

## **Investigating The Use Of Hydrogen As An Alternative Fuel**

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## **Executive Summary**

Growing concerns about the detrimental effects on the environment resulting from widespread use of fossil fuels to power vehicles has led to rapid advancements in technology in the field of environment friendly fuel alternatives. Sustainability of fuel production in the long term is also an important concern to be addressed. This project presents a comparison between the fuels used to power vehicles today, and some of the promising alternatives in the form of hydrogen and electricity. The project also attempts to provide recommendations to improve the efficiency and economy of manufacturing liquid hydrogen on a large scale.

Initially, the impact on society of widespread transition to environment friendly fuels is discussed. Some safety concerns associated with these fuels are also presented, on the individual level as well as for the society at large. The primary concern behind using compressed liquids as fuels is storing the liquid at pressures up to 10,000psi in a tank on-board the vehicle. Any minor leak has the potential to cause a catastrophic explosion leading to serious injury or death of the occupants as well as bystanders. The tanks are also prone to rupturing resulting in an explosion during the event of a collision, especially with a heavy vehicle.

The pollution resulting from the use of these prospective alternative fuels is compared to that caused by vehicles using conventional fossil fuels. It is proved that the more the consumer is willing to spend on making the change from a fossil fuel, the less is the damage caused to the environment and the organisms living in it. This poses questions of practicality and acceptability, since the consumer has to be prepared to spend a lot more to make the transition. It is also observed that one of the most viable and effective alternatives – hydrogen – is very uneconomical to use on a daily basis. Safety is a concern as well when utilizing high pressure liquid hydrogen.

The discussion narrows down towards the use of liquid hydrogen either as a substitute to gasoline in modified internal combustion engines, or in fuel cells. The major issue of compact and safe storage of hydrogen is addressed. Methods such as high pressure tanks, material based storage, chemical based storage, and carbon based storage are discussed. The adverse effects of these technologies on society are also presented.

Finally, a hydrogen manufacturing plant is analyzed in order to observe which aspects of the manufacturing process require the highest expenditures and thus recommend directions for

further investigations and efforts towards producing hydrogen. The primary drawback is that the extraction of hydrogen is exceedingly energy intensive, and at the same time the energy density by volume of liquid hydrogen is low (2.81kWh/liter<sup>9</sup>). As a result, the small amount of energy extracted from one liter of hydrogen does not warrant large amounts of energy being utilized for its extraction. The low efficiency of the extraction process is the major challenge to be overcome in the production of hydrogen.

It is observed that current technologies are inadequate to justify an immediate widespread switch from fossil fuels to hydrogen, since the manufacturer incurs heavy losses if the hydrogen produced is sold at similar rates by volume to gasoline. If hydrogen is to entirely replace the use of fossil fuels, it will have to provide at a minimum the conveniences offered by regular use of fossil fuels, such as reasonable running costs/mile and short fill-up times. Hydrogen tanks also require high maintenance which involves frequent checks for leaks. Unless efficiencies of energy production are improved drastically, or far less energy-intensive procedures are developed to produce and store hydrogen at high pressures, a mass switch over to liquid hydrogen as the standard fuel for vehicles will not be justified from the manufacturer's point of view.

## **Abstract**

Escalating apprehension about the harmful effects of widespread use of conventional fossil fuels in vehicles, has led to vast amounts of effort and capital being directed towards researching and developing sustainable alternative energy sources. One of the most promising and abundant of these sources is hydrogen.

This project analyzes the scope of liquid hydrogen as a replacement for conventional fuels, in comparison to other alternatives as well as gasoline. Recommendations are made on improving methods of hydrogen generation and storage, and a major drawback is observed in the fact that hydrogen requires high amounts of energy for its extraction, but the fuel itself has a low energy density.

## 1. Introduction

The current energy crisis urges us to explore a variety of alternate methods to satisfy the world's energy demands. A major market solution for the energy crisis is increasing supply and reducing demand for crude oil. By increasing the list of feasible fuel alternatives, the demand on crude oil reduces. Among all the potential environment-friendly alternative fuels of the future, hydrogen is one of the most promising in terms of practicality, long term feasibility and low pollution levels. Thus it has the capability to contribute majorly towards solving two major issues: energy security and climate change.

Hydrogen has a very low energy density when compared to gasoline. This is a disadvantage for storage, transport and safety purposes since it will need to be stored at very high pressures. In addition, hydrogen cannot be used to produce energy by combustion at temperatures below 0 celsius, since the fuel requires a higher temperature to burn. Therefore the challenge becomes storing hydrogen at extremely high pressures without drastically reducing the temperature.

## **2. Societal Impact of Alternative Fuels**

The intended transition from the use of gasoline and other fossil fuels as “mass” fuels, to hydrogen and electricity to power most automobiles, is predicted to considerably reduce the detrimental consequences of fossil fuels on the environment. One of the primary negative effects is global warming. But what effect will this change have on the individual and on the society as a whole? How do these bio-friendly fuels measure up to fossil fuels in other areas? This chapter discusses the potential negative consequences of alternative fuels in the areas of pollution, health, safety, and annual expenses. This encompasses the effects of a large scale migration to bio-friendly fuels on the individual as well as the society at large. A comparison is also drawn between the polluting substances from conventional fossil fuel driven vehicles as against those from a few alternative environment friendly fuels.

### **2.1. Safety of the Individual**

This is a cause of concern during accidents in pure electric and hybrid electric cars, since they are designed to be light to compensate for the low power provided by an electric motor compared to an internal combustion motor, as well as provide a longer travel range on a single charge-up. A drawback of a light weight chassis and frame is reduced safety for the occupants in the event of an accident. In the case of serious accidents, the cost of healthcare becomes an issue for society as well as the owner of the electric car. There is a higher likelihood of injury as the structure of the car is weaker.

To cite an example, the average annual total cost of spinal cord injuries vary from \$16,792 for a thoracic incomplete spinal cord injury to \$28,334 for a cervical complete spinal cord injury<sup>1</sup>. This data is the result of the average cost measured across 675 spinal cord injury patients in the USA. The average yearly health care and living expenses vary greatly according to the severity of the injury. First-year injury costs range from \$218,504 for incomplete motor function at any level, to \$741,425 for high tetraplegia injuries<sup>1</sup>. Thus it is apparent that jeopardizing the safety of

the occupants can come at a much higher cost when considered from the individual occupant's point of view.

A safety concern associated with the widespread use of hydrogen and other compressed fuels such as Compressed Natural Gas is the on-board storage of fuel in a tank. Appropriate materials for use in compressed tanks need to be developed and thoroughly tested until they can be extensively used in vehicles sold to the public. Even if the tanks are placed safely behind the occupants and surrounded by a framework, the fear of them exploding always exists, since some hydrogen tanks are compressed up to 10,000psi. The potential danger increases in an accident, when the tanks may be struck due to the framework around them being damaged, causing a catastrophic explosion.

The next section presents the dangers posed to society by the use of four types of environment friendly fuels.

## 2.2. Dangers Posed to Society Categorized by Fuel

### Compressed Natural Gas

Since CNG is stored at a pressure of 2900psi<sup>2</sup> in vehicles, there is a danger of explosion of the tank. There is also the possibility of undesired escaping of gas, which could very easily ignite, causing an explosion. Another danger is the possible re-ignition of gas after a fire is extinguished.

In order to recognize these dangers, measuring equipment is used to monitor the pressure and flow of gas along with other parameters to ensure regulated levels. An artificial odor is added to the otherwise odorless natural gas to help detect leaks.

Other safety devices installed to keep these dangers in check include electromagnetic valves, which are mounted at each gas tank and will close the tank in case of an accident or when the engine or the ignition is turned off. A release limiter will also reduce the amount of gas that can be released in case of a leak in the gas lines. A built in pressure relief device opens the tank in case of intensive heat to avoid an increase in pressure that could lead to an explosion of the gas tank.

Other safety procedures to prevent accidents involve keeping the gas tank at a safe distance from the passenger compartment, and avoiding ignition sources. The vehicle should be well ventilated, and if the gas ever ignites, the burning gas should not be extinguished.

### Hydrogen (internal combustion engine)

Since hydrogen is stored at up to 10,000psi in on-board tanks, the dangers are similar to those in CNG vehicles. Therefore the possible dangers include release of gas and accumulation of gas in confined spaces. Since hydrogen requires a very small amount of energy to be ignited, there is a danger of self-ignition leading to explosion. Other dangers include the re-ignition of gas after a

fire is extinguished. Furthermore, a hydrogen flame is very difficult to see under daylight conditions.

The safety devices used in hydrogen powered vehicles consist of electromagnetic valves and hydrogen sensors, which detect leaks. Pressure relief devices are installed, which in some cases use vent lines that redirect the hydrogen from the tank to a high point in the vehicle (the roof area), that can be located in roof pillars. Care should be taken that these are not cut with rescue tools.

Possible malfunction recognition signs include hissing sounds, warnings from measuring equipment for pressure and flow, and hydrogen leak indicators.

The procedures to avoid accidents are the same as those in CNG vehicles. These consist of keeping a safe distance between the hydrogen tank and the passenger compartment, and surrounding the tank with a strong material. Ignition sources should be avoided, and burning gas should not be extinguished. The vehicle should be well ventilated.

### **Hydrogen (fuel cell)**

Dangers associated with these kinds of vehicles consist of leaking of battery pack materials. Since electricity is used to power the vehicle, it could conduct to undesired locations which is hazardous to the occupants. Also, it is important to monitor the status of the electric motor during the course of its operation. Safety devices used here include power cutoff switches to handle power surges.

One problem associated with fuel cell powered vehicles is that it is difficult to detect faults and possible dangers in the electricity generation and drivetrain. Safety procedures to avoid accidents involve immobilizing the vehicle by deactivating the drivetrain as soon as a potential source of danger is diagnosed. Also, there should be no unauthorized tampering with the battery or any other components. Electrical cables that carry high current are colored bright orange or blue so their detection is easy.

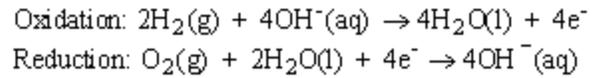
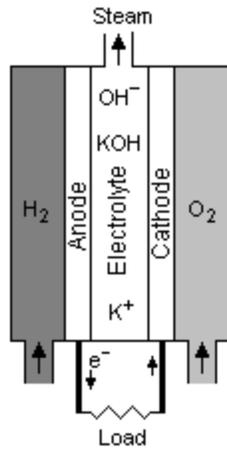


Figure 1 - Method of production of electricity in a hydrogen fuel cell<sup>3</sup>

## Hybrid

These vehicles combine the advantages of both internal combustion as well as electric-powered vehicles. As a result, there are also the disadvantages that come with both types of engines when it comes to the aspect of safety.

The high voltage of about 42V to 450V<sup>2</sup> supplied by the battery pack poses a high risk if any of the components malfunction. However, safety devices are built in that shutdown the vehicle when an accident is detected. Capacitors inside the hybrid system could keep a residual current for a few minutes after the system is shutdown. All electrical components with a higher current are normally marked bright orange so they can be easily identified. Another danger involved with electrically-powered vehicles is that their running status cannot be identified easily; that is it is difficult to tell whether the car has been switched on or not.

The safety precautions followed here are the same as those on hydrogen fuel cell vehicles. These are immobilizing the vehicle by deactivating the drivetrain, and observing extra caution when handling the battery and other drivetrain components.

### 2.3. Pollution and Costs

This section will help obtain a broader understanding of the long term societal and environmental effects of using different types of fuels. The costs and pollution involved in producing and using five different types of fuels is analyzed, along with their negative effects on the environment and as a result on human beings. These five basic fuels are conventional gasoline, other hydrocarbons such as LPG and CNG, hydrogen, and electricity. The methods of producing hydrogen in a fuel cell are also discussed, along with the pollutants associated.

The analysis will be performed based on the energy required to propel an average automobile 100 miles at a constant speed of 50 mi/hr. The fuel efficiency at this speed is approximately 27 mi/gal, which implies that 3.7 gallons of fuel are used for this distance at 50 mi/hr. The energy contained in 3.7 gallons of gasoline is 132.87 kWh, since the energy density of gasoline is 34.2MJ/L<sup>9</sup>. Thus an approximation can be made for the amount of energy required using this data for gasoline. It is assumed that for LPG, CNG and hydrogen, the energy conversion efficiencies in a vehicle are the same as for gasoline.

#### Conventional Gasoline

Crude oil prices were close to their all time high in the year 2008, leading to gasoline prices of \$3.25/gallon. Using data for this year, the price of a gallon of regular gasoline can be broken up into Cost of crude oil (69%), Federal and state taxes (13%), Distribution and marketing (12%), and Refining costs and profits (7%)<sup>4</sup>.



Source: Energy Information Administration.

Figure 2 - Price breakup of gasoline<sup>4</sup>

From this data, profits make up about 4% of the total price of gasoline. Since 3.7 gallons of gasoline are required for 100 miles at the given speed, the cost of 3.7 gallons or 14 liters of gasoline as of 2008 was \$12<sup>4</sup>. Out of this 4% or 48 cents are contributed towards profits for the company. This neglects other costs such as maintenance and capital investments in gas stations, but these will be ignored for the purpose of this analysis since they depend on factors such as how long the gas station was in service and the location of the gas station. This assumption is made uniformly across the analysis for consistency.

From a pollution point of view, the carbon dioxide emitted from the average gasoline powered vehicle is 190 gCO<sub>2</sub>/km<sup>5</sup>, which results in overall CO<sub>2</sub> emissions of 30,571g over a 100 mile range.

## Liquefied Petroleum Gas - Propane

One of the commonly used energy rich liquefied petroleum gases or LPG's that are found mixed with natural gas and oil is propane, or  $C_3H_8$ . Propane is 270 times more compact as a liquid than as a gas, and thus it is stored and transported in its liquid state. In order to use it, a valve on its container is opened and the propane is released not as a liquid but as a gas<sup>6</sup>. The pressure at which the liquid is stored in the containers in an automobile is between 7 and 9 bars, or about 115 psi<sup>7</sup>. The liquefying temperature is  $-42.1\text{ }^\circ\text{C}$ <sup>8</sup>.

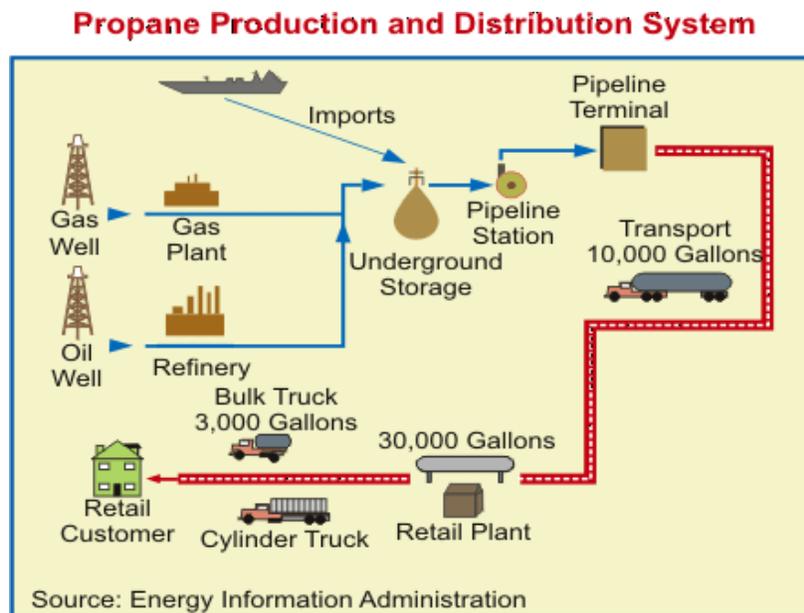


Figure 3 - Propane production and distribution schematic<sup>6</sup>

Since the energy density of propane LPG burned in air is  $7\text{kWh/L}$ <sup>9</sup>, 19 liters or 5 gallons of propane LPG are required to propel the car 100 miles. At current prices in the USA for commercial propane LPG, 5 gallons will cost  $\$10.45$ <sup>10</sup>. The percentage profit for the manufacturer of propane is about the same at 4%. This implies a profit of 42 cents for the manufacturer.

Since typical LPG cars emit about 145 gCO<sub>2</sub>/km<sup>11</sup>, the total CO<sub>2</sub> emissions from an LPG over a 100 mile range is 23,330g. In Table 1 below, the only pollutant released at an increased rate is methane; whose emissions are increased by 10% when propane is used as a fuel.

**Emissions of Converted Propane and Reformulated Gasoline LDVs**

Pollutant	Percent Reduced
Volatile Organic Compounds (VOC)	0%
Carbon Monoxide (CO)	20% to 40%
Oxides of Nitrogen (NO <sub>x</sub> )	0%
Particulate Matter (PM)	80%

Table 1 - Propane vs Gasoline emissions<sup>12</sup>

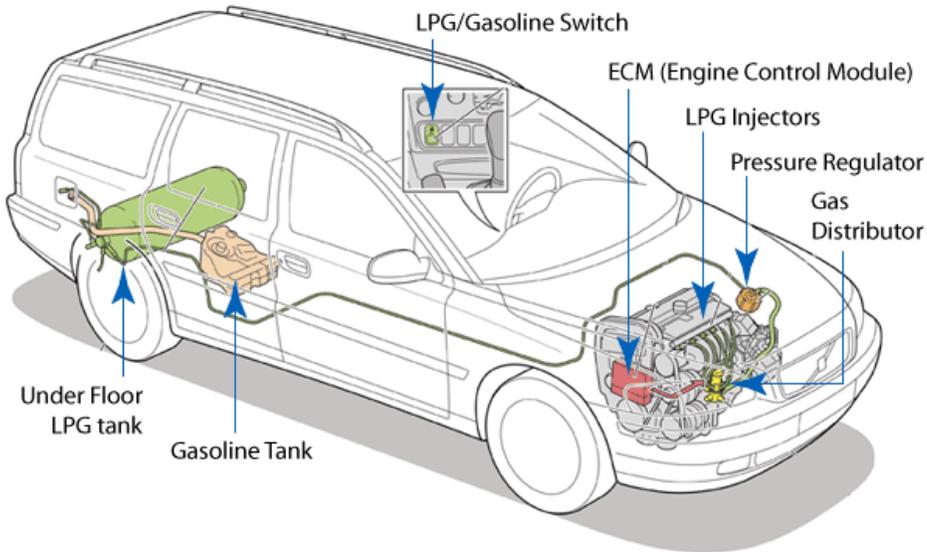


Figure 4 - LPG/CNG converted vehicle schematic<sup>13</sup>

## Compressed Natural Gas

CNG is much safer than most other alternative fuels since it is lighter than air; so in the event of a spill it disperses easily. It is stored and dispersed in hard containers at a pressure of 2900-3200psi<sup>14</sup>.

The cost of a gallon of CNG in the USA is about \$1.78<sup>15</sup>. The energy density of CNG burnt in air is 2.5kWh/L<sup>9</sup>. Thus the volume of CNG required to take the average car 100 miles is 14 gallons. The total cost of this amount of fuel for the consumer is \$25. The profit for the company is then \$1, assuming a 4% profit rate.

