HYDROGEN: FUEL OF THE FUTURE

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Abstract

Hydrogen is an energy carrier that can transform our fossil-fuel dependent economy into a hydrogen economy, which can provide an emissions-free transportation fuel. Literature reviews and independent research were the main methods of research. Hydrogen storage and transport are issues of intense research due to hydrogen's characteristic low density. Is hydrogen a justifiable means to the attainment of an environmentally beneficial transportation fuel when methods of production are not utilizing clean, renewable energy sources? What exactly are the completely emissions-free methods of producing and utilizing hydrogen in transportation? Can hydrogen be the fuel of the future?

Hydrogen is the fuel of the future. As an avid researcher of alternative fuels and an ambitious chemistry student, this researcher understands the importance of a shift to a hydrogen economy. Hydrogen is an energy carrier that can be used in internal combustion engines or fuel cells producing virtually no greenhouse gas emissions when combusted with oxygen. The only significant emission is water vapor. Hydrogen production and storage is currently undergoing extensive research. A solar-hydrogen system can provide the means of a totally emissions-free method of producing hydrogen. Although steam reformation of methane is currently the major route to hydrogen production, the emissions involved can also be controlled much more efficiently than our current system of transportation fuel.

Climate change is a serious issue becoming increasingly evident to much of the population. Rising CO_2 levels have directly contributed to the global warming phenomenon. As shown in Figures 1 and 2, the CO_2 levels have rising dramatically in the past 200 years, along with the global average temperature.

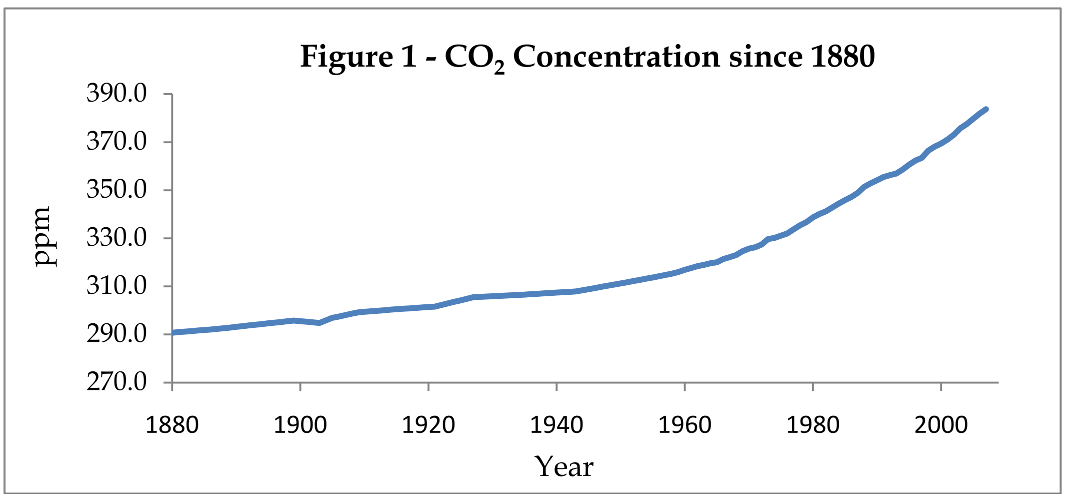
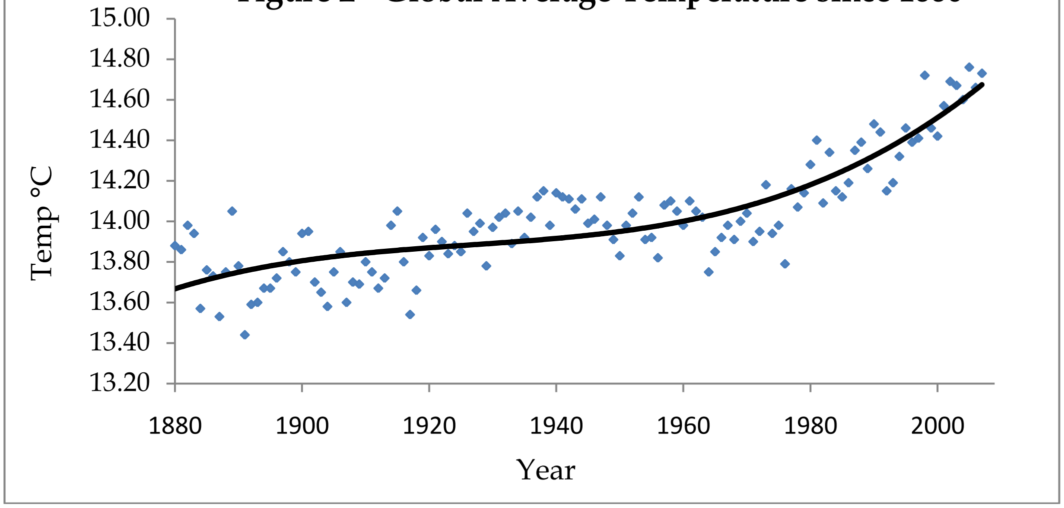


