressures or as a liquid, at very low temperatures, along with the problems these methods have (more details can be found in section 2.1). In spite of these and other shortfalls of direct hydrogen, a number of experts are now calling for the U.S. to take this path over the liquid fuel options because it will be more economically efficient overall (BEES/TRB, 2005, p.91).

## 5. Potential First Steps Toward a Hydrogen Transportation Economy

It is currently believed that the most efficient mode of large-scale hydrogen production in the future is to have centralized plants using a variety of technologies, from steam reforming of methane to renewable energy-powered electrolysis, combined with an extensive pipeline distribution network to get the hydrogen where it needs to go. This network cannot be realized in the short term, however, because it will require a substantial capital investment (potentially on the order of $100 billion overall, though some claim this is significantly overestimated). This is the center of the major stumbling block on the way toward a hydrogen economy. The problem is analogous to the "chicken-and-egg" problem, as the energy companies are hesitant to invest in the distribution network before fuel cell cars prove to be competitive in the transportation market, while automobile corporations are reluctant to begin mass-producing FCVs until there is an established fuel supply. Each industry would prefer if the other made the first move (Dunn, 2001, p.54).

### *5.1: The Fleet Solution*

A potential solution to this problem, proposed by Dr. Olson and her associates, is to begin by targeting vehicles in centralized fleets. In the U.S., it is estimated that 900,000 new vehicles are sold into centrally refueled fleets each year. This breaks down into about 300,000 cars, 540,000 light trucks, and 28,000 buses (not including school buses, nor rental cars as they are not centrally refueled). The benefit of these fleets is that the vehicles do not generally travel extreme distances before refueling, so a pressurized hydrogen storage system is adequate, and all vehicles in a particular fleet can be serviced at a single location, so the extensive infrastructure is unnecessary. A simple off-board natural gas steam reformer could produce the hydrogen for the fleet, and all maintenance could be performed by a few mechanics specially trained to work with FCVs (Ogden, 2004, p.18).

During this initial period, automotive corporations could start small, producing only a few FCVs in the first few years to act as prototypes and demonstration vehicles in the target fleets. Production could ramp up from there, to a few thousand vehicles per year made at a pilot factory, and then finally the company could construct a commercial factory and output FCVs at a rate of hundreds of thousands of vehicles per year. Ogden predicts that, assuming a constant decrease in production price for each successive doubling of output quantity, it would take approximately 1.2 million sales for direct hydrogen FCVs to become competitive with HEVs (Ogden, 2004, p.21). Clearly, with 900,000 new vehicle purchases each year, the targeted fleets could provide the necessary demand, and this point could be reached. If these predictions are correct, FCVs could then compete in the market on their own, and investors would hopefully see the proof of the demand they desired. The chicken-and-egg problem would be solved, and, hopefully, the construction of the hydrogen infrastructure could begin.

### *5.2: The Role of Public Policy*

In 1976, when the Hydrogen Economy became a buzzword in the years after the first OPEC oil embargo, the Stanford Research Institute conducted a study assessing the technology that would be needed to realize that economy and break this country's dependence on foreign oil. One of the conclusions of that study was: "Because the transition to hydrogen energy is genuinely only a long-term option and would take more time to implement than the private sector is normally concerned about, the role of hydrogen in the future U.S. energy economy is rightfully a matter of public policy." (SRI, 1976). It is widely accepted today that the government will play a key role in the development of hydrogen technologies. Some kind of economic incentive will be necessary in order to "buy down" the price of a fuel cell vehicle.

Potential policies include some sort of emissions tax (or, equivalently, fuel tax or vehicle tax), green vehicle subsidies, or stricter zero-emission vehicle (ZEV) regulations, which currently stipulate that a certain number of cars in each automotive company's product line must be zero-emission vehicles. All of these policies could internalize the cost of environmental damage, making it no longer an externality, which will promote FCVs over even the relatively clean HEVs (unless the gasoline fueled FCVs are used, which do not provide emissions benefits over HEVs). Possibly the best solution would be to combine this financial incentive with the policy of replacing government fleets with the first FCVs. By purchasing the early FCVs, the government would be, in effect, subsidizing the initial production of the vehicles by providing a demand for those first, more expensive and more difficult to sell models. Combined with a financial incentive for others fleet owners to follow suit, this policy could create the early fleet-based market required to "buy down" the cost of FCV production to allow the shift to mass-production.