Since the emissions from using CNG as a fuel are 143 gCO<sub>2</sub>/km<sup>16</sup>, the total emissions are 23,008gCO<sub>2</sub> over a 100 mile range.

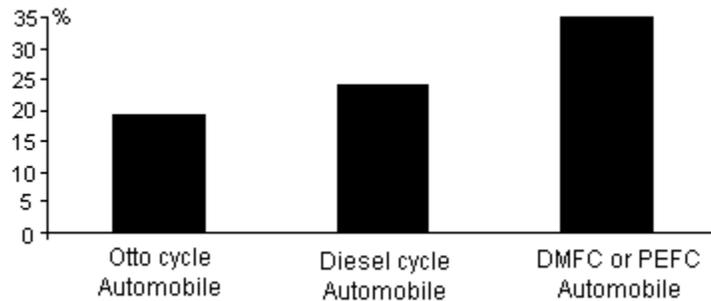


Figure 5 – Estimated efficiencies using hydrocarbon fuels<sup>3</sup>

## Hydrogen (internal combustion engine)

There are two types of hydrogen-powered vehicles. In the type analyzed in this report, stored or on-board produced hydrogen is used as fuel in an internal combustion engine to power the vehicle. The other type of hydrogen-powered vehicle uses hydrogen to produce electricity in a fuel cell that powers an electric motor. These vehicles are also equipped with batteries that store the electricity that cannot be used by the motor immediately.

From this data, the energy density of liquid hydrogen is 10.1MJ/L or 2.81kWh/L<sup>9</sup>. Thus 47.3 liters or 12.51 gallons of hydrogen are required to drive the car 100 miles. At current rates of hydrogen available (\$9.45/gal<sup>59</sup>), 12.51 gallons of hydrogen would cost \$118.22.

Since accurate information regarding the breakup of the cost of one gallon of hydrogen is not easily available, one can assume the profit for the manufacturer to be about 10% of the selling price since there are no refining costs involved. However, transportation and storage costs are high since the hydrogen is highly compressed at up to 10,000psi. A profit rate of 7-10% of the selling price results in \$8.28 - \$11.82 of profit for the company, when enough hydrogen to propel a car 100 miles is sold.

This is obviously very uneconomical for the consumer, and although the profit figures for the company are steep, they are used to recover the high capital investment made to set up a hydrogen manufacturing plant as will be seen later on.

An alternative method to solar power can be used to obtain the required electricity to electrolyze hydrogen from water, such as nuclear power. The cost of electricity from a nuclear power plant is around 12 cents/kWh<sup>24</sup>. The energy required to produce, compress and store 1 liter of hydrogen is 1.75kWh<sup>17</sup>. This would cost 21 cents when using electricity produced in a nuclear power plant. Since 47.3 liters of hydrogen or 82.8kWh of energy is being used here, the cost of electricity is \$9.94.

Since the CO<sub>2</sub> emissions when obtaining electrical energy from nuclear power is 66 gCO<sub>2</sub>/kWh<sup>25</sup>, the total CO<sub>2</sub> emissions are 3,953g when a car travels 100 miles.

Figure 6 presents the percentage increase or decrease of greenhouse gas emissions of hydrogen manufactured by various methods, in comparison to emissions from gasoline.

### Percent Changes in Greenhouse Gas Emissions (Relative to Baseline Gasoline Vehicles)

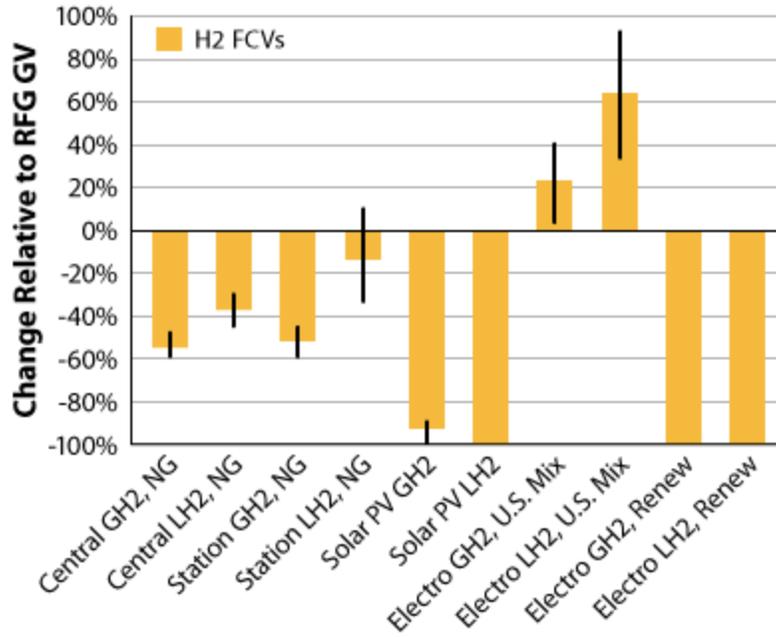


Figure 6 - Pollution advantage of H<sub>2</sub> over gasoline<sup>18</sup>

**Hydrogen Production and Distribution Pathways**

<b>Pathway Number</b>	<b>Description</b>
1	Central GH2, NG: Gaseous hydrogen produced from natural gas via steam methane reforming in a centralized plant. This is currently the most popular pathway.
2	Central LH2, NG: Liquid hydrogen produced via pathway #1. Liquid hydrogen enables longer driving range but requires strict heat insulation and can suffer from boil-off loss.
3	Station GH2, NG: Gaseous hydrogen produced from natural gas via steam methane reforming at a refueling station. Producing hydrogen at the station instead of a central plant limits hydrogen transportation costs.
4	Station LH2, NG: Liquid hydrogen produced via pathway #3.
5	Solar PV GH2: Gaseous hydrogen produced by electrolyzing water with electricity produced by photovoltaic solar panels in a central location.
6	Solar PV LH2: Liquid hydrogen produced via pathway #5.
7	Electrolysis GH2, U.S. Mix: Gaseous hydrogen produced by electrolyzing water with average U.S. grid electricity at refueling stations; 54% of the U.S. grid electricity comes from coal, 18% from nuclear, 15% from natural gas, 1% from oil, and 12% from other energy sources.
8	Electrolysis LH2, U.S. Mix: Liquid hydrogen produced via pathway #7.
9	Electrolysis GH2, Renewables: Gaseous hydrogen produced at refueling stations by electrolyzing water with electricity produced by renewable sources.
10	Electrolysis LH2, Renewables: Liquid hydrogen produced via pathway #9.

Table 2 - Explanation for Figure 6<sup>18</sup>

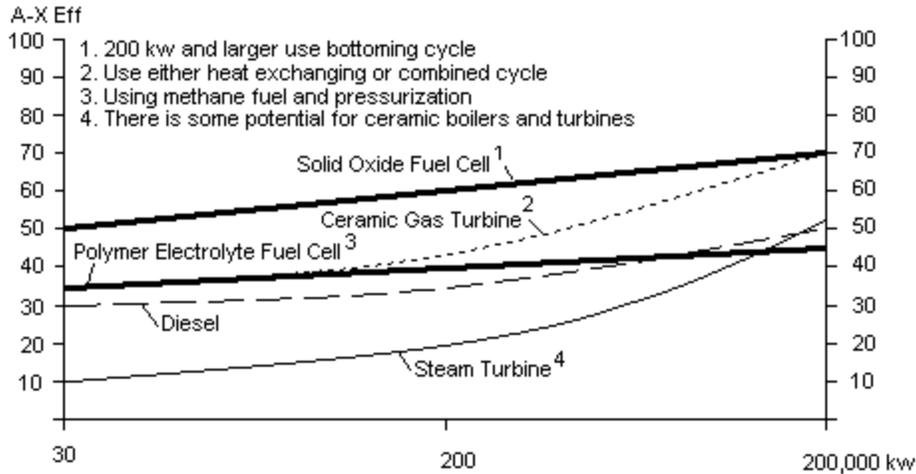


Figure 7 - Projected efficiencies for future electricity generating power plants<sup>3</sup>

## Hydrogen (fuel cell)

A comparison will be drawn between the harmful by-products of producing energy in a hydrogen fuel cell as compared to those from a gasoline powered internal combustion engine.

If gasoline is assumed to contain 100% octane or  $C_8H_{18}$ , the following are the reactions that occur when octane combusts using oxygen from the air<sup>19</sup>:



On the other hand, the reaction that occurs when a hydrogen fuel cell produces energy from  $H_2$  and oxygen in the air is<sup>19</sup>:

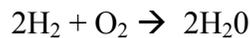


Table 3 shows the bond energies of the various bonds involved in these reactions<sup>19</sup>:

Bond Type	Bond Energy (kJ/mole)
C single	347
C double	611
C triple	837
C – H	413
H – H	436
O – O	146
O = O	498
C – O	358
CO <sub>2</sub>	803
C = O	745
H – O	464

Table 3 - Bond Energies<sup>19</sup>

Using the information in this table, the energies released per mole in each step of the reaction can be calculated. The difference in energies between the products and the reactants in the gasoline combustion reaction is  $42400 - 32176 = 10224$  kJ/mole. This means that the energy released per H atom produced is  $10224/36 = 284$  kJ/mole, and the energy released per fuel mass is  $10224/228 = 44.84$  kJ/mole. On the other hand, the difference in energies of products and reactants in the hydrogen fuel cell reaction is  $1856 - 1370 = 486$  kJ/mole. The energy released per H atom is the same as the energy released per fuel mass which is  $486/4 = 121$  kJ/mole.

To summarize the calculations, the gasoline reaction releases 2.35 times as much energy per hydrogen atom, and 0.37 times as much energy per fuel mass when compared to the hydrogen fuel cell reaction. The mass ratio of water released per unit mass of gasoline used is 1.4, and for hydrogen it is 9. Thus, for equal masses of gasoline and hydrogen, the hydrogen fuel cell releases 2.35 as much water per unit mass as compared to gasoline combustion.

Since the ignition temperature of gasoline is around 260°C, the water released is in vapor form. The water vapor and the carbon dioxide released are harmful greenhouse gases. Since the

operating temperature of hydrogen in the fuel cell is 50 – 250 °C<sup>19</sup>, all the water released is either as a hot liquid or low temperature steam. This is not an environmental hazard.

Next, a comparison will be drawn between the annual emissions from an average car running on gasoline versus hydrogen. These emissions will then be related to their corresponding harmful effects on humans, animals and the environment.

Table 4 below assumes that the average car travels 12,500 miles/year with a fuel consumption rate of 22.5 miles/gallon<sup>20</sup>.

<b>Pollutant</b>	<b>Grams/mile</b>	<b>Pounds/year</b>
Carbon Dioxide	363	10000
Carbon Monoxide	22	606
Gasoline	123	3376
Hydrocarbons	2.9	80
Nitrogen Dioxides	1.5	41

Table 4 - Pollutants from gasoline Cars<sup>20</sup>

The next table contains the same data for average pickups, vans, minivans and SUV's<sup>20</sup>. The data assumes the light truck travels 14,000 miles/year with an average fuel efficiency of 15.3 miles/gallon<sup>20</sup>.

<b>Pollutant</b>	<b>Grams/mile</b>	<b>Pounds/year</b>
Carbon Dioxide	544	16800
Carbon Monoxide	29	894
Gasoline	181	5616
Hydrocarbons	3.7	114
Nitrogen Dioxides	1.9	59

Table 5 - Pollutants from gasoline light trucks<sup>20</sup>

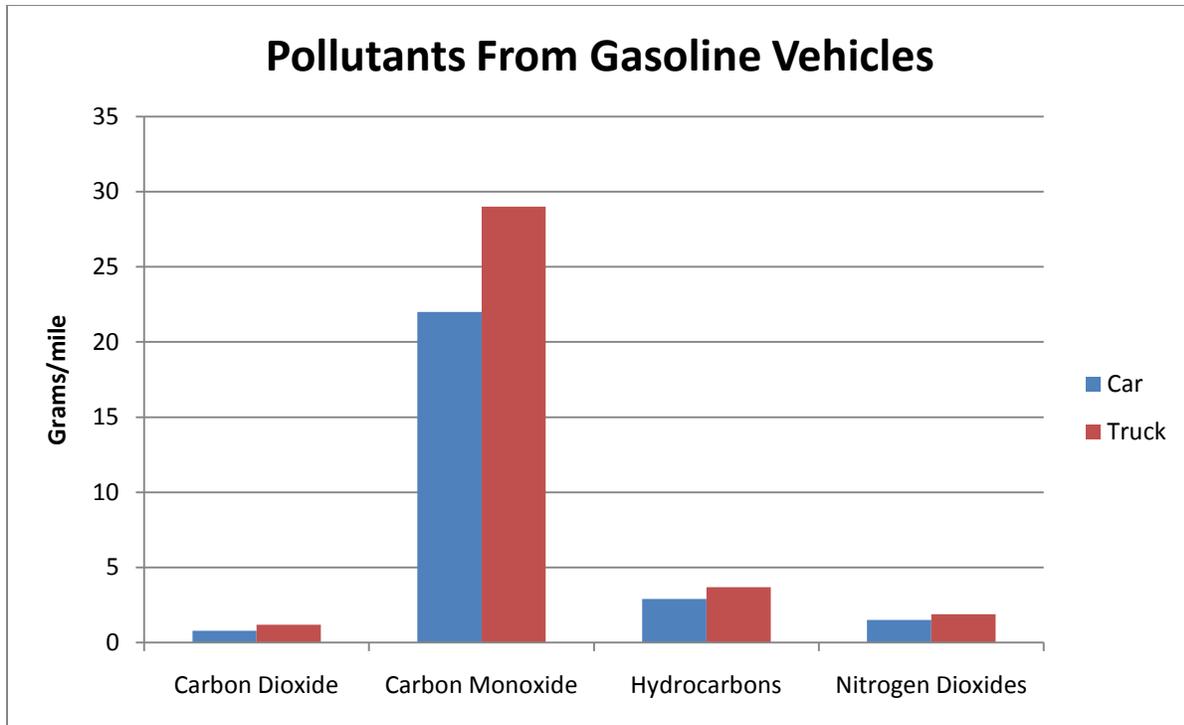


Figure 8 - Pollutant Chart<sup>21</sup>

Figure 8 above shows the high amount of carbon monoxide emitted when compared to the other pollutants released from a gasoline engine. Also, despite the low proportion of carbon dioxide released, even this small amount is enough to create a global warming hazard when millions of cars are considered. On the other hand, the only by-product from the hydrogen fuel cell energy conversion is water at high temperature or low temperature vapor.

Carbon dioxide is present in the atmosphere at a low concentration of about 0.035%<sup>22</sup>, and absorbs infrared energy making it a greenhouse gas thus contributing to global warming. However, automobile engines are not the single greatest contributor of carbon dioxide as a pollutant.

Carbon monoxide is emitted from cars due to incomplete combustion, and its main source in cities is the internal combustion engine. At peak traffic levels in cities, the carbon monoxide level can be upwards of 50-100 ppm<sup>22</sup>, which is well above the safe limit for the human body. This gas is poisonous since it limits the ability of the blood to transport oxygen by sticking to haemoglobin thus reducing the capacity of the blood to transport oxygen around the body.

Hydrocarbons are released into the atmosphere when an engine is not working properly resulting in an increase in unburned fuel. They also evaporate from fuel tanks. Hydrocarbons are detrimental to human health and can cause photochemical smog, which is a harmful brown haze caused when oxides of nitrogen react with pollutant hydrocarbons.

Nitrogen oxides are produced when elemental nitrogen in the air is broken down and oxidized at temperatures exceeding 1000 K<sup>22</sup>. They also contribute to photochemical smog.

However, there are other hazards and downfalls of using hydrogen to generate energy, in addition to the high cost of hydrogen. Methods of storage of highly compressed hydrogen are still being developed, and cannot yet be considered entirely safe and reliable. These unreliable storage tanks pose a safety hazard to the occupants of the vehicle as well as those in close proximity with it.

### **Electric Power Plants**

The approximate power consumption in a pure electric car such as the Tesla Roadster is 22kWh/100mi<sup>23</sup>. On the other hand, some conversion electric cars and hybrid vehicles such as the Honda Insight consume 45kWh/100mi<sup>23</sup>.

In order to avoid the use of fossil fuels, the electricity used may be sourced from nuclear power plants. The average cost of electricity from a nuclear plant is 12 cents/kWh<sup>24</sup>. Thus the cost of electricity for 100 miles is \$3.48 for the pure electric car, and the fuels cost \$7.2 in total for the hybrid vehicle, assuming the efficiency of the battery is 75%.

The estimated “cost to the environment” of nuclear power is 2.91 cents/kWh<sup>24</sup>. This includes 0.11 cents/kWh for routine operations, 2.3 cents/kWh for accidents and 0.5 cents/kWh for decommissioning costs<sup>24</sup>. This means a total cost (from generating only the electric power) of 84 cents/100mi to the environment from the electric car and \$1.75/100mi from the hybrid car. The carbon dioxide emissions from a nuclear power plant can be taken as an average of 66gCO<sub>2</sub>/kWh<sup>25</sup>. This results in a net carbon dioxide emission of 1,914 gCO<sub>2</sub>/100mi for the electric vehicle, and 8,783 gCO<sub>2</sub>/100mi. In addition, nuclear power plants use radioactive

isotopes whose radiations affect people within a 50 mile radius of the plant. Nuclear meltdowns and improper disposal of nuclear waste cause humans to be exposed to very harmful levels of radiation.

It is difficult to make an estimate of the cost to society of producing this electricity from coal power plants, since the baselines and comparisons used for a study are subjective. Different assumptions can be made for an analysis, but one study concluded that the national cost of coal power plant emissions was \$62 billion in 2005<sup>26</sup>. The same study claimed that the damage from automotive emissions, including light vehicles and medium and heavy duty trucks, was \$56 billion<sup>26</sup>. The study placed the value of a premature human death at \$6 million. This implies that about 10,000 people die every year from exposure to coal power plant emissions, and 10,000 from exposure to automotive emissions. Since these are the results from 2005, the cost of emissions will be considerably higher in 2009. Even these figures are considered a miscalculation, since estimates of coal-pollution related deaths were just below 30,000 in 2005<sup>26</sup>, as compared to the predicted value of 20,000.

**Lifecycle Emissions and Fuel Use per Mile for Gasoline and EV Passenger Cars**

	<b>Conventional Car on RFG</b>	<b>Electric Car</b>	<b>Percent Reduction (increase)</b>
	<i>Grams/Mile</i>	<i>Grams/Mile</i>	
<b>Carbon Monoxide (CO) Total</b>	2.906	0.113	96%
<b>CO: Urban</b>	2.767	0.005	100%
<b>Volatile Organic Compounds (VOC) Total</b>	0.209	0.036	83%
<b>VOC: Urban</b>	0.148	0.000	100%
<b>Oxides of Nitrogen (NO<sub>x</sub>) Total</b>	0.212	0.778	-267%
<b>NO<sub>x</sub>: Urban</b>	0.048	0.015	69%
<b>Particulate Matter 10 (PM10) Total</b>	0.047	0.077	-64%
<b>PM10: Urban</b>	0.032	0.022	31%
<b>Sulfur Oxides (SO<sub>x</sub>) Total</b>	0.085	0.925	-988%
<b>SO<sub>x</sub>: Urban</b>	0.008	0.002	75%
<b>Carbon Dioxide</b>	449	371	17%
<b>Greenhouse Gases (GHG)</b>	473	384	19%
	<i>BTU/Mile</i>	<i>BTU/Mile</i>	
<b>Fossil Fuels</b>	5827	4201	28%
<b>Petroleum</b>	4573	89	98%

Table 6 – Emissions/mile for gasoline vs electric Cars<sup>21</sup>

Table 7 below summarizes the discussion over a 100 mile range, which requires 132.87kWh for the average car in the United States.