Figure 2 - Global Average Temperature since 1880



Source: Compiled by Earth Policy Institute, with long term historical data from Worldwatch Institute, Signposts 2001, CD-Rom (Washington, DC: 2001); 1960 to 2007 from NOAA/ESRL, "Atmospheric Carbon Dioxide - Mauna Loa," at: www.esrl.noaa.gov/gmd/ccgg/trends/co2_data_mlo.html.

While I will examine numerous aspects involved in the hydrogen economy, I will not compare hydrogen to other alternative fuels. Government policy will be briefly referenced, but not detailed. The core of the research concerns the advantages of hydrogen and the current progress related to the disadvantages of hydrogen as a transportation fuel. Much work is in progress to initiate a shift from a fossil-fuel economy to a hydrogen economy. What are the advantages and disadvantages of this hydrogen economy? Who is funding this research and what are their true intentions? Is there a possibility that hydrogen will be the fuel of the future and also accomplish the goal of being emissions-free?

Materials and Methods

This research is based on independent research and literature reviews. The various sources of research include recent journal articles from opposing sides of the hydrogen economy. The United States Department of Energy website was referenced for current statistics relating to the transportation sector and the various alternative energy sources being researched.

Table 1 - Use of Hydrogen as a Transportation Fuel

Advantages	Disadvantages
High energy yield (122 kJ/g)	Low density (large storage areas)
Most abundant element	Not found free in nature
Produced from many primary energy sources	Low ignition energy (similar to gasoline)
Wide flammability range (hydrogen engines operated on lean mixtures)	Currently expensive
High diffusivity	
Water vapor is major oxidation product	
Most versatile fuel	

Results

Hydrogen is an energy carrier that can be produced and converted into energy through a variety of ways. Table 1 provides a brief explanation of the advantages and drawbacks of hydrogen as a transportation fuel. Electrolysis of water is deemed to be the cleanest route tothe production of hydrogen. However, the advantages of this proposed hydrogen economy is dependent on the use of clean, renewable resources as the source of electricity. Today burning coal and nuclear fission generates 68% of the US electricity. For instance, the major routes to employable hydrogen gas involve the use of electricity. Until a dramatic shift is made toward renewable energy sources, the production of hydrogen cannot be emissions free.

Figure 1 – Electricity Consumption (2006)

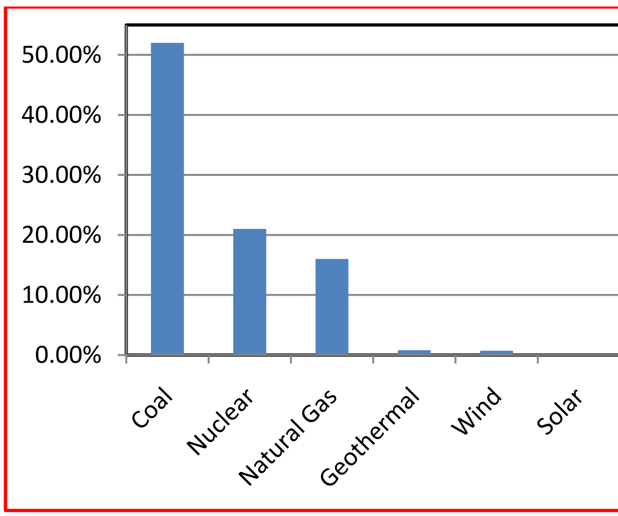
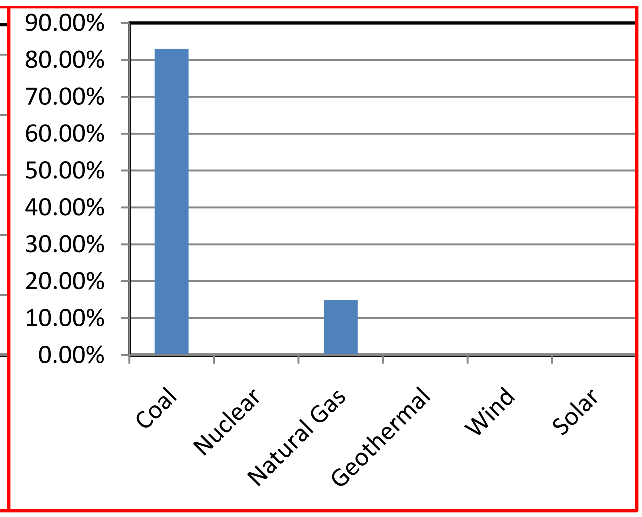


