**Economic Viability of Hydrogen as a Fuel**

Abhi Kamboj

11th Grade

Wayzata High School

**ABSTRACT**

Currently, about 85% of energy consumed in the United States comes from fossil fuels such as coal and gasoline. The repercussions of this dependency manifest themselves as increased pollution and greenhouse gas emissions, which have widespread effects on the environment and public health. As energy consumption increases to meet the demands of a fast-paced, modernizing society, these adverse effects become increasingly prominent and the need for alternative energy production becomes vital. Based on ongoing research efforts to develop alternative energy, it can be argued that hydrogen energy proves to be a uniquely effective source of energy. This literature review examines the following question: if the abundant element hydrogen results in zero harmful pollutants or greenhouse gases, what prevents countries from running on hydrogen economies and how can these barriers be overcome? The research done in this paper, by analyzing numerous statistics of extensive published data, demonstrates that hydrogen energy can effectively replace coal and gasoline in today’s economy. Proton exchange membrane (PEM) fuel cell was used to demonstrate generation and use of hydrogen. A Visual Basic program was designed to examine the effectiveness of hydrogen against conventional fuels. Current barriers to a hydrogen economy include its cost and finding an efficient method to create hydrogen from water. After comparing the negative effects of fossil fuels to those of producing hydrogen, it was determined that the use of electrolysis powered by wind energy most effectively delivers a sustainable hydrogen source to provide clean energy at an affordable cost.

**INTRODUCTION**

The U.S. energy mix is dominated by the three major fossil fuels—petroleum, natural gas, and coal for more than 100 years(Figure 1) 1.

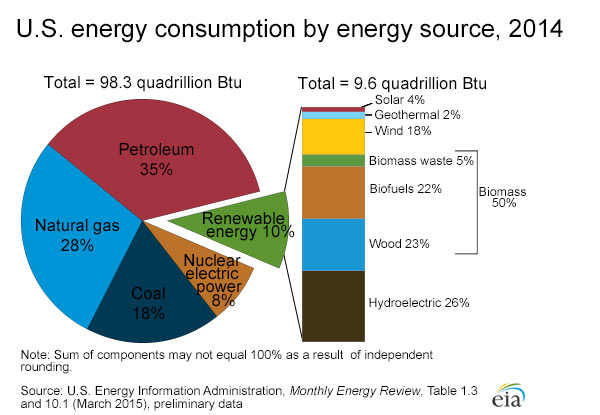


Figure 1: US energy consumption by different types of energy sources

These fossil fuels are the main source of pollution in the environment today. Their use constantly emits carbon, nitrogen and sulfur based pollutants into the air that everyone breathes (Figure 2) 2.

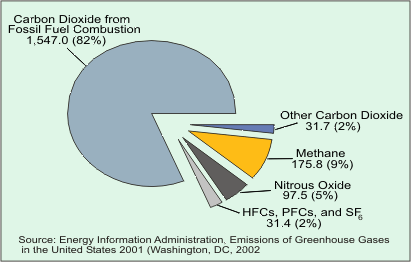
Amounts of ozone layer depletion, acid rain, smog, and pollution are several times the limits acceptable for the good health of citizens. In many cities, these factors are causing diseases like skin cancer, lung cancer and many others at levels never seen before and deaths at a rate never seen before 2.

Figure 2. U.S. Anthropogenic Greenhouse Gas Emissions by Gas, 2001

This problem is so prevalent that many researchers are desperately looking for technologies to remove these pollutants from our air. The Environmental Protection Agency (EPA) estimates that simply changing the safe concentration of sulfur allowed in chemicals from 30 PPM to 10 PPM will help avoid up to 2,000 premature deaths each year and 50,000 cases of respiratory ailments in children, saving from $6.7 billion to $19 billion annually in health care costs 3.

In the light of the aforementioned data would fossil fuels actually be cheaper, as claimed by many alternative energy skeptics? Note that the market cost of producing fossil fuels does not include the cost needed to clean up the pollution it generates. This means that the terminal effects of fossil fuel consumption tend to offset its immediate economic benefit. More importantly however, no amount of money can offset the suffering increasingly felt by society due to these silent killers.