<b>FUEL FOR 100 MILES</b>	<b>Consumer Cost (\$)</b>	<b>Company Profit (\$)</b>	<b>Grams CO<sub>2</sub></b>
<b>Gasoline</b>	12	0.48	30,571
<b>LPG</b>	10.45	0.42	23,330
<b>CNG</b>	25	1	23,008
<b>Hydrogen</b>	118.22	8.28 – 11.82	3,953
<b>Electric (pure)</b>	3.48	-	1,914
<b>Electric (hybrid)</b>	4.82	-	8,783

**Table 7 - Summary of fuels analyzed for a 100 mile range**

From Table 7 it is clear that a reasonable sacrifice has to be made from the consumer’s point of view in order to prevent polluting the environment. In the case of Gasoline and LPG, the convenience of long range and easy refueling exists. On the other hand, Hydrogen is very expensive but has an acceptable range and safety standard. The overall CO<sub>2</sub> emissions per 100 miles are 83% reduced over LPG, and 87% reduced from those of Gasoline. The emissions from LPG are similar to those of CNG; however LPG is a lot cheaper. Pure electric cars are extremely cheap to run, but have very low range and are slow. However, they are the most environment friendly in terms of CO<sub>2</sub> emissions. It must also be mentioned here that the materials used to make the batteries such as lithium-ion, nickel, cadmium are a serious health and environmental hazard if they are not disposed of properly. Finally, hybrid electric cars offer both reasonable range and almost 100% lower CO<sub>2</sub> emissions when compared to gasoline.

In each case, the CO<sub>2</sub> emissions as well as other pollutants result in varying amounts of additional money spent on healthcare, not just by the owner of the polluting car but by innocent residents of the region as well. It is hard to predict the long term costs of each pollutant to the environment, but these costs are sure to be immense.

## 2.4. Acceptability

As it was mentioned earlier, an issue with the widespread transition from using fossil fuels to more environment-friendly ones is the capacity of these “new” fuels to replace the capability and conveniences of fossil fuels. These conveniences with regard to gasoline, which are often taken for granted, include fast and easy refueling, relatively affordable costs, high radius of travel per tank of fuel, and safety. Gasoline cars also have comparatively very high performance standards, especially when it comes to acceleration of the vehicle.

On the other hand, hydrogen as well as pure electric vehicles do not offer a high radius of travel per tank of fuel because of their low energy densities by volume. In the case of hydrogen, this leads to a much higher running cost. Hydrogen vehicles offer average levels of performance, but electrical vehicles are the ones that are severely lacking in this department. Hybrid vehicles offer the best combination of both gasoline and electric power. When the vehicle requires high amounts of power, for example acceleration from rest, the internal combustion engine is made to provide this power. And when the vehicle reaches a cruising speed where not much power is required, the power source switches to electric. This helps to cut running costs, but these cars are expensive to purchase.

To evaluate the long term running and maintenance costs, a comparison will be drawn between the ongoing costs of owning cars that run on Gasoline, LPG, CNG, Hydrogen, Electricity, and Hybrid cars. Across the board costs which are independent of the type of fuel used such as body maintenance are excluded for the purpose of comparison.

Where required, it will be assumed that the tank size of the car is 15 gallons or 56.7 liters for the purpose of calculating travelling radius and refueling costs. The basis of the calculation for energy requirements is that the car being used requires 132.87kWh of energy to travel 100 miles at 50mi/hr, as in the comparison performed in the “Pollution” section. This will be the average requirement assumed per 100 miles travelled, for a total distance of 12,500 miles/year. Finally, it is assumed that the car is owned for 5 years, leading to a total mileage of 62,500 miles.

	<b>Gasoline</b>	<b>LPG</b>	<b>CNG</b>	<b>Hydrogen</b>	<b>Electric</b>	<b>Hybrid</b>
<b>Vehicle Purchase Cost (\$)</b>	25,000	30,000	30,000	40,000	40,000	45,000
<b>Total Cost of Fuel (\$)</b>	7,500	6,530	15,625	73,890	1,650	3012.50
<b>Cost of Refuel (\$)</b>	48.75	31.35	26.70	141.75	2.40	51.15
<b>Range of Travel (mi)</b>	405	300	107	120	68	473
<b>Fuel Specific Maintenance (\$)</b>	350	300	300	200	100	450
<b>Total Cost (\$)</b>	32,850	36,830	45,925	114,090	41,750	48,462
<b>Cost Per Mile (cents)</b>	52.6	59.0	73.5	183	66.8	77.5
<b>Total Additional Cost Over Gasoline</b>	-	3,980	13,075	81,240	8,900	15,612
<b>Positives</b>	Convenient, cheapest	Convenient, cheap	Convenient	Cleanest	Clean, cheap	Relatively clean & convenient
<b>Negatives</b>	Most polluting	Polluting	Polluting	Very expensive	Low range	Somewhat polluting

**Table 8 - Comparing Maintenance and Running Costs for Various Fuels<sup>27</sup>**

Data for the cost of fuel is used from the “Pollution” section and adjusted for 12,500 miles/year for 5 years. The cost of fuel when operating the hybrid car is calculated using a gasoline fuel efficiency of 27mpg as well as the cost of recharging the battery. It is assumed that the battery in the electric car as well as the hybrid car has a capacity of 20kWh, and the efficiency is approximately 75%. For the “Fuel Specific Maintenance”, the costs over and above all the other uniform costs are tabulated. This draws a comparison between the extra costs incurred due to the specific fuel used.

Figure 9 presents a comparison between the total cost of 5-year ownership to the total cost of 5-year fuel, for all 6 fuels considered. Figure 10 presents the fraction of total fuel cost over the 5-

year period to the total cost of ownership, as a percentage. Figure 11 compares the cost of refueling to the range per refuel.

The percentage cost of ownership in relation to overall ownership cost is small, and roughly the same fraction for gasoline and LPG. Fuel cost percentage is increased for CNG over Gasoline and LPG. For hydrogen, the fuel cost makes up the majority of the cost of ownership at 64%. Since running costs are low for the electric and hybrid cars, the cost of fuel is a small fraction of the overall cost of ownership in both cases.

KEY: 1 – Gasoline, 2 – LPG, 3 – CNG, 4 – Hydrogen, 5 – Electric, 6 – Hybrid

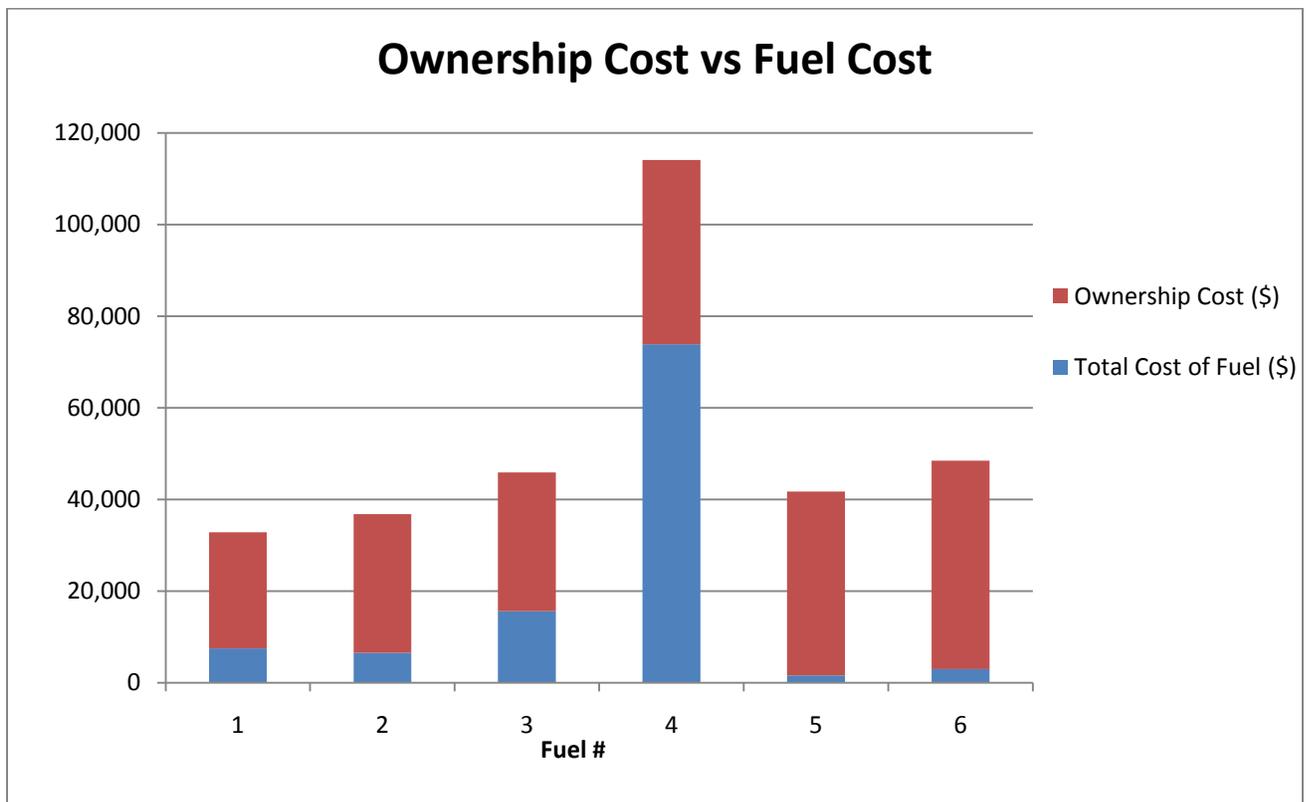


Figure 9 - Ownership cost vs fuel cost

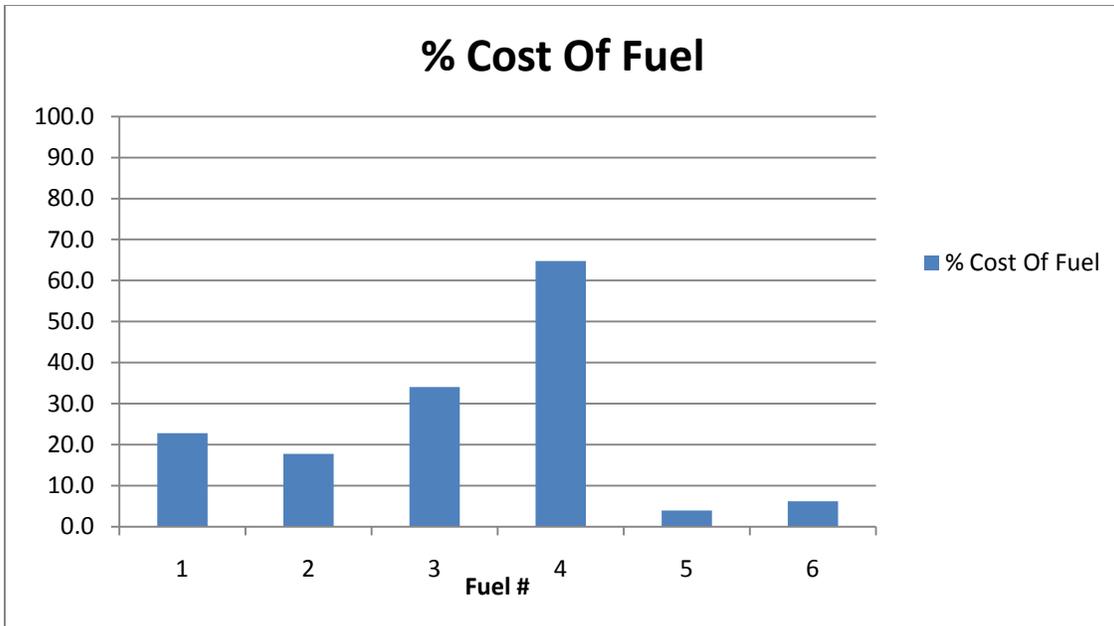


Figure 10 - Cost of fuel as a percent of ownership cost

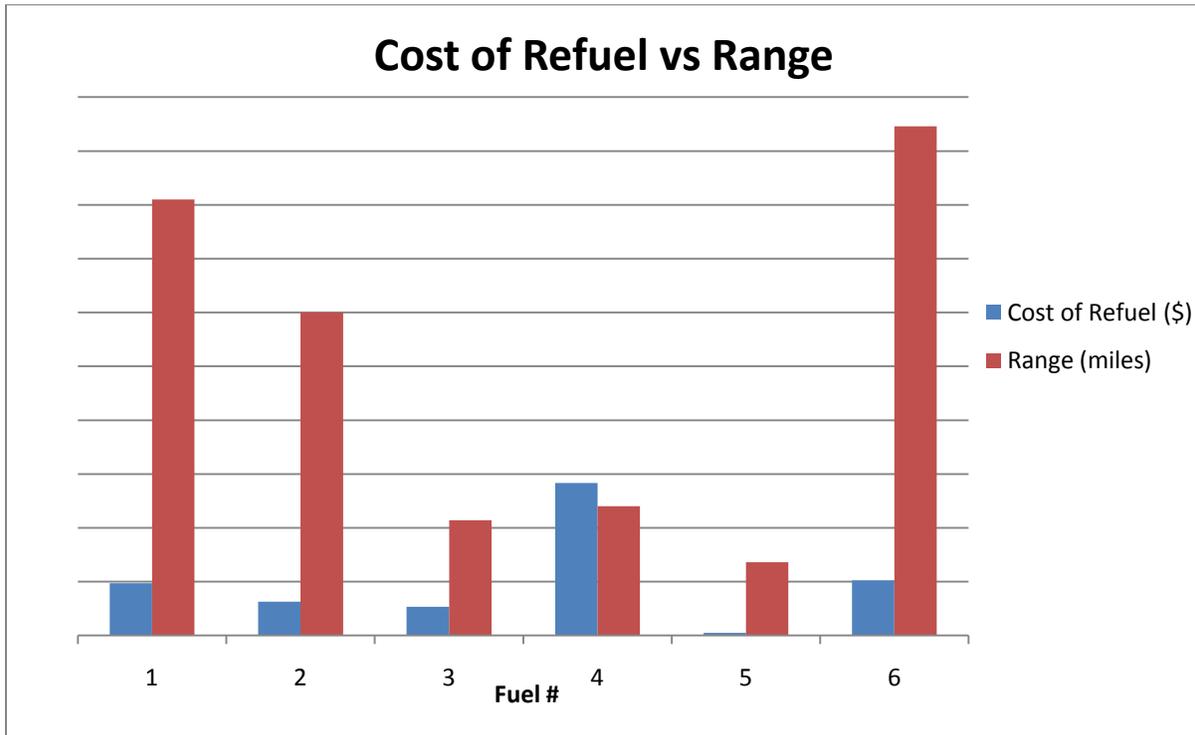


Figure 11 - Cost of refuel vs range

	Cost per gallon	Energy density (vol)	Energy density (mass)	Cost per mile	Mileage
Gasoline	\$2.50/gallon	9.5kWh/liter	12.9kWh/kg	\$0.11/mile	22 mile/gal
Hydrogen (liquid)	\$9.45/gallon	2.81kWh/liter	39.75kWh/kg	\$1.77/mile	5.35 mile/gal

Table 9 - Comparison between hydrogen and gasoline<sup>9</sup>

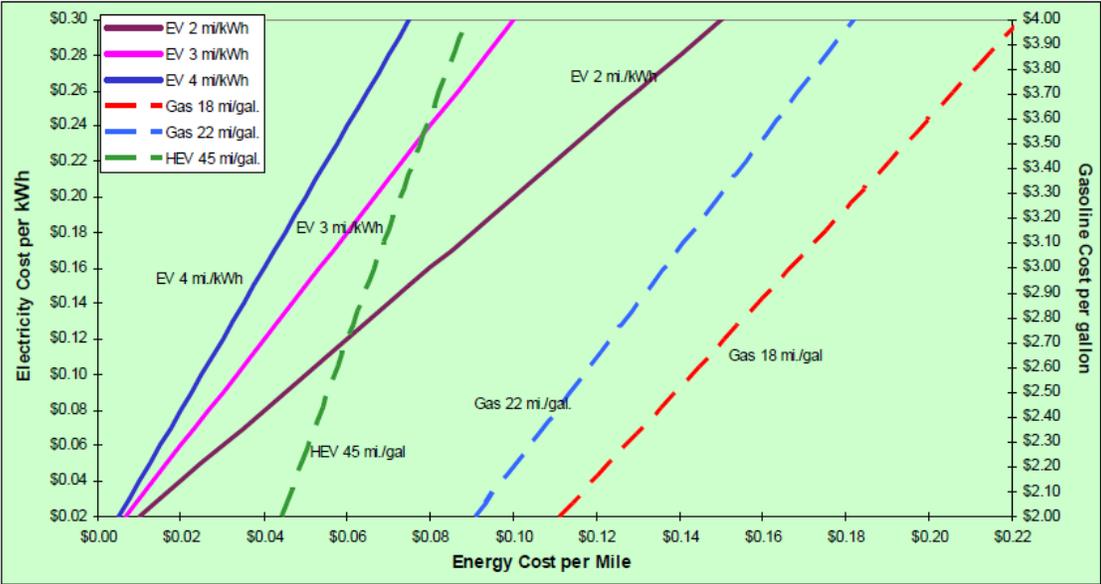


Table 10 - Comparison between electricity and gasoline<sup>28</sup>

### **3. Extraction and Storage of Hydrogen**

An important issue with isolating hydrogen for our use is that highly polluting fuels are being used to power the processes that extract hydrogen. The most common method of extraction involves reacting steam with natural gas itself. Most of the hydrogen fueling stations planned in the next few decades will use fossil fuels as the source for hydrogen<sup>29</sup>. The Green Hydrogen Coalition, a leading promoter of hydrogen fuel cells, is propagating the use of environmental friendly power sources such as wind and solar energy for the extraction of hydrogen.

#### **3.1. A Few Methods of Obtaining Hydrogen**

A very cost-efficient method to separate pure hydrogen from a gas mixture was developed by FuelCell Energy, Inc. This is an EHS or Electrochemical Hydrogen Separator and is a clean method to produce hydrogen for vehicles and industrial purposes. This technology does not rely on compression and has no moving parts. A prototype of the EHS has been built and is being tested in Connecticut, and currently produces 1200 liters/hour of pure hydrogen<sup>30</sup>. Hydrogen is three to four times as expensive to produce as gasoline, and this technology will help reduce the cost of production.