Figure 2 – CO_2 Emissions for Electricity Generation (2006)



Source: US Dept of Energy

Hydrogen can be produced from several different methods, with only a couple being environmentally beneficial. Electrolysis of water requires electricity, which can be provided by clean and renewable energy sources. Tables 2a and 2b provide a summary of the various ways to produce hydrogen.

Table 2a – Various Methods to Produce Hydrogen		
Method	Process	Implementation
Steam reforming of methane gas	In presence of nickel catalyst & at 700 – 1100 °C: $CH_{4(g)} + H_2O_{(g)} \rightarrow CO_{(g)} + 3H_{2(g)}$ Next reaction at lower temperature: $CO_{(g)} + H_2O_{(g)} \rightarrow CO_{2(g)} + H_{2(g)}$	Current major source of hydrogen
Hydrogen from coal (Gasification)	At high temperature and pressure: Coal + $H_2O_{(g)} + O_{2(g)} \rightarrow$ syngas Syngas = $H_2 + CO + CO_2 + CH_4$	Current method of mass hydrogen production
Electrolysis of water	Electric current passed through water: $2H_2O_{(l)} \rightarrow 2H_{2(g)} + O_{2(g)}$	Not in widespread use due to cost of electricity
Solar – Hydrogen system	Electric current passed through water: $2H_2O_{(l)} \rightarrow 2H_{2(g)} + O_{2(g)}$	Not in widespread use due to cost of renewable energy sources

Table 2b – Various Methods to Produce Hydrogen		
Method	Advantages	Disadvantages
Steam reforming of $CH_{4(g)}$	65 – 75% efficiency Economical (least expensive method) Established infrastructure	Nonrenewable resource Produces CO_2 emissions
Gasification	Large supplies of coal in US Inexpensive resources	Produces CO_2 emissions Carbon sequestration would raise costs 45% efficiency
Electrolysis of water	Depend on electricity source	Input into production may require more energy than released Produces CO_2 emissions if coal is energy source
Solar – Hydrogen System	No emissions 65% efficiency	Expensive

Hydrogen storage and transport is a critical issue involving intense research. The problem is the low density of hydrogen gas. Three possible solutions have been proposed. These potential hydrogen delivery systems include compressed tube trailers, liquid storage tank trucks, and compressed gas pipelines. One major disadvantage of each system is the high capital costs.

Table 3 - Possible Storage Forms for Hydrogen		
Storage Form	**Advantages**	**Disadvantages**
Compressed Gas	Reliable Indefinite storage time Easy to use	Higher capital & operating costs Heat can cause container rupture
Liquid	High density at low pressure	High cost Low temperatures needed Escape can cause fire or asphyxiation
Metal Hydride	High volume efficiencies Easy recovery Very safe	Expensive materials Heavy storage tanks

The use of metal hydrides is the most promising storage material currently. The advantages are high volume efficiencies, easy recovery, and advanced safety. The most common metal hydrides in current research are listed in Table 4.

Table 4 - Hydrogen Storage Properties of Metal Hydrides				
Metal	**Hydride**	**% Hydrogen by mass**	**Equilibrium Pressure (bar)**	**Equilibrium Temperature (K)**
Pd	$PdH_{0.6}$	0.56	0.020	298
$LaNi_5$	$LaNi_5H_6$	1.37	2	298
ZrV_2	$ZrV_2H_{5.5}$	3.01	10^{-8}	323
FeTi	$FeTiH_2$	1.89	5	303
Mg_2Ni	Mg_2NiH_4	3.59	1	555
TiV_2	TiV_2H_4	2.60	10	313

Source: Kraus T; "Hydrogen Fuel – An Economically Viable Future for the Transportation Industry?" Duke J., Economics Spring 2007; XIX.