There is currently lots of research in progress with the goal of developing clean renewable energy sources. Ideally this energy source should not produce any pollutants and exist in abundance in order to serve humanity’s consumption needs today and in the future, without harming anybody or disturbing the balance in nature that society is already hindering; as indicated by ozone layer depletion, accelerated arctic glacier melting and rising ocean levels.

Several alternative energy sources are being used every day, such as windmill farms and solar panels, but they also present many challenges. Firstly, storing energy generated by these sources would use technologies like batteries, which only give back 62% of the energy given to them. The manufacturing of these batteries further creates significant pollution. In addition, the power grid is limited by how much power it can hold. Windmill owners are sometimes instructed to stop windmills when grids are in overload condition. In some countries, power companies must even provide compensation to wind farm owners to stop windmills. A letter, published on Ofgem’s website and uncovered by a British newspaper, “The Sunday Telegraph,” discloses that the “constraint costs” for 23 “large generation” projects – 20 of which are wind farms – totaled £69.4 million in the 12 months to March 31 2014. This is more than triple the constraint cost of the previous year 4. Although wind proves to be the most efficient way to generate electricity, it is still not as efficient as it could be without an effective way to store the energy. On the spot hydrogen generation before electricity even hits the grid will help produce the cheapest energy source, as discussed in this paper.

Significant progress has been made in the search for cleaner fuels. Hydrogen as a fuel in particular has many features that make it a leading candidate, as it is the cleanest and most abundant of all elements5. Hydrogen generation can also be used to store excess energy produced by cleaner alternative energy sources 6. Moreover, interest in hydrogen is rising due to technical advances in fuel cells, which are the potential successors to batteries, power plants and internal combustion engines 7. During this research, several methods for producing hydrogen were analyzed, including the use of hydrocarbons to produce hydrogen, but the research focuses mainly on hydrogen generation using water (also known as electrolysis). The big questions this research addresses are: Is society there yet? What is the cost of generating hydrogen from water? What is cost of using hydrogen as energy, now and in future? What is the future outlook for hydrogen economy? What pollutants are eliminated in a hydrogen economy and by how much? These are some of the topics that are researched and discussed in the current study.

In addition to analytical research, a Visual Basic program was designed as a part of this project, and it will take as inputs the amount of fossil fuel that is used in a given system, namely, coal, gasoline, diesel, natural gas and finally hydrogen. This program will generate an output to show how much carbon, nitrogen and sulfur compounds in addition to other pollutants are generated in the environment. The program results will make a recommendation on how much zero-pollution hydrogen fuel is needed to stop generating the estimated pollution and replace the fossil fuels to generate the same amount of energy.

**MATERIALS AND METHODS**

**Proton Exchange Membrane Electrolyzer/Fuel Cell**

A PEM fuel cell kit (Horizon Fuel Cell Technologies Fuel Cell Car Science Kit) was used to understand the principle behind fuel cell technology and demonstrate the generation of electricity. This fuel cell used electrolysis to generate hydrogen using water. The resultant hydrogen was used to generate electricity that powered a LED light bulb and motor.



Figure 3: PEM Fuel Cell Kit

**Data Collection**

This research is based on a literature review and is done as an independent research project. The various sources of research include papers from different journals like the International Journal of Hydrogen Energy and the Journal of Power and Energy Engineering. Furthermore, numerous websites describing different types of energy sources including the US Department of energy and the National Renewable Energy laboratory were reviewed for current statistics relating to pollution, fuel consumption and the economy.

**Designing a Computer Program to analyze the data**

The editor Visual Studio Enterprise 2015 was used to create a Visual Basic program functioning as a tool to model various situations of energy consumption based on a hydrogen economy. Using the data tables provided in this essay, the program determines how much hydrogen is needed to produce the same amount of energy as other fossil fuels. The program further demonstrates how beneficial a hydrogen economy is over the current use of fossil fuels by displaying the amount of greenhouse gas and harmful pollutant emissions the hydrogen fuel saves compared to the fossil fuels.