The method of obtaining hydrogen from steam is a multiple stage circulatory process. Initially carbon monoxide is reacted catalytically with steam producing carbon dioxide and hydrogen. This carbon dioxide is then reacted with steam and sulfur dioxide giving sulfuric acid and carbon dioxide. The sulfuric acid is split into sulfur trioxide and steam; and this sulfur trioxide is dissociated into oxygen and sulfur dioxide. The carbon monoxide and sulfur dioxide are fed back into the process to give hydrogen and oxygen as end products.

Another possible method for obtaining hydrogen which is still in the experimental stages is from coal/waste and tire mixture. Technically applicable gas with a high hydrogen content of ca 78% is obtained by pyrolyzing the mixture of bituminous coal with 15% waste tire rubber<sup>31</sup>. Incorporating a thermal degradation module induces the decomposition of volatile products increasing the yield of hydrogen. Also, the carbonaceous residue can be used as a smokeless fuel.

The high pressure proton exchange membrane (PEM) electrolyte water electrolyzers electrochemically generate hydrogen at 2,000psi or greater<sup>54</sup>, thus eliminating the need for mechanical compression. These are environmentally harmless since they use only pure water as feedstock and working fluid, and no liquid electrolyte. They also require minimal maintenance. Currently, the PEM electrolyzers are capable of producing up to 500kg/day/unit<sup>32</sup> of gaseous hydrogen.

Figure 12 helps illustrate the concept behind the proton exchange membrane electrolyzers.

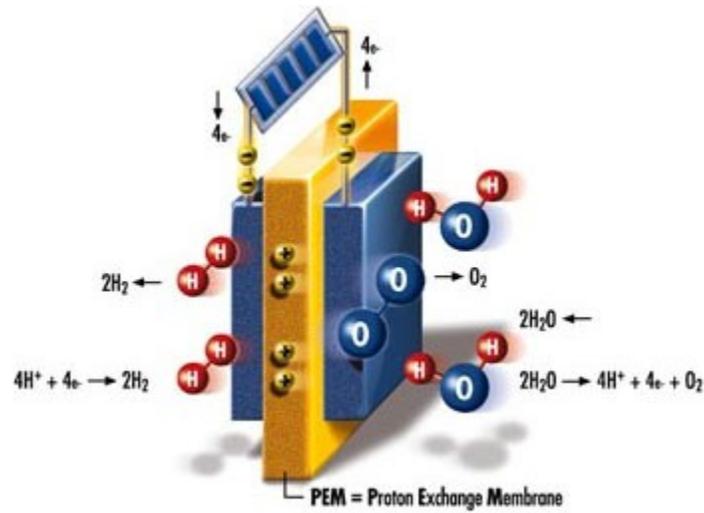


Figure 12 - PEM electrolyzer concept

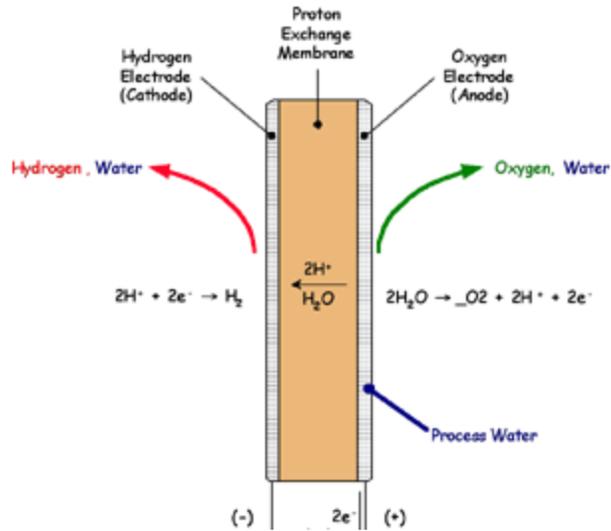


Figure 13 - PEM electrolyzer schematic

### 3.2. Extraction of Materials Used In Fuel Cells

As of now some promising hydrogen fuel cells are made from platinum group metals or PGMs. These cells resist corrosion while successfully catalyzing hydrogen with oxygen to produce energy. The problem with the PGMs is that they come from hard-rock mining and smelting of nickel and copper, which are exceedingly polluting practices that release toxins such as sulfur dioxide into the air. Norilsk Nickel is a mining company that produces PGMs as by-products. They are a leading polluter, and a deal settled on between them and George Bush gives them a major stake in the American as well as the world's hydrogen economy<sup>33</sup>.

However, there are companies that primarily produce platinum group metals. Stillwater Mining Company in Montana is the world's largest PGM producing company, and is also a lot less polluting than Norilsk Nickel. They mine for platinum and palladium and the waste products are far less toxic than those of coal mining companies.

### **3.3. Storage Challenges Faced**

The primary technical issue for on-board storage of hydrogen is storing the quantity of hydrogen required to drive car a minimum of 300 miles, since this is the minimum range that we are accustomed to today. The restrictions on storing hydrogen off-board are far less stringent than for storage in the car itself. The vehicular constraints here include weight, volume, efficiency, safety and cost.

Currently the weight and volume of hydrogen storage systems are much higher than a petroleum storage system for the same range when used in a light-duty vehicle. This is because the volumetric energy efficiency of hydrogen is extremely low (0.01079 MJ/L for gas and 10.1 MJ/L for liquid)<sup>34</sup>. The energy required to get hydrogen in and out of solid state materials on board an automobile is high, which also results in low energy efficiency. Further, the energy associated with compression and liquefaction must be considered when working with compressed and liquid hydrogen technologies. Materials and components are required that allow hydrogen storage systems with a lifetime of 1500 cycles<sup>35</sup>. Refueling times for hydrogen are much longer than desired (about 2-5 minutes), because of the low energy density and high pressure of the hydrogen. The cost of on board hydrogen storage systems is very high when compared with conventional petroleum storage systems. Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and ensure safety and public acceptance, have not been established.

### **3.4. Methods of Storage**

#### **High Pressure Tanks**

Storing hydrogen at pressures high enough to increase volumetric efficiency considerably requires improvements in material design to ensure safety. Carbon-fiber reinforced 5,000 and 10,000 psi tanks for compressed hydrogen are being developed. The inner lining of the tank is a high molecular weight polymer that serves as a hydrogen gas permeation barrier. Over the liner

is a carbon fiber epoxy resin composite shell and constitutes the gas pressure load-bearing component of the tank. Finally, an outer shell is placed on the tank for impact and damage resistance. The pressure regulator for the 10,000-psi tank is located in the interior of the tank. There is also an in-tank gas temperature sensor to monitor the tank temperature during the gas-filling process when tank heating occurs.

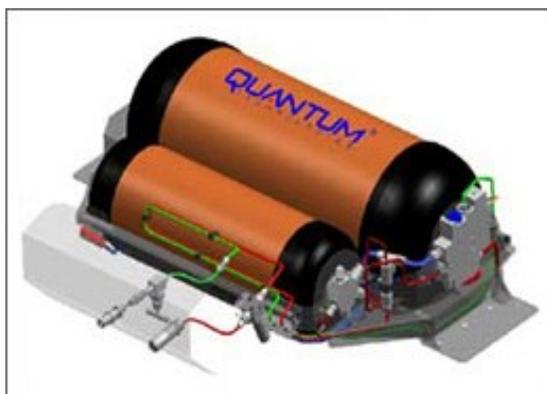


Figure 14 - Compressed hydrogen gas tanks<sup>34</sup>

The cost of the carbon fiber used to line the tank is a big factor in the cost of the overall hydrogen tank. Carbon fiber is used for lightweight structural reinforcement. Low-cost carbon fibers should be secure even with a reduced wall thickness so that a higher volume of hydrogen can be stored. Thus it becomes a challenge to reduce cost and at the same time provide structural integrity.

Methods are being investigated to increase volumetric and gravimetric storage capacities of compressed hydrogen gas tanks. One of these approaches uses the fact that at a fixed pressure and volume, the volumetric capacity of the tank increases as the tank temperature decreases. For example, when a nitrogen tank is cooled from room temperature to liquid nitrogen temperature ( $77^{\circ}\text{K}$ )<sup>36</sup>, the volumetric capacity of the tank increases by a factor of four. However, the volumetric capacity of the system will be less than this due to the increased volume required by the cooling system. These tanks are called cryo-compressed tanks.

Another method involves using conformable tanks, whose structures depend on the location of structural supporting walls. To provide even higher conformability, internal cellular load bearing structures could be developed. The liquid gasoline tanks used today are highly conformable so

they can take maximum advantage out of the space available for storage. This is easier than in liquid hydrogen storage, since pressures are much lower (near atmospheric pressure).

Compressed hydrogen tanks [5000 psi (~35 MPa) and 10,000 psi (~70 MPa)] have already been certified worldwide. Some composite 10,000 psi tanks have shown a safety factor of 2.35 at 23,500 psi burst pressure<sup>36</sup>.

It has already been discussed that the energy density of hydrogen can be improved by storing it as a liquid. However, the issues with LH<sub>2</sub> tanks are hydrogen boil-off, the energy required for hydrogen liquefaction, volume, weight, and tank cost. The energy required to liquefy hydrogen is very high (11kWh/kg of liquid hydrogen<sup>36</sup>) because of the low pressures that have to be generated; usually about 30% of the heat energy stored in the hydrogen is required for liquefaction<sup>36</sup>. Liquid hydrogen (LH<sub>2</sub>) tanks can store more hydrogen in a given volume than compressed gas tanks. The volumetric capacity of liquid hydrogen is 0.070 kg/L, compared to 0.030 kg/L for 10,000-psi gas tanks<sup>36</sup>.

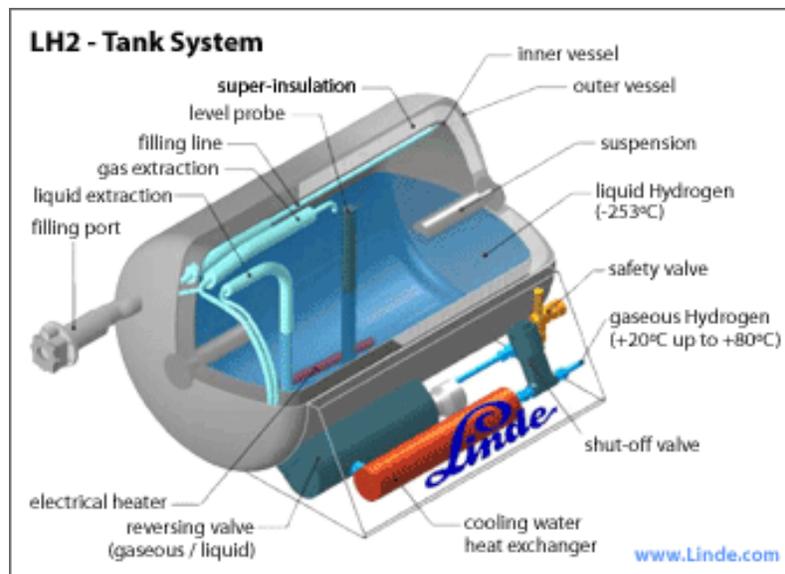


Figure 15 - Liquid hydrogen gas tanks<sup>36</sup>

Hybrid tanks that use both high-pressure gas and cryogenic methods of storage are being investigated. These insulated pressure vessels are both compact than high-pressure vessels and lighter than hydrides. Also, the temperatures required are not as low as they are for liquid

hydrogen, and no energy is required to liquefy the gas. There are less evaporative losses as against liquid tanks as well.

### **Material Based Storage**

There are currently three methods known for storing hydrogen in other materials. One is adsorption, which may be subdivided into physisorption and chemisorption based on the energetics of the adsorption mechanism. Physisorbed hydrogen is more weakly and energetically bound to the material than is chemisorbed hydrogen. Highly porous materials are required by sorptive processes. This is so that the surface area for hydrogen sorption to occur is maximized, and hydrogen can easily be absorbed and released from the material. Another method is absorption of hydrogen directly into the bulk of another material. In this method, atomic hydrogen is absorbed into interstitial sites in the crystallographic lattice structure. The third method involves displacive chemical reactions for both hydrogen generation and hydrogen storage. Sodium alanate-based complex metal hydrides are an example of what can be used. This hydrogen generation reaction is not reversible under normal conditions of temperature and pressure. This implies that the hydrogen can be generated on board the vehicle but cannot be added into the original material on board. This need to be done under controlled conditions off board. Sodium borohydride is an example<sup>37</sup>.

### **Metal Hydride Storage**

This method uses an alloy that can absorb and hold large amounts of hydrogen by bonding with hydrogen and forming hydrides. These alloys are designed to be able to absorb and release hydrogen without any changes in their own composition.

Some alloys (in boldface in the table below) store hydrogen at a higher density than pure hydrogen<sup>38</sup>.

Material	H-atoms per $\text{cm}^3$ ( $\times 10^{22}$ )	% of weight that is hydrogen
H <sub>2</sub> gas, 200 bar (2850 psi)	0.99	100
H <sub>2</sub> liquid, 20 K (-253 C)	4.2	100
H <sub>2</sub> solid, 4.2 K (-269 C)	5.3	100
<b>MgH<sub>2</sub></b>	6.5	7.6
<b>Mg<sub>2</sub>NiH<sub>4</sub></b>	5.9	3.6
<b>FeTiH<sub>2</sub></b>	6.0	1.89
<b>LaNi<sub>5</sub>H<sub>6</sub></b>	5.5	1.37

**Table 11 - Storage densities of hydrogen in some alloys<sup>38</sup>**

These alloys absorb only hydrogen; they absorb large quantities of hydrogen and release it several times without there being any deterioration. The absorption and release rates may be controlled by adjusting the temperature or pressure<sup>39</sup>.

The hydrogen storage alloys in common use occur in four different forms: AB<sub>5</sub> (e.g., LaNi<sub>5</sub>), AB (e.g., FeTi), A<sub>2</sub>B (e.g., Mg<sub>2</sub>Ni) and AB<sub>2</sub> (e.g., ZrV<sub>2</sub>)<sup>40</sup>.

## Characteristics of AB<sub>5</sub> Metal Hydride Alloy

P-C-T diagram (pressure-composition-isotherms)

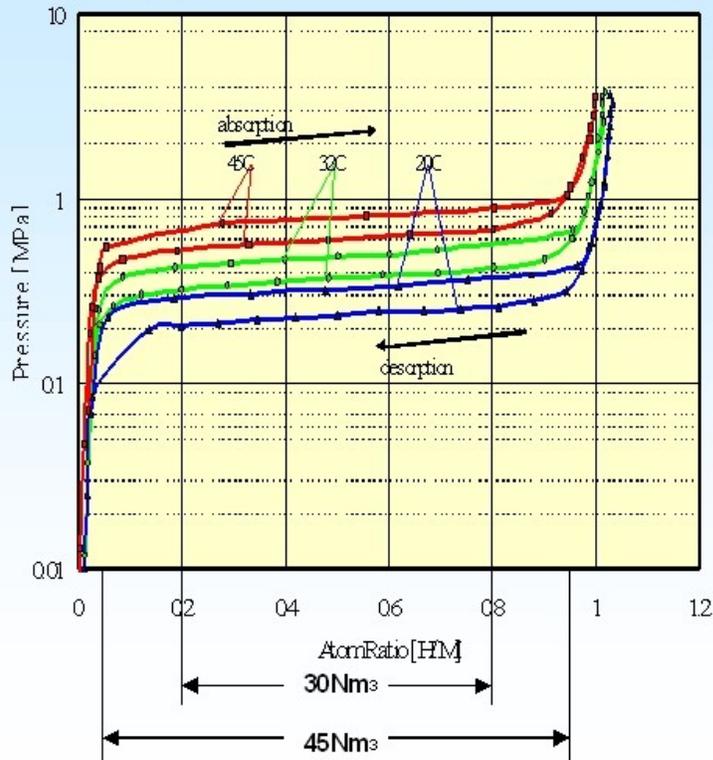


Figure 16 – Characteristics of AB<sub>5</sub> metal hydride alloy<sup>41</sup>

Metal hydrides can store hydrogen on-board and release it at low temperatures and pressures. The optimum pressure – temperature range for fuel cells in vehicles is 1-10 atm and 25-120°C<sup>42</sup>. This is founded on the concept of using the waste heat from the fuel cell to “release” the hydrogen from the media. While the waste heat at less than 80°C is available, as high temperature membranes develop there is a prospect of obtaining waste heat at higher temperatures. While a simple metal hydride which includes hydrogen in its crystal structure, such as LaNi<sub>5</sub>H<sub>6</sub> may function at this range, the disadvantage is that its gravimetric capacity is too low (~1.3 wt.%) and it is more expensive to be used for vehicular applications<sup>42</sup>.

Complex metal hydrides such as alanate (AlH<sub>4</sub>) materials are capable of operating with higher gravimetric hydrogen capacities as opposed to simple metal hydrides. This is due to the

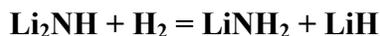
following two step displacive reaction for sodium alanate whereby alanates can store and release hydrogen reversibly if catalyzed with titanium dopants<sup>42</sup>:



The first reaction becomes thermodynamically favorable at a temperature above 33°C and can release 3.7 wt.% hydrogen at 1 atm pressure whereas the second reaction takes place above 110°C and can release 1.8 wt.% hydrogen<sup>42</sup>. The key parameter which is used to determine system (net) gravimetric and volumetric capacities is the amount of hydrogen that a material can release instead of only the amount the material is capable of holding.

Concerns with respect to complex metal hydrides involve low hydrogen capacity, slow uptake and release with kinetics and cost. The maximum material (not system) gravimetric capacity of 5.5 wt.% hydrogen for sodium alanate is below the 2010 DOE system target of 6 wt.%. Thus so far, 4 wt.% reversible hydrogen content with alanate materials is only experimental. Not only are hydrogen release kinetics too slow for vehicular applications but also the packing density of these powders is low (for example, roughly 50%), and the system-level volumetric capacity is a challenge. Thus, while sodium alanates will not meet the 2010 targets, one does hope that their continued study may lead to a strong, intrinsic understanding that can be applied to the design and development of more improved types of complex metal hydrides.

A recent development on a new complex hydride system based on lithium amide shows the following reversible displacive reaction taking place at at 285°C and 1 atm<sup>42</sup>:



In this case the 6.5 wt.% hydrogen can be reversibly stored with potential for 10 wt.%<sup>42</sup>. It is to be noted that the current operating temperature is not in the purview of the vehicular operating window. However, the temperature of this reaction may be lowered to 220°C<sup>42</sup> with magnesium substitution, though at a higher pressure. It is possible that additional research on this system will lead to added improvements in operating conditions with improved capacity.

On a perusal of the issues with complex metal hydride materials it is seen that thermal management during refueling could be a problem, due to the reaction enthalpies involved. Depending on how much hydrogen is stored and how often it is to be refueled, megawatts to half a gigawatt should be handled during recharging on-board vehicular systems with metal hydrides. A demonstration on the reversibility of these and new materials should be done for over thousand cycles.