## 6. Conclusions

The current energy system in the U.S. is not sustainable. There is too much reliance on foreign countries and their limited oil reserves and not enough attention on the environmental impacts of current fuels. The transition to a hydrogen economy could fundamentally transform the U.S. energy system into one that is clean, flexible, and secure. The transition has already begun on one of the world's island nations, Iceland, which is striving to develop renewable energy and hydrogen economies in order to reduce its almost complete dependence on foreign energy sources. The efforts by the Icelanders (and by Shell, the energy company heading the development) may lay the foundations for larger countries to develop hydrogen-based energy systems (Dunn, 2001). However, the transformation of a larger country, such as the U.S., will require far different strategies and technologies, and cannot be achieved through simple incremental advances from the groundbreaking work being done in Iceland, just as the current problem of hydrogen storage cannot be solved by mere incremental advances. New, innovative research thrusts must be made to find our own solution to the problems we face.

It is my belief that these challenges can be met here in the U.S. They will require new legislation and government leadership, in addition to creativity and dedication in the many scientists currently researching hydrogen-related phenomena, and also a few bold private investors and energy company executives willing to take big risks for a chance at the huge payoffs of attaining a sustainable hydrogen economy. If these elements can come together to solve the hydrogen storage problem and open the FCV market, there will be little restraining the growth of a sustainable hydrogen transportation system in this country. This system could then provide the backbone for the ultimate energy goal: the development of a complete hydrogen economy.

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Physics 80 Term Paper Review

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| Author: | A. Honorable Student |
| Title: | Toward a Hydrogen Transportation System: The Problem of Hydrogen Storage and Selecting an Energy Carrier |
| Reviewer: | Peter N. Saeta |

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|---|---|
| **Fair & Balanced** | You have done a good job of describing many alternative approaches to achieving the high hydrogen storage density that will be required for practical automotive transportation based on hydrogen, as well as the possible alternatives of methanol- and gasoline-based on-board reformers. You have also thrown into the mix a couple of different possibilities that are looking for market penetration already at this early stage.<br>Nathan Lewis seemed to be fairly agnostic regarding the fuel we'd end up using, whether it will be methanol, some other hydrocarbon, or hydrogen. To some people it seems that hydrogen might be a possible end point, but given the storage density problems it isn't obvious that a liquid fuel won't be preferable. You mention the toxicity of methanol as a potential drawback to its deployment as a replacement for gasoline. It would be worthwhile to inquire whether it is more or less toxic than gasoline.<br>Perhaps most importantly, however, is the issue of the energy content of the hydrogen. Insofar as there are no deposits of molecular hydrogen to extract, we will have to generate the hydrogen from some other energy source. Although not the central issue of your paper, it might be appropriate to mention that this is a challenge if we wish to effect the transition to hydrogen as the primary transportation energy carrier while simultaneously reducing our carbon emissions. |
| **Source Quality** | Lots and lots of web stuff, but some government sources. I'm a little nervous about the cold fusion reference, however! |

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| **Tech Depth** | Very nice, although there was plenty of room to go into depth about one or more of the fuel cell types appropriate for transportation. |
| **Social Depth** | Many good points come to mind. In particular, the recommendation from the SRI report of 1976 that government fleets be used as a test bed for fuel cell technology, coupled with the evident pursuit of this strategy by the current administration. |
| **Writing Quality** | The paper is quite well written. It flows well, is divided up into logical sections and even has a roadmap (although at the end of the second section rather than the first). Nice going. |
| **Best Aspect** | The discussion of the various possible approaches to achieve adequate hydrogen storage density both in volume and mass. |
| **To Improve** | Explanations for some of the technical aspects of fuel cells. |
| **Grade** | A- |