Hydrogen can be used as the primary fuel in an internal combustion engine or in a fuel cell. A hydrogen internal combustion engine is similar to that of a gasoline engine, where hydrogen combusts with oxygen in the air and produces expanding hot gases that directly move the physical parts of an engine. The only emissions are water vapor and insignificant amounts of nitrous oxides. The efficiency is small, around 20%. A polymer electrolyte membrane (PEM) fuel cell produces an electrical current from hydrogen fuel and oxygen in the air. Hydrogen is split into hydrogen ions and electrons by a platinum catalyst at the anode. The PEM allows only the hydrogen ions to pass through to the cathode where these ions react with oxygen to produce water. The electrons travel down a circuit creating an electrical current. The fuel cells are arranged in stacks in order to provide enough electricity to power a vehicle. The use of a fuel cell eliminates the nitrous oxide emissions. Furthermore, the fuel cell is 45-60% efficient.

Internal Combustion Engine	PEM Fuel Cell

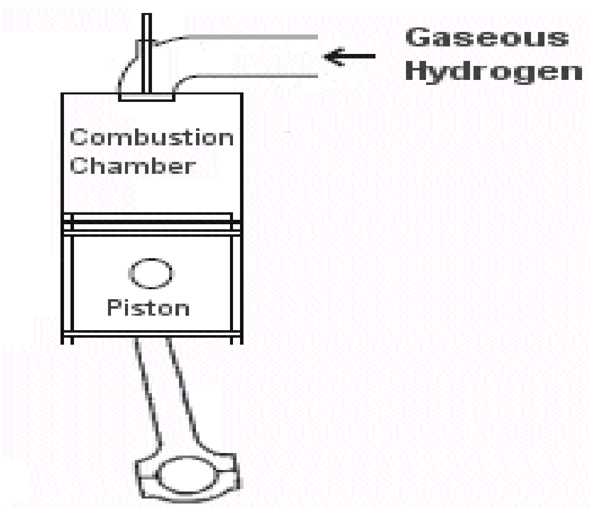


Figure3[1]

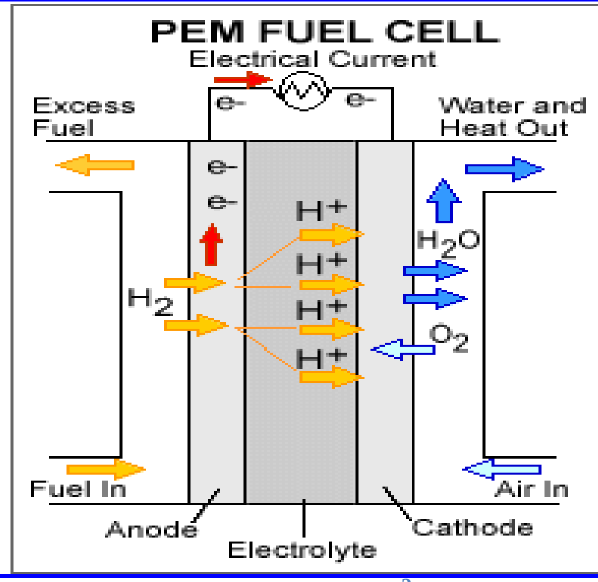


Figure 4[2]

[1] Hydrogen-engine.gif; http://hydroxene.net/images/hydrogen-engine.gif (Nov 12, 2008)
[2] PEM Fuel Cell; http://www.lbl.gov/Science-Articles/archive/assets/images/2007/Jan/24-Wed/Fuelcell.gif (Nov 12, 2008)

Discussion

An alternative fuel must be technically feasible, economically viable, easily convert to another energy form when combusted, be safe to use, and be potentially harmless to the environment. Hydrogen is the most abundant element on earth. Although hydrogen does not exist freely in nature, it can be produced from a variety of sources such as steam reformation of natural gas, gasification of coal, and electrolysis of water. Hydrogen gas can used in traditional gasoline-powered internal combustion engines (ICE) with minimal conversions. However, vehicles with polymer electrolyte membrane (PEM) fuel cells provide a greater efficiency. Hydrogen gas combusts with oxygen to produce water vapor. Even the production of hydrogen gas can be emissions-free with the use of renewable energy sources. The current price of hydrogen is about $4 per kg, which is about the equivalent of a gallon of gasoline. However, in fuel cell vehicles, such as the 2009 Honda FCX Clarity, 1 kg provides about 68 miles of travel [3]. Of course the price range is currently very high. Ongoing research and implementation toward a hydrogen economy is required to make this fuel economically feasible.