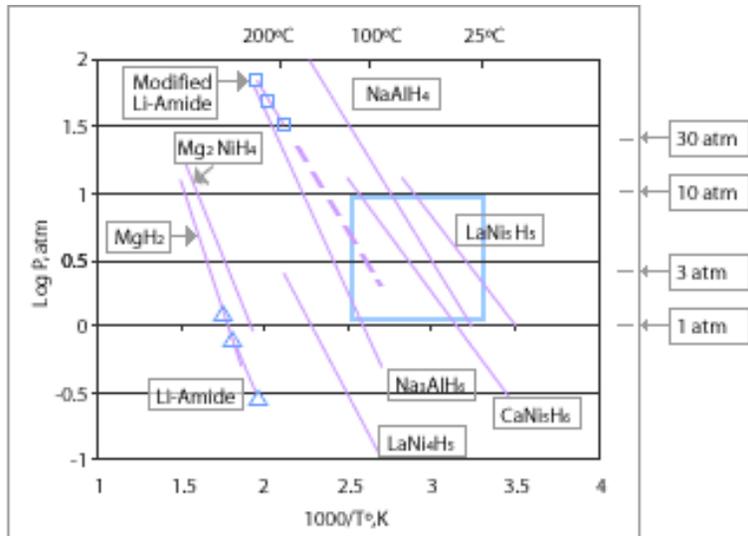


Figure 17 – Log pressure vs. temperature graphs for storage agents<sup>42</sup>

## Metal Hydride Hydrogen Storage and Supply System

### Overall System Concept

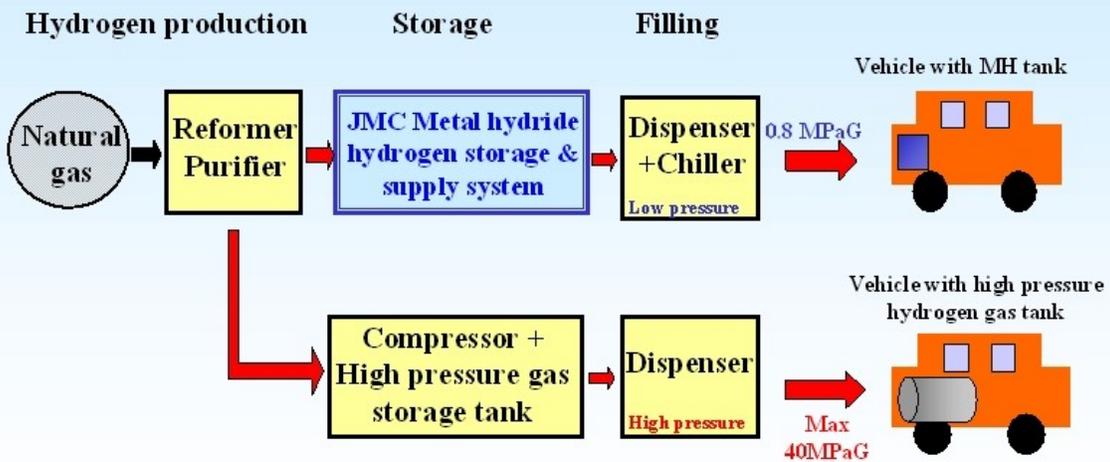
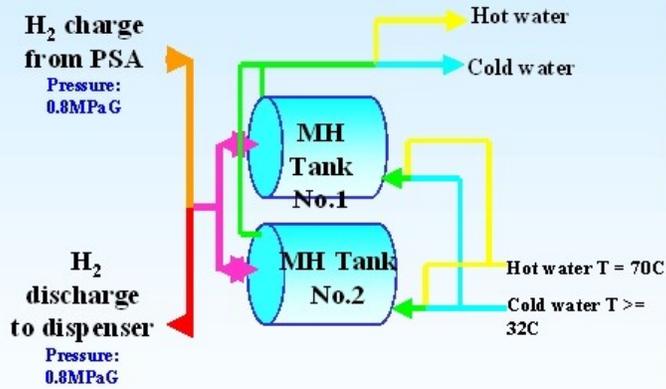


Figure 18 – Example of metal hydride hydrogen storage and supply system<sup>43</sup>

# Metal Hydride Hydrogen Storage and Supply System



## Specifications

Parameters	Specifications
Number of MH tanks	2
Nominal H2 capacity	30 l/m <sup>3</sup> /tank
Max. H2 capacity	45 l/m <sup>3</sup> /tank
MH alloy	AB <sub>5</sub>
MH vessel type	Shell & tube *
System mass MH alloy	325 kg / tank
System mass vessel etc	approx. 600 kg / tank
Charge pressure	0.8 MPaG
Charge H2 flowrate	30 l/m <sup>3</sup> /h
hydrogen purity	Min 99.99 vol.%
hydrogen impurities	CO 10ppm max CO <sub>2</sub> 100ppm max H <sub>2</sub> O 100ppm max
Cold water flow rate	75 L/min.
Discharge Pressure	0.7 - 0.8 MP aG
Discharge H2 flowrate	>=150 l/m <sup>3</sup> /hr (25 l/m <sup>3</sup> /10min.)
Hot water flow rate	approx. 350 L/min.

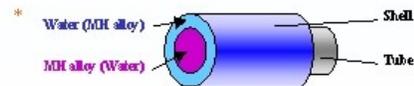
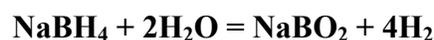


Figure 19 – Example of metal hydride hydrogen storage and supply system (continued)<sup>44</sup>

## Chemical Based Storage

The expression "chemical hydrogen storage" is used to describe the storage technologies in which hydrogen is generated through a chemical reaction. A more common reaction includes chemical hydrides with water or alcohols. Characteristically, these reactions are not reversible easily on-board a vehicle. It is for this reason that the “spent fuel” and/or byproducts are to be removed from the vehicle and regenerated off-board.

In a hydrolysis reaction, there is the oxidation reaction of chemical hydrides with water to produce hydrogen. The most studied of these is the reaction of sodium borohydride which is as follows<sup>45</sup>:



At first, there is a slurry of an inert stabilizing liquid which protects the hydride from contact with moisture and makes the hydride pumpable. On usage, the slurry is mixed with water, and the consequent reaction produces high-purity hydrogen<sup>45</sup>.

This reaction may be controlled in an aqueous medium via pH with the use of a catalyst. When the material hydrogen capacity may be high and the hydrogen release kinetics fast, the borohydride regeneration reaction should take place off-board. Investigation and research with respect to issues such as regeneration energy requirements, cost and impacts on life-cycle are being carried out.

Millennium Cell has reported that their NaBH<sub>4</sub>-based Hydrogen on Demand™ system possesses a system gravimetric capacity of about 4 wt.%<sup>45</sup>. Like other material approaches, concerns include system volume, weight and complexity, and water availability.

Safe Hydrogen is researching on a hydrolysis reaction which is the reaction of MgH<sub>2</sub> with water to form Mg(OH)<sub>2</sub> and H<sub>2</sub>. In this reaction particles of MgH<sub>2</sub> are contained in a non-aqueous slurry to inhibit premature water reactions when hydrogen generation is not required. The material-based capacities for this may be as high as 11 wt.%<sup>45</sup>. But again the Mg(OH)<sub>2</sub> must be regenerated off-board and the water must be carried on-board the vehicle in addition to the slurry, just like in the sodium borohydride approach.

Hydrogenation and dehydrogenation reactions have been studied for many years as a means of hydrogen storage. For example, the decalin-to-naphthalene reaction can release 7.3 wt.% hydrogen at 210°C via the reaction<sup>45</sup>:



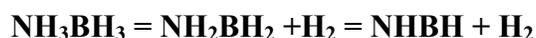
A platinum-based or noble-metal-supported catalyst is necessary to improve the kinetics of hydrogen evolution.

A more recent development by Air Products and Chemicals, Inc. involves a new type of liquid-phase material which shows a 5–7 wt.% gravimetric hydrogen storage capacity and a volumetric capacity greater than 0.050 kg/L hydrogen<sup>45</sup>. Future research aims at lowering the

dehydrogenation temperatures. The advantages of such a system are that, unlike the other chemical hydrogen storage concepts, the dehydrogenation does not require water. Since it is an endothermic reaction the system uses the waste heat from the fuel cell or the internal combustion engine to produce hydrogen on-board. In addition to this, the liquids allow help in easier transport and refueling. There is also no need for heat removal during refueling as regeneration takes place off-board the vehicle. For this reason the replenished liquid must be transported from the hydrogenation plant to the vehicle filling station. Key factors to keep in mind involve off-board generation efficiency and cost.

In order to achieve the 2010 and 2015 hydrogen storage targets new chemical advances are required. An innovative concept of reacting lightweight metal hydrides such as LiH, NaH, and MgH<sub>2</sub> with methanol and ethanol (alcoholysis) has been propounded. These alcoholysis reactions are said to produce controlled and convenient hydrogen production at room temperature and below. Again as in hydrosis reactions, the products in this reaction must be recycled off-board the vehicle. The alcohol should be carried on-board which affects the system-level weight, volume and complexity.

Another new chemical approach may be hydrogen generation from ammonia-borane materials by the following reactions<sup>45</sup>:



In the first reaction, which occurs at less than 120°C, 6.1 wt.% hydrogen is released whereas the second reaction, which occurs at approximately 160°C, releases 6.5 wt.% hydrogen<sup>45</sup>. Latest studies observe that hydrogen-release kinetics and selectivity are improved by incorporating ammonia-borane nanosized particles in a mesoporous scaffold (T. Autrey, Pacific Northwest National Laboratory, "Chemical Hydrogen Storage: Control of H<sub>2</sub> Release From Ammonia Borane," Poster presented at the 2004 DOE Hydrogen Program Review, May 2004, Philadelphia).

Research is being conducted to modify the compositions of these base alloys by alloying with various other elements. These modifications allow them stability during charging and



Ni-MH batteries are commonly used in portable computers, cell phones, power tools and other electronics. They are used in the upcoming hybrid vehicles. These batteries eliminate the need for separate recharging as they both supply energy to, and draw energy from the gas-powered motor.

### **Carbon Based Storage**

This category of materials-based storage technology includes carbon-based materials like carbon nanotubes, aerogels, nanofibers (including metal-doped hybrids) and metal-organic frameworks, conducting polymers and clathrates. The hydrogen storage may be enhanced if these structures may be modified at the nano-scale.

Due to published hydrogen gravimetric capacities in the range of 3–10 weight %<sup>47</sup> at room temperature, single-walled carbon nanotubes are now being considered as hydrogen storage materials. A controversy has arisen with respect to the difficulty in reproducing these results. Thus the current research is more focused on ascertaining reproducibility. Results at NREL have shown that while no hydrogen storage was observed in pure single-walled carbon nanotubes, roughly 3 weight %<sup>47</sup> was measured in metal-doped nanotubes at room temperature, as is shown in the graph below.

The room temperature gravimetric capacity measured in carbon nanotubes is below the 2010 system target of 6.0 weight %<sup>47</sup>, and further improvements must be made. Furthermore to make single-walled carbon nanotubes more economically sustainable in vehicular applications, a low-cost, high-volume manufacture process must be developed. The DOE Hydrogen Program has a go/no-go decision point planned on carbon nanotubes at the end of FY2006 which is based on a reproducibly demonstrated material hydrogen storage gravimetric capacity of 6 weight %<sup>47</sup> at room temperature.

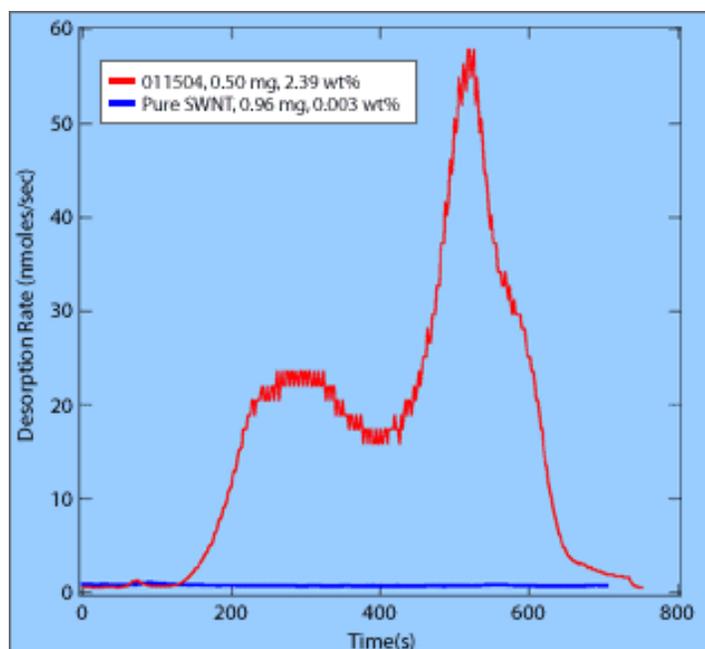
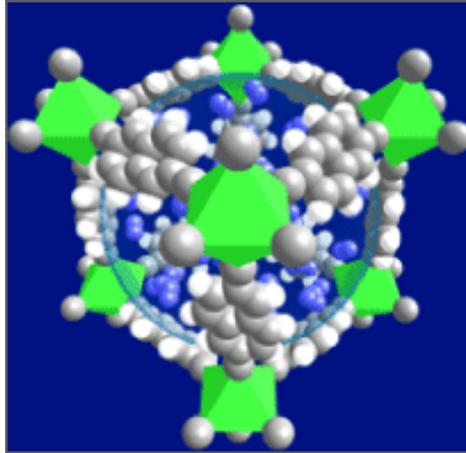


Figure 20 – Hydrogen desorption rate vs. time<sup>47</sup>

There is an urgent need for the discovery and investigation of new reversible materials. A promising area which may be tapped is that of high-surface area hydrogen sorbents which are based on microporous metal-organic frameworks (MOFs). These are synthetic, crystalline and microporous and are also composed of metal/oxide groups linked by organic struts. The hydrogen storage capacity at 78K (-195°C)<sup>47</sup> has been observed to be as high as 4 weight % through an adsorptive mechanism with a room temperature capacity of approximately 1 weight %<sup>47</sup>. Yet, due to the highly porous nature of these materials there may be a concern with respect to volumetric capacity.

An added class of materials for hydrogen storage may include clathrates, which are primarily hydrogen-bonded H<sub>2</sub>O frameworks. Investigations show that a considerable amount of hydrogen molecules may be incorporated into the clathrate. These are particularly feasible for off-board storage of hydrogen without the need for high pressure or liquid hydrogen tanks.

Other examples of new materials and concepts are conducting polymers. By applying new processes such as sonochemistry, one may create unique, nano-structures with enhanced properties for hydrogen storage.



Source: University of Michigan

Figure 21 – H<sub>2</sub> storage nano-structure<sup>47</sup>

### 3.5. Current Status and Technologies

The current status in terms of weight, volume, and cost of various hydrogen storage technologies is shown below. These values are estimates from storage system developers and the R&D community and will be continuously updated by DOE as new technological advancements take place.

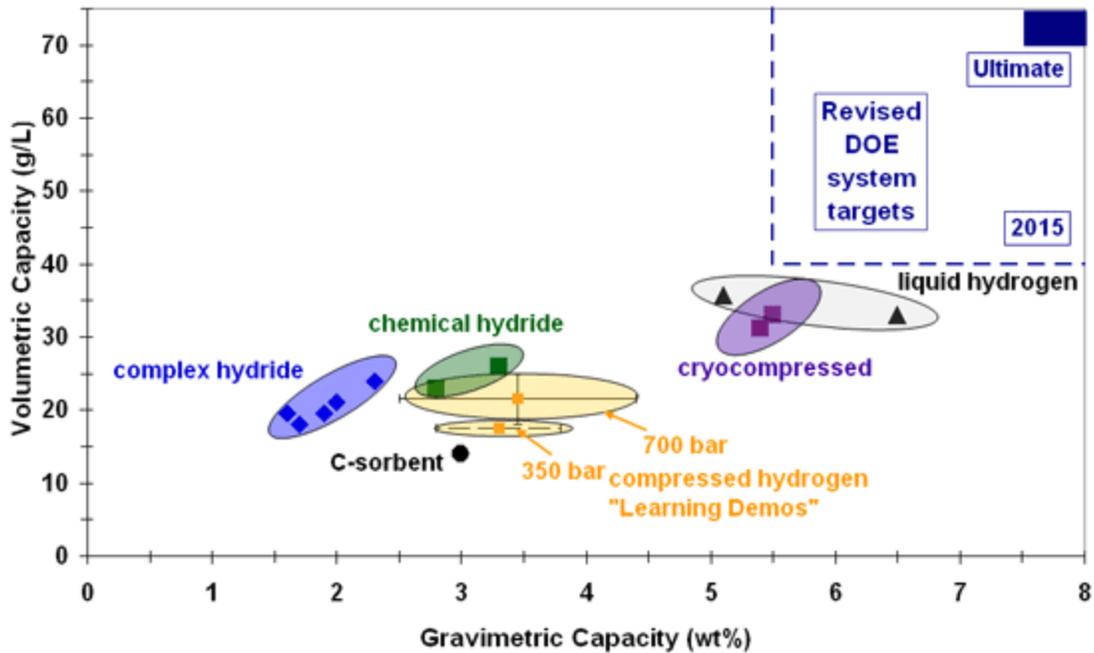


Figure 22 – Volumetric vs. gravimetric storage capacities of storage agents<sup>48</sup>

### 3.6. Society Response

The purpose of this investigation is to explore the possibility of using hydrogen as an alternative fuel. If Hydrogen does not offer the convenience that gasoline does for everyday transport, it will fail to successfully replace gasoline used today. Some of these conveniences include cheap running costs, and quick and safe refueling. If it can do so, utilization of hydrogen in vehicles is surely to become popular among the masses. It also has the added advantage of producing a smaller mass of pollutants per mile driven when compared to gasoline.