An additional function of this program compares costs for optimal energy efficiency of various sources of energy. The user inputs the amount of energy they wish to produce and their budget. Based on these values, the program uses statistics from the Environmental Protection Agency and the US Energy Information Administration to calculate and output the amount of each source of energy that is necessary to satisfy the user’s budgets while minimizing pollution and greenhouse gas emissions. In order to achieve this result, the program’s algorithm uses nested For Loops that alter the power distribution to among each energy source. These iterative controls allow for the repeated calculation of GHG emissions and costs. While iterating through these define loops, the program identifies and stores the values that create the least GHG emissions and pollutions while costing no more than the budget value.

**RESULTS AND DISCUSSION**

Fossil fuels are most widely used in the world as the main source of energy, although they generate lots of pollutants. Research is being done to find alternative sources of energy. The use of hydrogen as energy has great potential to lead society to a renewable energy economy 8. A hydrogen economy with hydrogen and electricity acting as complimentary energy carriers has been envisioned for decades 9. The major roadblock in the way of that vision is cost. However, the technology behind this form of energy has taken some significant leaps, enough so to reconsider the cost. More specifically, this research looks at different approaches for technological advances and compiles different methods that can be used to generate hydrogen energy.

**Is society ready for hydrogen energy?**

To answer the big question ‘is society there yet,’ a detailed study was conducted in light of new technological developments and recent breakthroughs. Cost and convenience are the two critical factors that could be the driving force to transitioning away from a fossil fuel economy to a hydrogen economy. As seen from the following data and discussion, society is capable of a hydrogen economy. Looking at the cost of pollution to society, a hydrogen economy wins out in feasibility over our current fossil fuel economy.

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| --- | --- | --- | --- |
| **Table 1: Cost Effectiveness of Hydrogen as a Fuel** | | | |
| **Source of Energy** | **Fuel Type** | **Cost of Production** | **Cost to Drive a Midsize Car** |
| **Hydrogen** | Thermo-Chemical Process Using Nuclear Reactor | $1.30/Kg | $1.94/100 miles |
| Windmill and Electrolyzer Combination using Water | $2.16/Kg | $3.22/100 miles |
| Electricity from Grid | $11.88/Kg | $17.73/100 miles |
| Solar and Electrolyser Combination using Water | No calculation performed due to high subsidies to power producers | |
| **Fossil Fuel** | Gasoline | $2/gal | $5.40/100 miles |

As shown in Table 110, 11, 12, systems that utilize hydrogen (modern fuel cells along with an electric motor) are a lot more efficient and cost somewhat less, when compared to systems utilizing gasoline. One gallon today, for example, can drive a Honda Fit, a small-sized car, for 37 miles. Its Gasoline gallon equivalent (GGE) of 1kg hydrogen can drive a midsize Toyota Mirai for 67 miles. This is an efficiency improvement of 81% 13. This dramatic improvement in efficiency further supports the notion that switching to a hydrogen economy would reap substantial economic benefits for society.

|  |  |
| --- | --- |
| **Table 2: Cost of producing Hydrogen Energy from different sources** | |
| **Using Electrolyzer** | **US Dollars per Kg** |
| With Grid | 3 |
| With Windmill | 2.2 |
| From Thermo-chemicals | 1.3 |

As indicated in Table 2, the thermos-chemical method of extracting hydrogen from water is cheapest when the cost of producing hydrogen is close to $1.30/kg. However, many critics will not advise using this technique because it uses a nuclear reactor for high temperature hydrogen separation.

Windmills sell energy at 22 cents/MWh (cents per Mega-Watt hours) or 2.2 cents/KWh (cents per Kilo-Watt hour). Each windmill capable of generating 1 MW is slightly less than US $1.5 million. A hydrogen electrolyzer is also around US $1.5 million. If 4.5 cents per KWh is the operating cost, knowing that 48 KWh is used to produce 1 kg hydrogen, the cost for producing 1 kg of hydrogen using wind is $2.16.