The current focus is directed toward hydrogen being a clean alternative fuel that produces insignificant greenhouse gas emissions. If hydrogen is the next transportation fuel, the primary energy source used to produce the vast amounts of hydrogen will not necessarily be a renewable, clean source. Carbon sequestration is referenced frequently as a means to eliminate CO_2 emissions from the burning of coal, where the gases are captured and sequestered in gas wells or depleted oil wells. However, the availability of these sites is not widespread and the presence of CO_2 may acidify groundwater.

Storage and transport is a major issue due to hydrogen's low density. Is the investment in new infrastructure too costly? Can our old infrastructure currently used for natural gas transport be retrofitted for hydrogen?

The burning of coal and nuclear fission are the main energy sources that will be used to provide an abundant supply of hydrogen fuel. How does this process help our current global warming predicament? The U.S. Department of Energy has recently funded a research project to produce hydrogen from coal at large-scale facilities, with carbon sequestration in mind. Is this the wrong approach? Should there be more focus on other forms of energy that produce no greenhouse gas emissions? If the damage to the environment is interpreted into a monetary cost, the promotion of energy sources such as wind and solar may prove to be a more economical approach.

The possibility of a hydrogen economy that incorporates the use of hydrogen into every aspect of transportation requires much further research and development. The most economical and major source of hydrogen in the US is steam reformation of natural gas, a nonrenewable resource and a producer of greenhouse gases. The electrolysis of water is a potentially sustainable method of producing hydrogen, but only if renewable energy sources are used for the electricity. Today, less than 5% of our electricity comes from renewable sources such as solar, wind, and hydro. Nuclear power may be considered as a renewable resource to some, but the waste generated by this energy source becomes a major problem. A rapid shift toward renewable energy sources is required before this proposed hydrogen economy can prove itself. Solar photovoltaic (PV) systems are the current focus of my research related to the energy source required for electrolysis of water. One project conducted at the GM Proving Ground in Milford, MI employed the use of 40 solar PV modules directly connected to an electrolyzer/storage/dispenser system. The result was an 8.5% efficiency in the production of hydrogen, with an average production of 0.5 kg of high-pressure hydrogen per day. Research similar to this may result in the optimization of the solar-hydrogen energy system.

Furthermore, the infrastructure for a hydrogen economy will come with high capital costs. The transport of hydrogen through underground pipes seems to be the most economical when demand grows enough to require a large centralized facility. However, in places of low population density, this method may not be economically feasible. The project mentioned earlier may become an option for individuals to produce their own hydrogen gas at home, with solar panels lining their roof. A drastic change is needed to slow down the effects of our fossil-fuel dependent society. Conservation can indeed help, but the lifestyles we are accustomed to require certain energy demands. Transportation is a necessary part of our current world and the switch to a hydrogen economy can provide a sustainable solution. Is hydrogen the fuel of the future? The research presented here encourages one to answer yes.

REFERENCES

1) United States Department of Energy. Annual Energy Review 2007. http://www.eia.doe.gov/emeu/aer/contents.html (October 20, 2008).
2) Veziroglu TN, Sahin S. 21st Century's energy: Hydrogen energy system. *Energy Conversion and Management*. **2008**, *49*, 1820-1831.
3) Balat M. Potential importance of hydrogen as a future solution to environmental and transportation problems. *International Journal of Hydrogen Energy*. **2008**, *33*, 4013-4029.
4) Dougherty W, Kartha S, Rajan C, Lazarus M, Bailie A, Runkle B, Fencl A. Greenhouse gas reduction benefits and costs of a large-scale transition to hydrogen in the USA. *Energy Policy* (2008), doi:\10.1016/j.enpol.2008.06.039
5) Baschuk JJ, Li X. A comprehensive, consistent and systematic mathematical model of PEM fuel cells. *Applied Energy*, **2009**, *86*, 181-193.
6) Gasification Technologies Council. http://www.gasification.org (October 20, 2008)
7) Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. Washington, D.C.: The National Academy Press. 2004.
8) Kelly, N.A.; Gibson, T.L.; Ouwerkerk, D.B.; A solar-powered, high-efficiency hydrogen fueling system using high-pressure electrolysis of water: Design and initial results. *Int. J. of Hydrogen Energy*. **2008**, *33*, 2747-2764.
9) Kim J, Lee Y, Moon I. Optimization of a hydrogen supply chain under demand uncertainty. *Int. J. of Hydrogen Energy*. **2008,** *33*, 4715-4729.

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