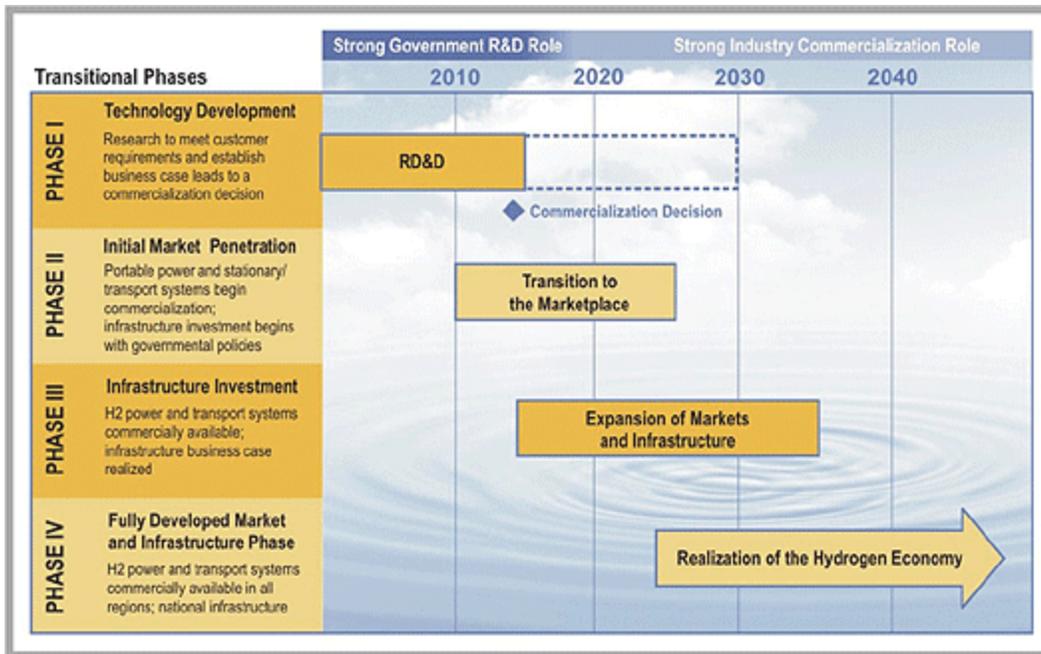


Figure 23 - Predicting the future of the hydrogen economy<sup>49</sup>

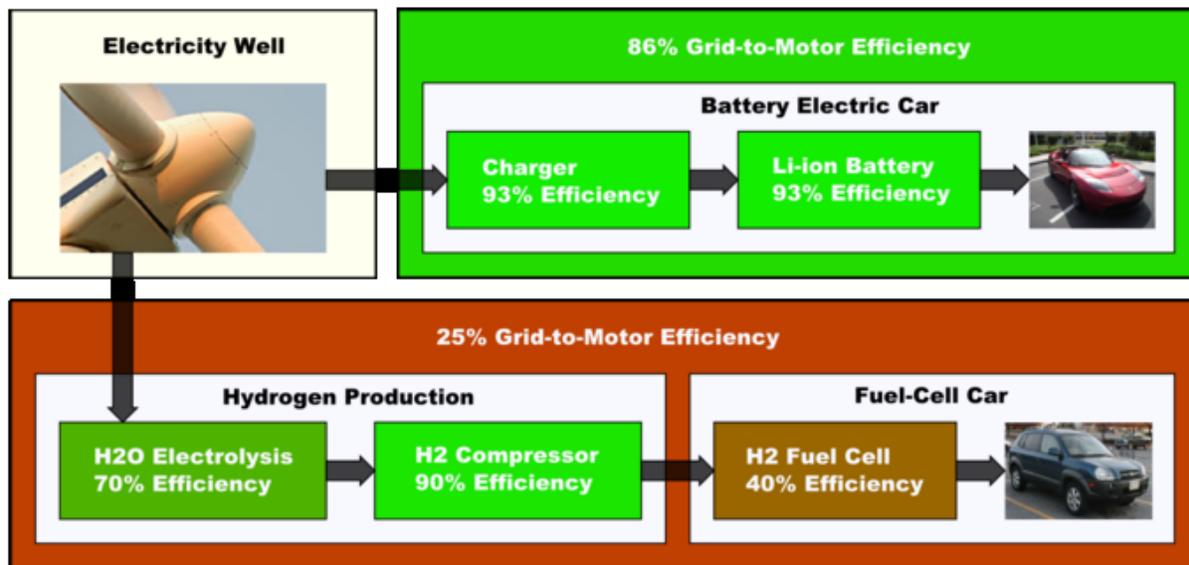


Figure 24 - Efficiencies of hydrogen generation in various applications<sup>3</sup>

## **4. Hydrogen Plant Analysis**

Having performed analyses that attempt to weigh the economic benefits of using conventional fossil fuels against the environmental benefits of using the alternative fuels listed earlier, it would be appropriate to perform a cost investigation of setting up and running a large scale plant that mass-produces an alternative fuel. The fuel produced will be hydrogen, since the high cost of hydrogen for the consumer is a major issue with mass producing and selling hydrogen ready for use in automobiles. This analysis will provide a better idea of what the chief costs are in producing hydrogen on a large scale, and suggest how these areas may be worked around in order to reduce the cost of commercially available liquid hydrogen. Since the environmental benefits of widespread use of hydrogen in vehicles are significant as shown earlier in the report, it is worth thoroughly investigating cost-cutting methods in the production and selling of hydrogen.

In order to ensure that the environment is affected in the least harmful way possible, the electrical energy required by the factory will be obtained from solar panels. Thus the factory is self-sustaining, and only depends on renewable solar energy for sustenance.

### **4.1. Extraction and Storage Methods Used**

Currently electrolysis is the most practical method of producing hydrogen on a large scale without the use of fossil fuels. Multiple electrolysis methods are constantly being analyzed, most of which will be combined with a solar electricity source to further reduce damage to the environment. Water electrolysis is expected to be the primary source of hydrogen in the near future. A conventional alkaline electrolyzer is the most economical one to produce hydrogen gas at the lowest values of the electrical current and voltage. Alkaline & Polymer Membrane are the types of fuel cells that generate a higher value of electrical energy than the others.

A typical solar hydrogen system is composed of a photovoltaic generator, a battery set, an electrolyzer, a metal-hydride system for hydrogen storage and a fuel cell. Electrolyzers can produce hydrogen at around 30 bar, enough to feed directly the metal hydrides, avoiding

pressurization steps. Metal hydrides work under pressure control in the temperature range 0–40 °C<sup>50</sup>. Kinetics of absorption–desorption of hydrogen is observed as an important limiting aspect for this kind of storage. Most systems are able to convert about 4–9%<sup>50</sup> of total solar energy irradiated in 1 year.

## 4.2. Target

Initially a production goal will be set for the factory so that the size of the plant required is known. Later on a sensitivity analysis can be performed to analyze the effect of varying major cost contributors on the number of years taken for the investment to break even. The larger the plant, the lower the potential cost per unit volume of hydrogen for the consumer. The hydrogen produced will be used as a replacement for gasoline in a modified version of the conventional internal combustion engine. The study does not assume the use of hydrogen in a fuel cell.

The weight goal for liquid hydrogen will be set at an average of 10 tons/day, or a volumetric goal of 37,217gal/day. The location of the plant is chosen as Parker, Arizona (AZ 85344), for its high average levels of sunlight round the year. Additionally, there exist vast open flat desert areas which are ideal for the installation of solar panels. The area is also well connected by road since there are major towns close by.

The solar energy available in the chosen area as a yearly average is 6.58kWh/m<sup>2</sup>/day<sup>51</sup>. Since this is a yearly average and values vary drastically over summer and winter months, it is assumed that the solar cells are operational during all sunlight hours of the day, regardless of the practicality of this assumption during summer. Thus, every day the factory will utilize all the electrical energy that can be produced by the solar cells during hours of sunlight, in order to manufacture hydrogen. This results in an average daily production target of 10,000kg/day of liquid hydrogen, although these values fluctuate hugely on a day-to-day basis.



Figure 25 - Undeveloped land in western Arizona<sup>52</sup>

### 4.3. Structure of the hydrogen plant

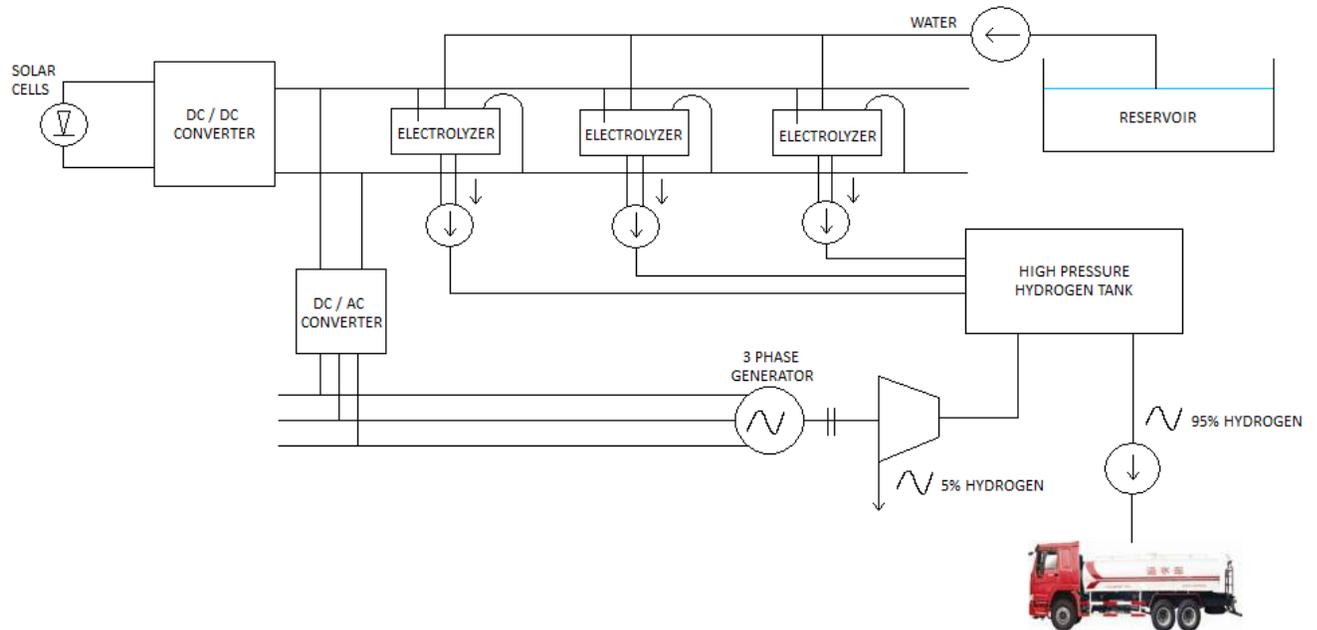


Figure 26 - Factory Schematic

The schematic in Figure 26 shows the proposed structure of the Hydrogen plant. The solar panels along with the DC to DC converter provide a constant DC voltage supply to the electrolyzers. The overall efficiency of the solar cells is 7.3% as mentioned earlier. A constant supply of pure water is fed to the electrolyzers from a tank after passing the water through a distiller. The gaseous hydrogen produced is then cooled, liquefied, and compressed to around 5,000psi and stored in high capacity hydrogen tanks.

95% of this hydrogen is sold and transported to various places to be used as fuel for vehicles. The remaining 5% of the hydrogen produced is fed into a turbine which powers a 3 phase generator that generates AC voltage. This is converted back into DC voltage using an AC to DC converter. The DC voltage helps power the electrolyzers.

### **Water Pump**

Since 1 liter of pure water yields 111.11 grams of hydrogen<sup>53</sup>, the factory requires 90,000 liters of pure water supplied per day or 9,000 liters/hr. The total investment in an industrial pump in order to provide this flow rate is \$50,000. The pump consumes 410kWh/day of electricity. It is assumed that there is a water source nearby, or that the cost of buying and operating the pump is replaced by the cost of transporting 90,000 liters of water to the factory location every day.

### **Electrolyzers**

Before the electrolysis takes place, a water distiller and deionizer are also required to purify the water coming from the reservoir. The volume of water purified is 10 liters/hr, and consumes 50W of power. The cost of 1 unit is \$5,500<sup>32</sup>. This implies a total investment of \$5 million for the distillers and deionizers. The power consumed is 0.5kWh/day.

From section 2.2 of this report, 1.75kWh/liter or 6.625kWh/gal is required to electrolyze, compress and store hydrogen. For 37,217gal/day, this corresponds to a total energy requirement of 246.5MWh/day. The efficiency of the photovoltaic process when producing electricity is assumed to be 7.3% of the total solar energy incident on the cells.

Most electrolyzers today generate hydrogen at relatively low pressures ( $\sim 200$ psi)<sup>54</sup>, and thus the hydrogen produced requires energy-intensive cooling and mechanical compression, which

decreases the overall efficiency of the production process. They also require high maintenance and regular replacement of components.

Another possible candidate for the electrolyzers is the “HGenerator” hydrogen gas generator. These convert distilled deionized water into hydrogen gas by using solid polymer electrolytes (SPE)<sup>55</sup>. The HGenerator releases hydrogen at relatively low pressures, and can be used as a hydrogen container replacement in many places.

Adjustable Rates / Model	H2O consumed ml/hour	kWh consumed per hour	H2 gas produced ml/min	H2 gas produced liters/hour	H2 gas produced cubic meters/hour	H2 gas produced kgs/hour	Megajoules produced/hour	H2 gas cost per Megajoules @ \$0.09/kWh	H2 gas cost per 30,000 liter gas hydrogen tank @ \$0.09/kWh	Affordable Price:
HG-50	41667	215	833333	50000	50	4.48	636.16	\$0.03	\$11.61	\$1.49M
HG-150	125000	645	2500000	150000	150	13.44	1908.48	\$0.03	\$11.61	\$1.89M
HG-300	250000	1290	5000000	300000	300	26.88	3816.96	\$0.03	\$11.61	\$2.49M
HG-400	314167	1621	6283333	377000	400	33.7792	4796.6464	\$0.03	\$11.61	\$3.24M
HG-500	404167	2086	8083333	485000	500	43.456	6170.752	\$0.03	\$11.61	\$3.99M

Table 12 - Available high capacity hydrogen generators<sup>32</sup>

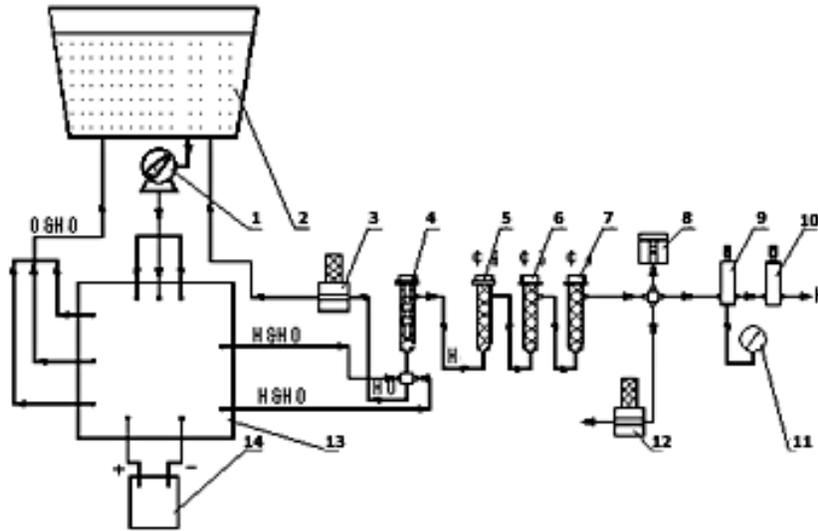
It consists of an SPE electrochemical cell, water tank, hydrogen/water separator, desiccant cartridge, sensor, digital display, control circuit board, main and supplementary constant current devices and a safety valve. The cell uses a perfluorinated membrane as the electrolyte. When the device is running, the pure water is electrolyzed to deposit hydrogen on the cell’s cathode and oxygen on the anode. The hydrogen and water are separated and oxygen is vented to the atmosphere. The hydrogen then passes through a desiccant cartridge which purifies it to greater than 99.99% purity and dries it. The pressure and flow of the hydrogen are regulated by a control circuit. The outflow pressure of the generator is 58psi (adjustable), and the voltage required is 220V 50-60Hz dual AC or 32-36V 25A DC. The current cost of a 43.5kg/hr HGenerator is \$4 million<sup>32</sup>. This is equivalent to 6171MJ/hour energy capacity or 485,000 liters/hour.



Figure 27 - Water distiller and deionizer

If the factory operates for an average of 10 hours per day through the year, the electrolyzers have 10 hours to extract 10 tons of hydrogen per day, or 1,000kg/hour. Since the electrolyzers yield

43.5kg/hr each, 23 of them are needed to fulfill this hydrogen requirement. Including 2 backup electrolyzers, this requires a total investment of \$100 million. The power consumed by the electrolyzers in order to function is 9kWh/unit/day, or 225kWh/day as a maximum for all the units combined.



No.	Item	No.	Item
1	Water Motor	8	Safety Valve
2	Water Tank	9	Pressure Regulator
3	Drain Valve	10	Flow Regulator
4	Hydrogen/Water Separator	11	Pressure Display
5	Desiccant Cartridge I	12	Solenoid Valve
6	Desiccant Cartridge II	13	Electrochemical Cell Combination
7	Desiccant Cartridge III	14	Power

Figure 28 - Schematic of the HGenerator<sup>55</sup>

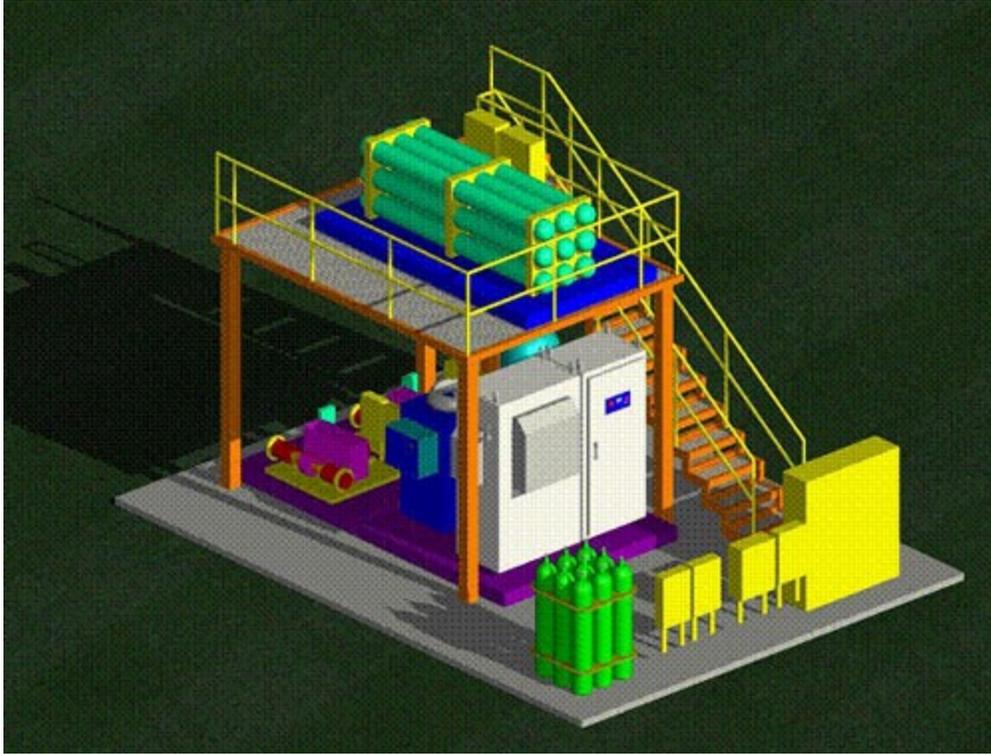


Figure 29 - Hydrogen gas-from-water electrolyzer, storage and dispenser: complete system<sup>32</sup>

### Compressors

The next step after obtaining pure and dry hydrogen is its compression to 5,000psi to allow for high pressure pipeline delivery. This is an energy intensive process that along with electrolysis requires 1.75kWh/liter of liquid hydrogen.

The compressor used is a single 6 throw compressor and has a maximum power output of 6.2MW. It compresses the hydrogen up to 5,000psi and is capable of compressing 1,000kg/hour of hydrogen, so the factory requires just one functional compressor and one backup compressor. The cost of each fully installed compressor is \$13.5 million, which includes foundations, piping, coolers, controls, electricals and other minor components and installation costs. The annual maintenance cost of one of these compressors is estimated at \$100,000.

