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THE FUTURE OF A HYDROGEN ECONOMY IN THE UNITED STATES

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ABSTRACT

The goal of this project is to present a detailed analysis on the feasibility of a hydrogen economy existing in the United States. While hydrogen technologies are still in their infancy, the enormous potential has already been realized. First, we examined the various types of hydrogen production that are available or in development, and compared the advantages and disadvantages. Then, by providing an in-depth overview of the safety and environmental advantages of hydrogen gas, as well as a fiscal analysis based on projections by top experts in the field, we proved that the benefits heavily outweigh the consequences. On top of that, we also examined the importance of consumer appeal and how hydrogen needs to be marketed properly in order for it to really work. Based on all of our research, we concluded that, as with any new emerging technology, for hydrogen to take off, it will need a huge backing from our government and key organizations, as well as an extensive framework of guidelines and milestones to be laid out and adhered to.

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1. INTRODUCTION

1.1 General Introduction

Gas-guzzling SUVs, must-have handhelds, and other commonplace luxuries have driven our image-obsessed culture into an inescapable reliance on massive amounts of energy. But with an exponentially depleting international oil supply, as well as the harsh reality that greenhouse gases are causing global warming, there has been a scramble to find renewable, green energies to take us into the future. Many energy sources have emerged in the past couple decades, such as solar and bio-diesel power, vying to be the next big energy source. However, low dependability and potency has long plagued solar power, and bio-diesel isn't technically zero emissions or renewable enough to reach our desired goal. What many people have realized – scientists, environmentalists, government representatives, and the everyday consumer – is that the potential in hydrogen gas and hydrogen fuel cells might very well be our saving grace.

Over the last 55 years, America has been consuming energy at an exponentially increasing rate through most of the 60's, all the way into the early 80's. America's energy consumption has finally started to slow down and level off over the last 7 years, thanks to the efforts of environmental lobbyists and government mandates. However, with increasing population and higher energy-consuming products emerging, there is no sign of it ever decreasing in the near future. Projections show that in the year 2025, America alone will consume 133.18 quadrillion (qn) Btu of energy, a staggering 33.43% increase from what was consumed in 2004. 85.89qn Btu of that projection will come from petroleum products and natural gas. That's 85.89qn Btu that, in an ideal production environment capable of yielding 100% output, could easily be supplied by hydrogen. **[1]**

1.2 Why Hydrogen?

Pure hydrogen gas has the highest gravitational energy density of any known energy carrier – 52,000 Btu/lb (LHV) – so it's clear why scientists have been trying to harness its power. While hydrogen does have a lower volumetric energy density than other popular energy sources, such as methane, propane or octane (gasoline), its environmental and renewable aspects supersede any of its competitors. When H2 is "burned" the only byproducts that are released is heat and water, as opposed to greenhouse gases and smog associated with other types of fuel burning. There are also production methods currently being developed to eliminate greenhouse gases during the formation of hydrogen. With greenhouse gases and smog eliminated from both the production and consumption phases, vast improvements in air quality are sure to follow shortly.

Hydrogen has the capability to fill fossil fuel's large boots, but it is up to researchers and scientists across the globe to develop a consistent hydrogen production method to the point where it's economic and efficient enough to draw consumers in. Current hydrogen prices and supplies are nowhere near competitive with fossil fuels, but scientists and researchers predict that with the maturation of hydrogen harvesting techniques, hydrogen will be a very viable alternative. Further in-depth analysis of the economic and environmental aspects of hydrogen is provided in sections 3.3 and 3.4, respectively.

1.3 Thesis

As with any new technology, in order for hydrogen to gain widespread acceptance, it must first be nurtured and cultivated. A major part of that nurturing is regulating standards and practices in order to create a more common starting ground for government and private companies alike. Space exploration really didn't take off until President Kennedy went to NASA and gave them large amounts of funding and a timeframe in which to land on the moon. Since then, it has lead to many advancements and achievements, such as the exploration of Mars and the first private space shuttle to be put into service for commercial space flights. The same can be said about the future of hydrogen. The technology is coming along, but is moving very slowly compared to pace it could be going, and without proper funding and regulations it will continue at this pace until it's possibly too late and we've tapped all our fossil fuel resources. In order for a hydrogen economy to firmly take root and gain widespread acceptance, the government needs to provide proper funding and incentives, as well as set milestones for the hydrogen industry to achieve over the next 25 years, before fossil fuels become severely limited.