Note that the onsite production of hydrogen avoids usage of the grid, cost of managing the grid and energy losses in the grid. These are the factors that make consumers pay 13 cents or more for 2.2 cents worth of electricity. Moreover, windmill locations with access to water are more suited for hydrogen production due to their location. Looking deeper into the hydrogen economy, the size of the economy will reduce cost of windmills and fuel cells even further as shown by Table 212 and Figure 311.

Electrolyzers are currently deployed at hydrogen pumping sites in California to generate and pump hydrogen in cars today13. Recent breakthroughs in electrolysis technologies and new non-platinum catalysts make water electrolysis even more promising.

**What is the future of the fuel cell that converts hydrogen to usable electric energy?**

Recent developments in fuel cell technologies have brought the cost of fuel cells down significantly. It is well known that fuel cells can be highly efficient in converting chemical energy to electrical energy and vice versa. They will play a key role in a future hydrogen economy. The demonstration that occurred with this research, models how a hydrogen fuel cell works. During electrolysis, the model used electrical energy generated from the solar panel to break water into hydrogen and oxygen. Then, the proton exchange membrane converted hydrogen to electrical energy used to light LEDs and run a motorized car.

Figure 3 below shows how economic modernization has made fuel cell prices to go down.

There are a few examples today in which people are powering their properties at remote locations using hydrogen fuel cells. They store energy in hydrogen using electricity from solar or wind sources and use that hydrogen to power their houses and cars. These so-called home hydrogen stations are being worked on by some manufacturers, including a partnership between Power Plug (a fuel cell manufacturer) and Honda Motors (A Japanese Car Company). The current drive towards clean energy plays an important role for the potential of alternative energy development in the future.

**What pollutants does hydrogen eliminate and how much?**

Different fossil fuels contain different amounts of energy per unit mass. Tables 31 below shows energy density of different fuels as indicated by their ability to generate 1MWh of energy.

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| --- | --- | --- |
| **Table 3: Energy in Different Fuels** | | |
| **Types of Energy Sources** | **Amount of Fuel used to Generate 1 MWh power** | **Cost (Dollars)** |
| Petroleum Gas | 70 gallons | 1.822$/gallon |
| Natural Gas | 1 million cubic feet | .0388$/gallon |
| Coal | 150 pounds | .02447$/pound |
| Hydrogen | 70 GGE | 1.30$/GGE |

These fossil fuels also produce different amounts of pollutants, as shown in Table 42.

|  |  |  |
| --- | --- | --- |
| **Table 4: Types of Pollutants Emitted** | | |
| **Types of Energy Sources** | **Carbon Dioxide Emission** | **Other Pollutants** |
| Petroleum Gas | 19.64 gallons/pound | Yes |
| Natural Gas | 117 Pounds of CO2/million British thermal units (Btu) of energy | Yes |
| Diesel | 22.84 gallons/pound | Yes |
| Coal | 2.014 poundsCO2/ pound Coal | Yes |
| Hydrogen | 0 | 0 |

**CONCLUSIONS**

A Hydrogen economy is viable today. The cheapest way to generate hydrogen is by using a thermo-chemical process to break water and produce hydrogen using a nuclear reactor. However, a more viable and practical way to generate hydrogen would be through using wind energy. This would provide a well distributed network for hydrogen generation and bottling and would take a heavy load off the energy grid thereby reducing costs that is needed to grow and manage the existing grid.

An economy of scale will make wind energy, fuel cells and electrolysis cheaper. Fuel cells which used to cost $125/kW are close to $45/kW today. They can eventually even make it to the $30/kW.

Electrolyzer technologies are seeing significant breakthroughs, and membrane-less electrolyzers for hydrogen production are being looked at 14. On the other hand, cheaper catalysts are being designed to replace expensive catalysts such as platinum15. These developments will make hydrogen production even cheaper.

Japan today is powering small buildings with fuel cell (heat/electric) energy generation 16. A large number of car manufactures are getting ready to roll different models that will run on hydrogen. The research and development behind hydrogen energy is strong and ready to push society away from fossil fuels and towards a greener future.

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