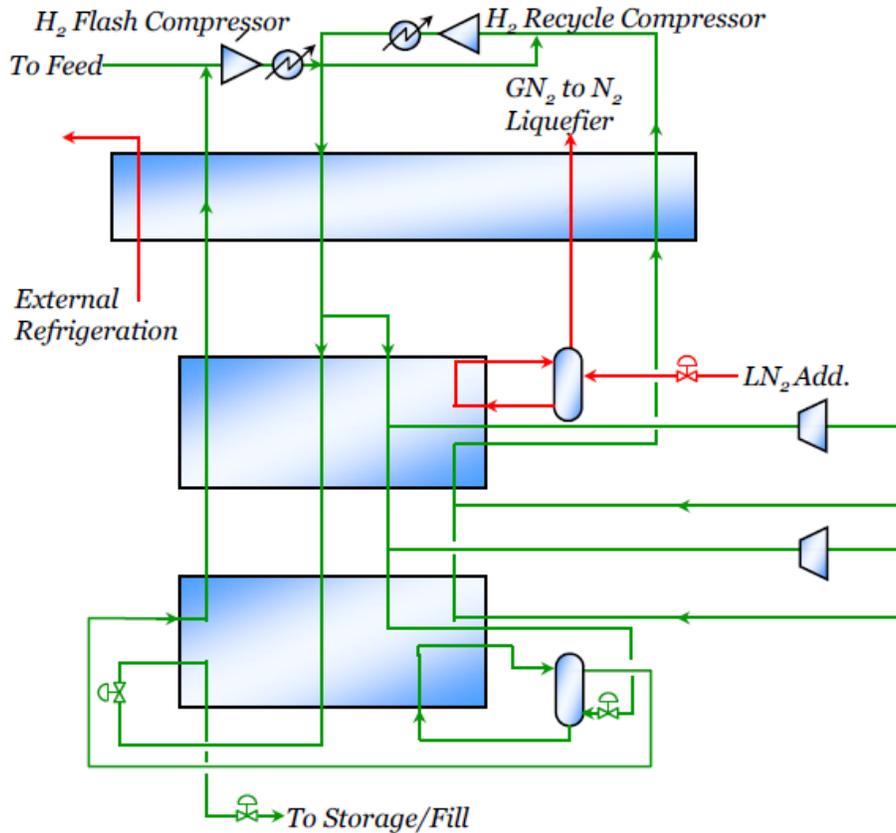


Figure 30 - Hydrogen compression process<sup>55</sup>

### 3 Phase Generator And Converters

The cost of the 3 phase generator setup that is powered by 5% of the produced hydrogen is about \$15,000. The cost of the required DC/DC and AC/DC converters is \$30,000.

### Boilers

The factory will also be capable of drawing electricity from the grid in case of an emergency when the input from the solar cells is low for long periods of time. In addition, boilers will be used to store any surplus energy produced that cannot be used by the plant immediately. This energy can then be used at a later date when required. Boilers are a cheaper and more environment-friendly energy storage option in comparison to batteries. \$30 million will be invested in the boilers, and about \$2 million/year is contributed towards their maintenance. Additionally, another pump will be required to supply water to the boiler. Another advantage of

boilers over batteries is that their life is not limited to 1,200 charge and discharge cycles<sup>56</sup> and so they do not need replacement every 3-5 years. Also, boilers exhibit up to 90% efficiency when reproducing stored energy.

### Photovoltaic Panels

The solar energy incident on photovoltaic cells in the selected region as a daily average round the year is  $6.58\text{kWh/m}^2/\text{day}$ <sup>51</sup>. Assuming an efficiency of 7.3%, they are able to produce  $0.48\text{kWh/m}^2$  of useable electrical energy every day. The total operating energy required by the factory including the energy requirements of all the components described is  $247\text{MWh}/\text{day}$ . To account for energy losses and to provide the extra power to be directed back to the electrolyzers to contribute to the electrolysis of water, the energy requirement to be satisfied by the solar cells will be rounded up to  $300\text{MWh}/\text{day}$ .

Since the objective is to supply all this energy using solar cells, it is now possible to estimate the area of solar cells required to supply enough energy to operate the factory independent of external energy sources. The area of photovoltaic cells required in the specified location is  $625,542\text{m}^2$  or 155 acres. The cost of installing this area of solar panels is \$425 million<sup>51</sup>. This includes a federal income tax rate of 28% and a state income tax rate of 4.5%. It also includes an Arizona tax credit and federal tax credit of 30%. 60% of the final cost of the solar panel setup is contributed towards the actual panels themselves. 10% of the remaining cost of the setup is contributed towards the inverter, 15% towards other parts such as wires, racking and safety shutoffs, and 15% towards installation labor.

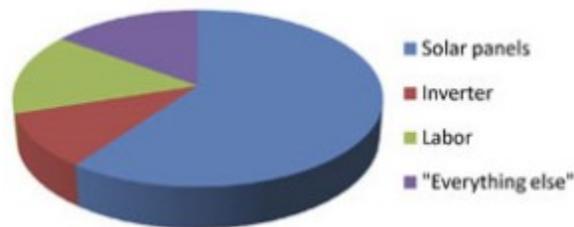


Figure 31 - Breakup of solar panel installation cost<sup>57</sup>

The cost of land in this area is approximately \$2,000/acre, leading to a total cost of \$310,000 to acquire the land for installation of the solar panels. If the land required for construction of the

factory is 25 acres, the total area of land needed is 180 acres. This costs \$360,000 at the selected location.

Solar panels are prone to high maintenance, for example panels getting dirty, cracked or corroded electrical connectors and panels, short circuits, natural interferences and worn out or broken inverters.

### Hydrogen Storage Tanks

The hydrogen storage tanks required by the factory should be capable of storing up to 30 tons of liquid hydrogen, which is the weight of hydrogen produced in 3 days. The hydrogen storage tanks selected should be capable of storing hydrogen at up to 5,000 psi. Since hydrogen has a low density at room temperature, it can easily seep through small fissures in the tank, which results in tanks that cost about \$600/kg of stored hydrogen<sup>58</sup>. About \$20 million is spent on the high capacity hydrogen tanks, and they require about \$1 million worth of maintenance annually.



Figure 32 - 5,000psi hydrogen storage tanks<sup>58</sup>



Figure 33 - 5,000psi hydrogen transportation<sup>58</sup>

The produced liquid hydrogen at 5,000psi is then transported to gas stations in tanks as shown in Figure 32 and Figure 33. At this pressure, the hydrogen weighs 0.024kg/liter<sup>58</sup>. This leads to a total weight of 800kg of hydrogen transported per truck. Therefore 13 trucks are required for every 10,000kg of liquid hydrogen produced, assuming each truck takes 5 hours to deliver hydrogen to a gas station and return to the factory.

#### 4.4. Capital investment and major ongoing costs

The total initial investment in the factory is \$627 million and includes the cost of the pumps, distillers, electrolyzers, compressors, phase generators, converters, boilers, solar panels, cost of the land and \$20 million for construction related expenditures.

Since solar energy is a renewable and free source of energy, the chief ongoing cost is maintenance of the equipment in the factory and electricity costs, if any. The components requiring high maintenance are the electrolyzers, compressors, boilers and solar panels. The total annual maintenance cost of equipment in the factory is estimated at \$30 million.

The current price of hydrogen available in gas stations is \$9.45/gallon<sup>59</sup>. Since distribution & marketing and federal and state taxes make up about 80% of this cost<sup>4</sup>, the supplier of crude oil receives \$7.50/gallon. This implies a daily income of \$281,360 assuming 10,000kg of hydrogen is produced and sold every day. This equates to a monthly income of \$8.44 million, and \$102.696 million annually.

The entire capital investment of \$627 million is assumed to be loaned from a bank at 5.5% annual interest and no down payment. Since maintenance costs are \$2.5 million/month, \$6 million/month is available to contribute towards paying back the loan. Thus the loan can be returned over a period of 12 years or 144 months<sup>60</sup>. A pay back chart is shown in Figure 34.

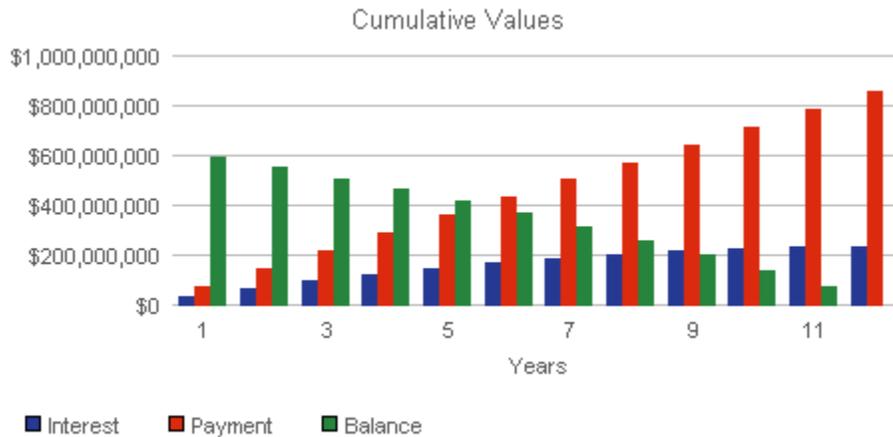


Figure 34 - Cumulative values for loan return<sup>60</sup>

12 years appears to be a reasonably short period of time, but this assumes a very high price of hydrogen. From Table 9, the fuel efficiency of hydrogen is only 5.35 miles/gallon since its energy density is extremely low at 2.81kWh/liter. From Table 1, the effective running cost of using this environment friendly fuel is \$1.77/mile as compared to a maximum of \$0.11/mile for conventional gasoline. Also, it cannot be ascertained that all the hydrogen produced by the plant will be sold and utilized as it is produced. However, this is assumed for the purpose of analysis.

#### **4.5. Sensitivity Analyses**

At this stage it is appropriate to perform sensitivity analyses where the annual earnings, loan return period, and profit in 25 years are monitored based on changing various factors such as, among others, the price of hydrogen for the consumer and efficiency of the solar cells when producing electricity. All other major contributing factors are kept constant at their originally assumed value during each analysis. The annual earnings is the total income earned by the company during the entire year before any reductions or payments. The break even period marks the point in time at which the loan taken to initiate the project is completely returned with interest. The profit in 25 years is the profit earned 25 years after hydrogen manufacturing was begun by the factory. The results from the initial investigation are tabulated in bold in all tables in this section.

##### **Varying Cost of H<sub>2</sub> for the Consumer**

The cost at which the produced liquid hydrogen is sold to the consumer is of vital importance to the overall cost analysis of the factory, as it ultimately determines the annual income from the project. 80% of the selling price of hydrogen sold at gas stations is received by the manufacturer of hydrogen<sup>4</sup>. The current price of hydrogen that can be bought at filling stations is \$9.45/gallon<sup>59</sup>. This implies that hydrogen is sold to the filling station at \$7.50/gallon. At this price, the investment in the hydrogen factory would break even in 12 years as discussed in section 5.5. The profit earned after 25 years of opening the factory is close to a billion dollars as shown in Table 11. The analysis is also performed when the liquid hydrogen is priced at current

high, low and average gasoline prices in the USA. These are \$2.68/gallon (low), \$2.86/gallon (average), and \$3.56/gallon (high)<sup>61</sup>. In all these cases an overall loss is incurred since the annual earnings are not even sufficient to cover the interest on the loan.

If the consumer buys liquid hydrogen for \$6/gallon, the investment will break even in 42 years. Even this price is more than twice the national average of the price of gasoline, and so it is still neither practical from the consumer's point of view nor from the company's. On the other hand, if the consumer buys liquid hydrogen at \$12.5/gallon, the break even period for the investment drops to 7.2 years, and the profit in 25 years leaps to almost 2 billion dollars. This is obviously a lucrative investment from the manufacturer's point of view, but results in an exorbitantly high price for the consumer.

<b>\$/gallon of H<sub>2</sub></b>	<b>Annual Earnings (\$ million)</b>	<b>Break Even Period (years)</b>	<b>Profit in 25 Years (\$ million)</b>
2.68	29	-	-
2.86	31	-	-
3.56	39	-	-
6	65	42	-
9.45	103	12	945
12.5	136	7.2	1887

Table 13 - Effect of varying prices of H<sub>2</sub>

Figure 35 shows the linear relationship between annual earnings and price of gasoline for the consumer.

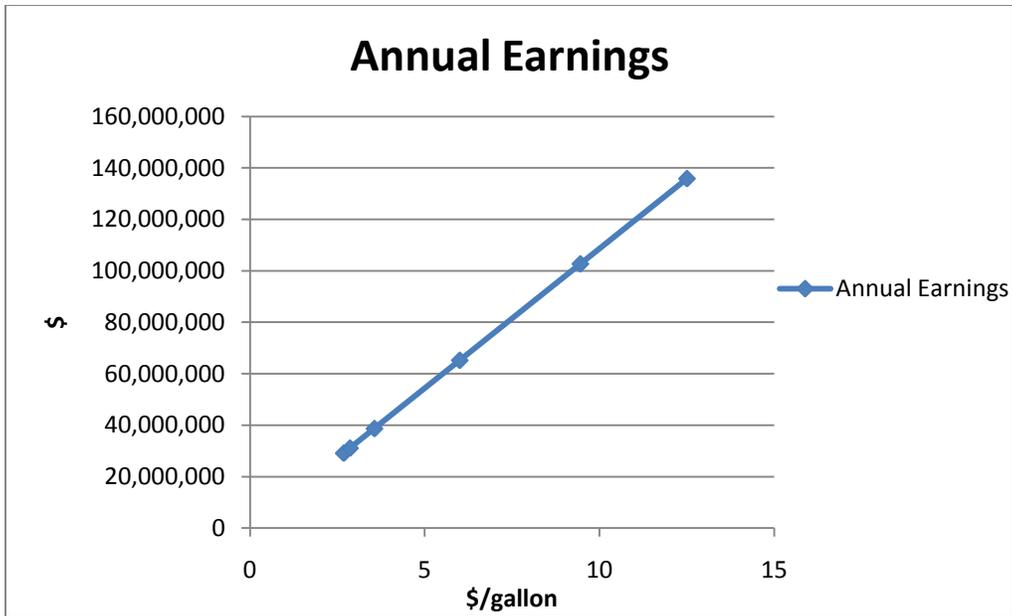


Figure 35 - Chart showing annual earnings vs price of hydrogen

### Varying Quantity of H<sub>2</sub> Produced Daily

As is seen in Figure 36, there is a fairly linear relationship between the weight of hydrogen produced per day, and the earnings per year and as a result the profits after 25 years. This is because the initial costs and other ongoing costs are directly proportional to the quantity of hydrogen that is desired per hour as output from the factory.

Table 13 - Effect of varying prices of H<sub>2</sub> shows the values that display a linear relationship with the weight of hydrogen produced.

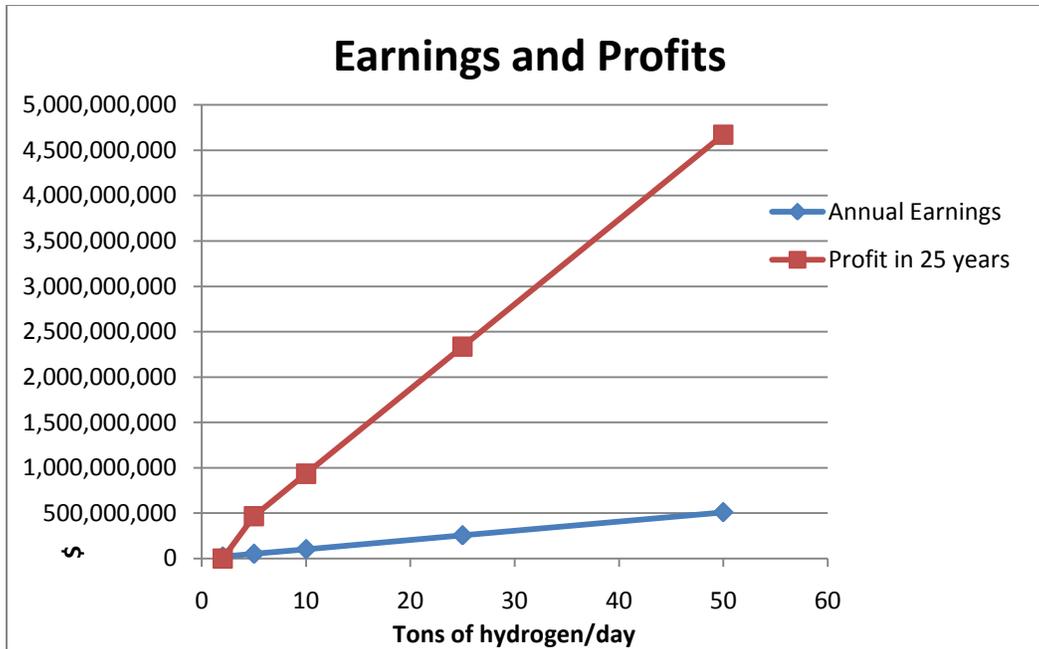


Figure 36 - Chart showing earnings and profits based on varied factory output

Tons/day of H <sub>2</sub>	Annual Earnings (\$ million)	Profit in 25 Years (\$ million)
2	20	-
5	51	467
10	102	934
25	255	2336
50	509	4672

Table 14 - Effect of varying factory output quantity

### Varying Efficiency of the Solar Electricity Generation Process

It is obvious that the area and consequently the cost of the solar panels required will reduce if the efficiency of the electricity generation process is improved. The reduction in panel area required reduces sharply as efficiency is increased, and then tends to level out at higher efficiencies. It is the opposite in the case of 25 year profits, where the profits increase sharply as efficiency increases, and then tend to level out. This is shown in Figure 37. Figure 38 shows a similar relation as the cost of panels. Therefore it can be inferred that low efficiencies need to be avoided as far

as possible, since high efficiency is a major contributing factor towards lowering the break even period. A shorter break even period implies less interest paid on the same loan amount.

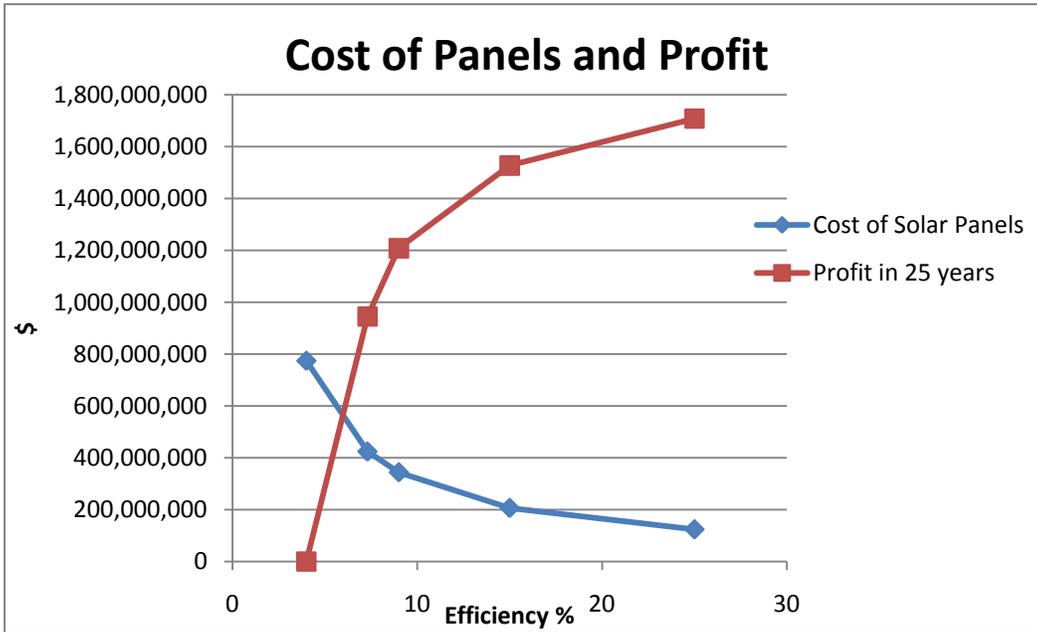


Figure 37 - Chart showing cost of solar panels and profits based on varied solar cell efficiencies

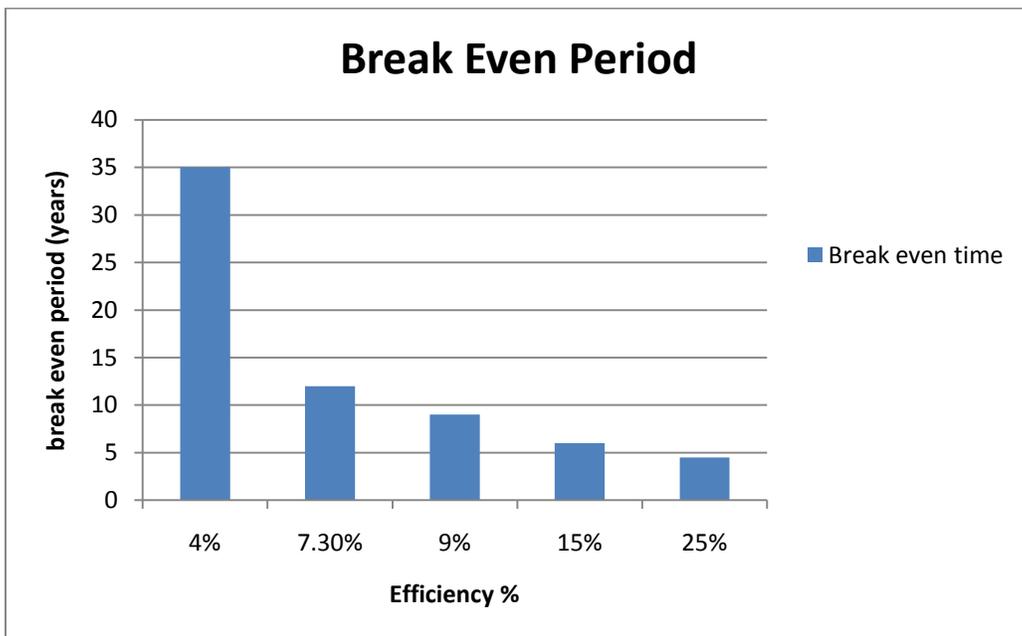


Figure 38 - Break even period vs solar panel efficiency

<b>Panel Efficiency (%)</b>	<b>Area of panels (thousand m<sup>2</sup>)</b>	<b>Break even period (years)</b>
4	1140	35
7.3	624	12
9	506	9
15	304	6
25	182	4.5

**Table 15 - Effect of varying efficiency of solar electricity generation**

### **Varying Location of Solar Panels**

As was seen with the efficiency analysis, improving the process of generating electricity from sunlight seems to be the most important factor towards reducing liquid hydrogen costs for the consumer. A drastic reduction in required solar panel area is observed when a location with high sunlight levels is chosen, as is shown in Figure 39. Places towards the north such as Seattle, WA, and Boston, MA have low levels of sunlight and require almost twice the area of solar panels as the chosen location (Parker, AZ) does. Regions of moderate sunlight such as Miami, FL and Sacramento, CA lead to a far more practical break even period. The break even time is 40 years for areas of low sunlight as shown in Table 15, and as low as 12 years in regions of high sunlight.

Theoretically, if there was a place that received 8 kWh/m<sup>2</sup> of sunlight every day, the break even period at this location would reduce to 10.5 years. It should be noted that although it might be impossible to set up a factory 180 acres in area at many of these locations, they are mentioned here for the purpose of analysis and understanding the importance of choosing a location with high sunlight levels.

Location	Incident Sunlight (kWh/m <sup>2</sup> )	Break Even Period
Seattle, WA	3.64	40
Boston, MA	4.16	34
Miami, FL	5.24	21
Sacramento, CA	5.55	19
Parker, AZ	6.58	12
(High Value)	8	10.5

Table 16 - Effect of different locations on break even period

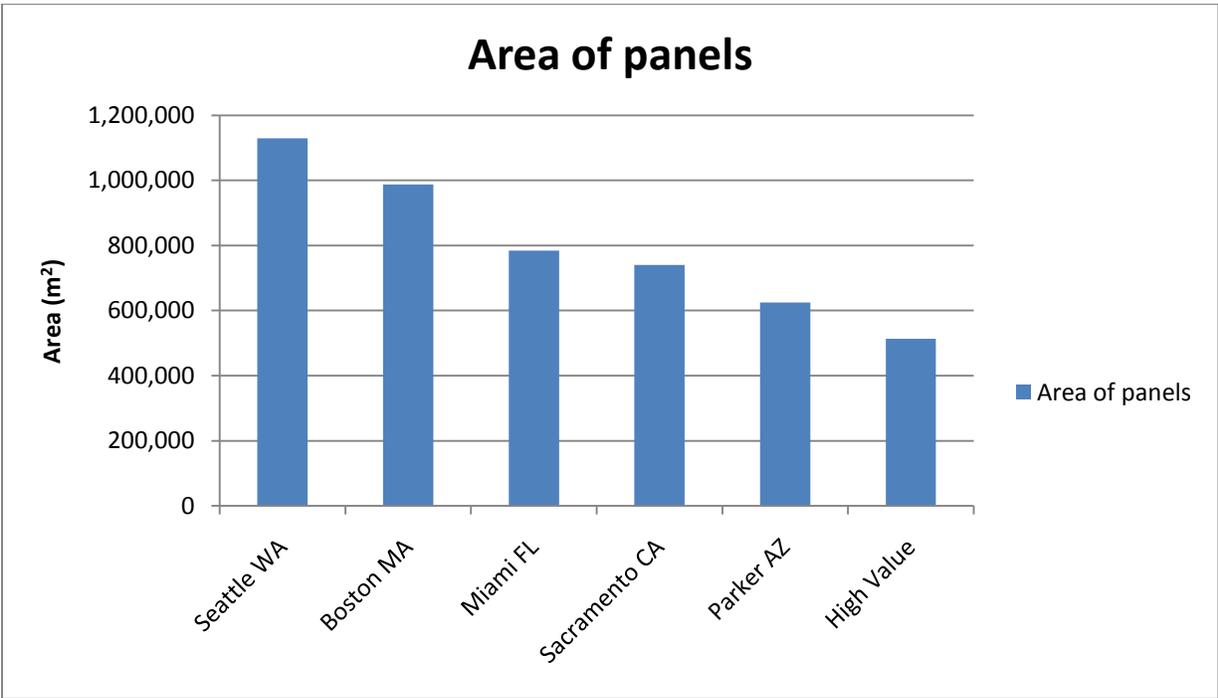


Figure 39 - Area of panels at different locations in the USA

Figure 40 helps to visualize how the incident solar energy at a location and the resulting break even period are inversely related.

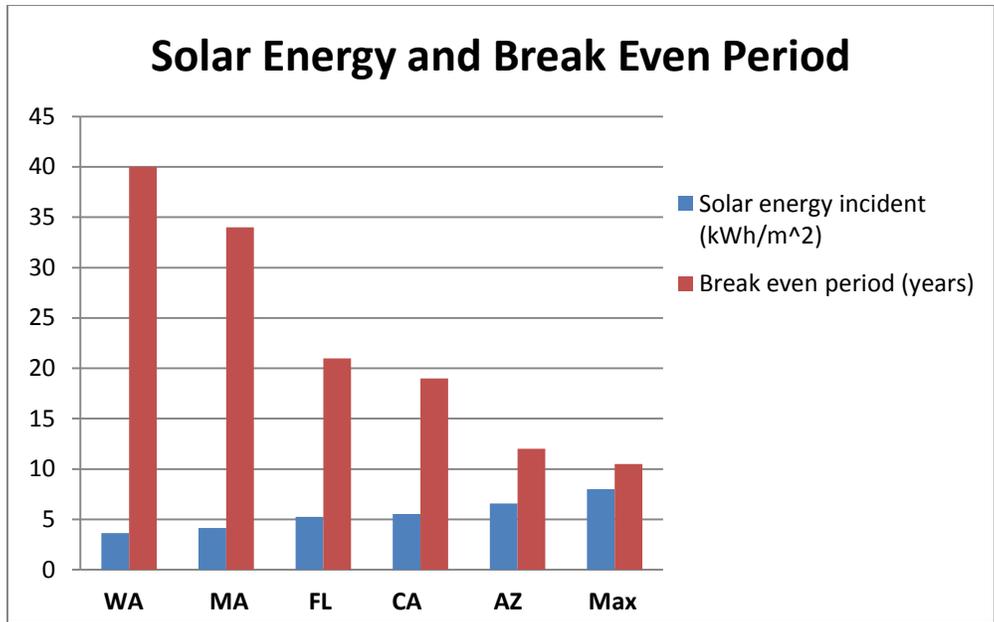


Figure 40 - Solar energy incident and break even period

**Varying Monthly Maintenance Estimate**

Figure 41 shows how the time taken to break even depends on the monthly maintenance requirement of equipment in the factory. The maintenance figures initially affect the time period to a small extent as maintenance costs increases, after which past an approximate value the break even period increases drastically with small increments in maintenance costs. Therefore the components chosen for the application should be very reliable. Sudden spikes in maintenance costs could significantly delay the recovery of the investment. The chart that relates profit after 25 years to monthly maintenance costs is shown in Figure 41.

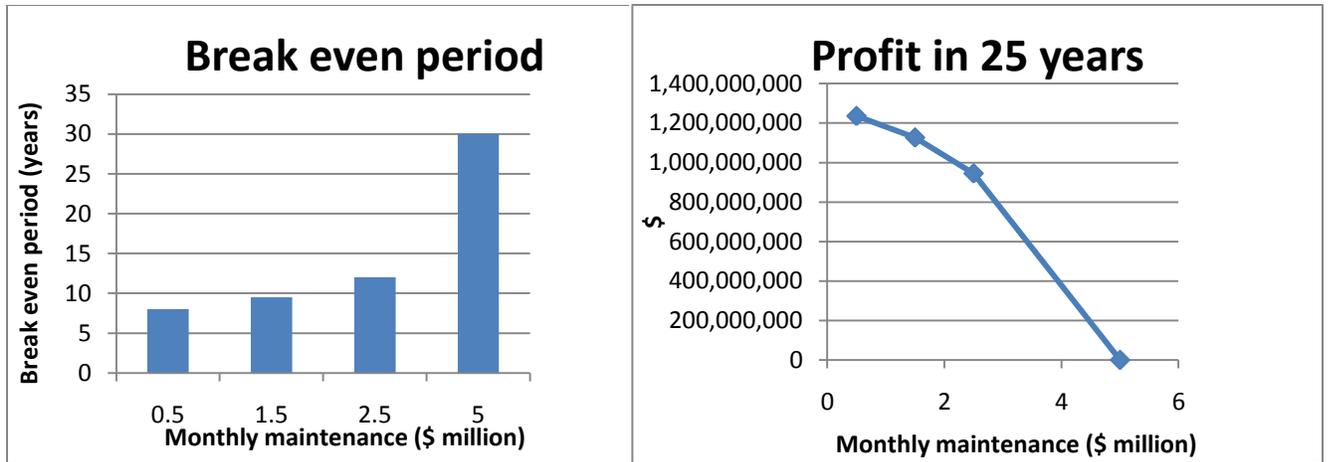


Figure 41 - Effect of monthly maintenance

### Varying Annual Interest Rate

Figure 43 initially shows a steady increase in the time taken to break even, with an increase in annual interest rate. As expected, the increase in the time period is sharper as interest rates rise further and further. The decrease in profits after 25 years is fairly gradual with increase in interest rates. Thus the interest rates if not within a reasonable range, can be an important factor in determining the profitability of the investment.

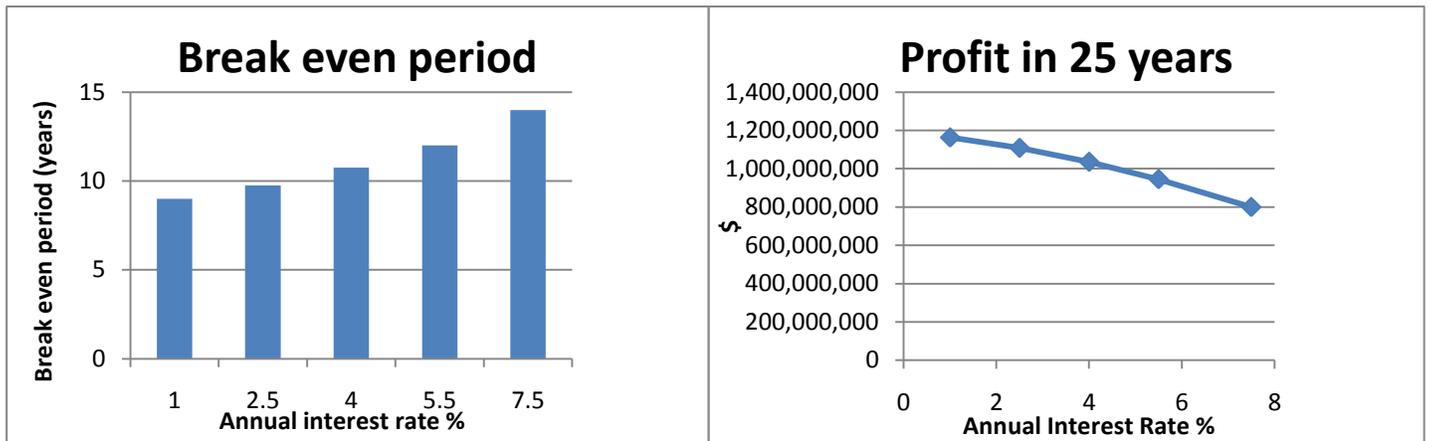


Figure 42 – Effect of Annual interest rate

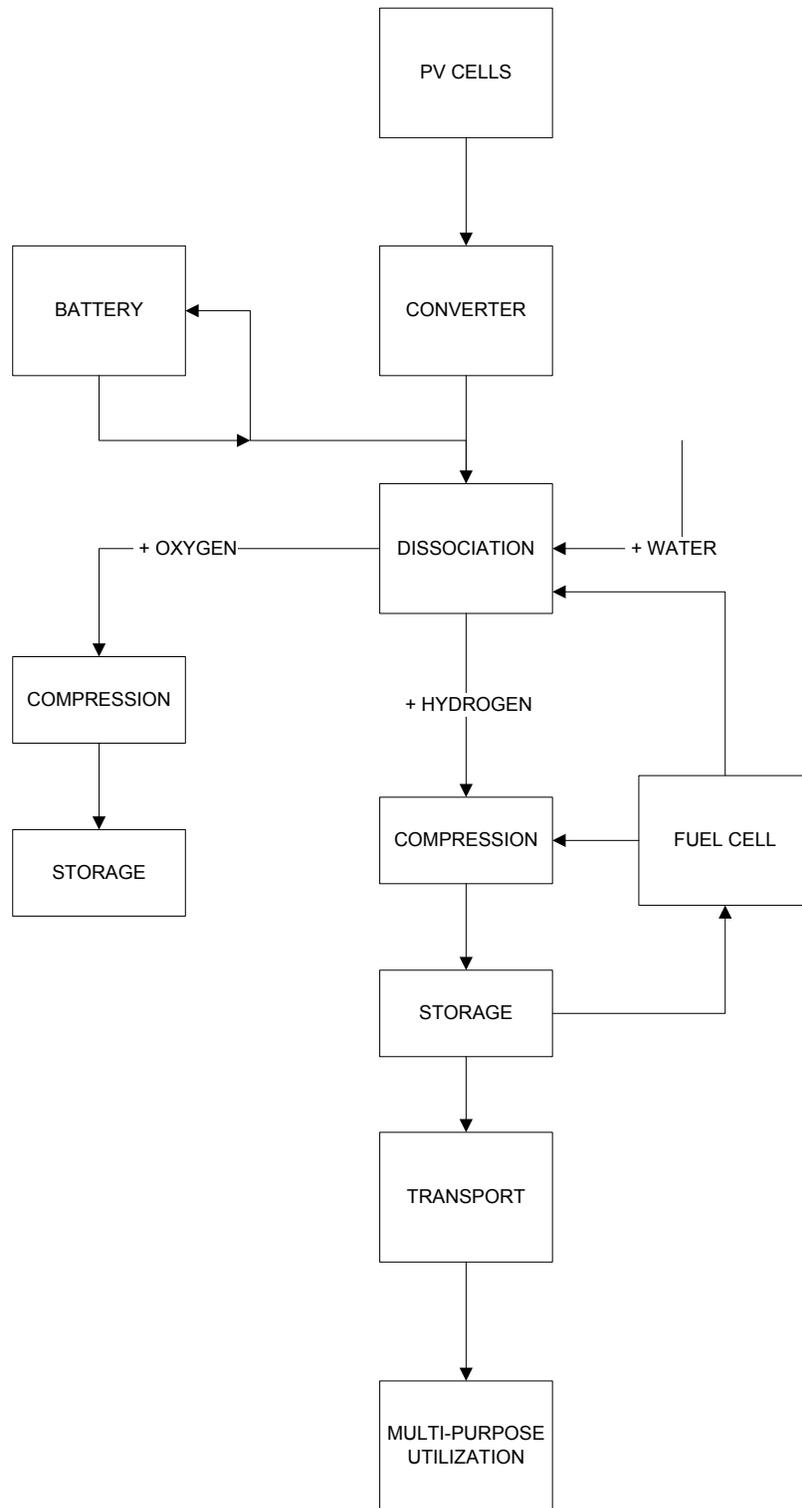


Figure 43 - Flowchart showing the hydrogen production and utilization process

## 5. Conclusions and Recommendations

It is clear from the various investigations and analyses that hydrogen has the potential to be a very promising eco-friendly fuel. Harmful emissions are almost negligible when compared to gasoline and other fossil fuels, and there is no cause of concern relating to the sustainability of the fuel as hydrogen is a vastly abundant element.

Attempts are being made at overcoming the major drawbacks such as high cost of extraction due to the high energy required, and low range due to low energy density. The continuous production of hydrogen on-board a vehicle is promising but does not provide a sufficient range of travel at a low cost.

In order for hydrogen to replace gasoline as the mass fuel, it is necessary for the fuel to provide the conveniences offered by gasoline such as reasonable running costs, low filling times and long range on a single tank. Until the technology to achieve this is developed for hydrogen, gasoline will continue to dominate the fuel market. However, once hydrogen is capable of offering the same conveniences as gasoline, it is sure to take the place of gasoline and other conventional fossil fuels, and remain there for a long time.

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