2. HYDROGEN PRODUCTION, DELIVERY AND SAFETY

2.1 Production Methods

The main source of hydrogen production in the United States is through a steam methane reformation (SMR) process, accounting for approximately 48% of the country's hydrogen output. The next two leading methods also rely on fossil fuels, oil (30%) and coal (18%).**[2]** While these methods yield higher output than any other technology we have so far, they still emit dangerous byproducts during the formation process, including CO_2. To counteract this, scientists are always looking for new, more efficient methods of hydrogen production to make it more economically and environmentally friendly. In this section, we will review the current technologies that the hydrogen industry has to offer as well as some promising technologies on the horizon. All forms of hydrogen production can be divided up into three major areas; thermochemical, electrolytic, and photolytic.

2.1.1 Thermochemical Production

Thermochemical hydrogen production methods convert hydrocarbon feedstocks to hydrogen through the use of heat and chemical reactions. Some examples of thermochemical methods are SMR, biomass gasification/pyrolysis, and ceramic membrane reactors.

SMR is an integral part of the strategy to introduce hydrogen into the transportation and utility sectors of society. This process will lead to other innovative methods of hydrogen production by helping reduce the current cost of conventional methods. SMR works by heating natural gas into a vapor and then collecting the hydrogen gas during the reformation process. Scientists are still finding ways to modify the conventional SMR process, such as incorporating an adsorbent for CO_2 during the reformation phase to remove it from the product stream, in order to make the process more advantageous and cost efficient.

Biomass gasification/pyrolysis harnesses hydrogen from biomass, such as agricultural wastes and residues, using a very similar method to the one used for fossil fuels. Biomass gasification occurs when biomass is heated in an environment with very little oxygen. The biomass is then broken down into a mixture of carbon dioxide, hydrogen/synthesis gas, and the hydrogen is harnessed from there. Pyrolysis is the thermal breakdown of biomass in an environment with virtually no oxygen. The pyrolysis creates a liquid, known as bio-oil, which contains a significant number of highly reactive oxygenated components that can be transformed into products, including hydrogen **[2]**.

Ceramic membranes are a new process still in development phases, but in theory the reactor would allow for the simultaneous separation of oxygen from air and partial oxidation of methane. If this method proves successful, this process could result in improved production of hydrogen and/or synthesis gas as compared to conventional reactors **[2]**. Other thermochemical technologies, such as ceramic membranes, currently being researched can be seen in Table 1.

DOE Major Fossil-Based Hydrogen Production Activities (FY2004)		
Technology	**Organizations**	**Project Focus**
Distributed Reforming of Natural Gas and Liquid Fuels	Praxair	Oxygen transport membrane for reforming followed by hydrogen transport membrane shift reactor/Low-cost hydrogen production platform
	Air Products and Chemicals, Inc.	Hydrogen refueling station using advanced natural gas steam methane reforming technologies
	GE Global Research	Fuel-flexible autothermal reformer
	National Energy Technology Laboratory	Advanced water gas shift membrane reactors
	Innovatek	Novel catalytic fuel reforming
	Startech Environmental	Plasma gasification and ceramic membrane hydrogen separation
Separations	Sandia National Laboratories	Defect-free thin film membranes for hydrogen separation
	Oakridge National Laboratory	Transport membrane development/Porous support tube fabrication
	Los Alamos National Laboratory	Microstructured membrane development
Centralized Hydrogen from Coal or Natural Gas	DOE Fossil Energy Office (FE)	Central natural gas reforming, coal gasification, carbon sequestration
	EERE in collaboration with FE	Advanced technologies for reforming natural gas and producer gas, shift technology, and separations and purification
High-temperature (700°-1000°C) thermochemical water splitting	University of Nevada, Las Vegas	Thermocatalytic decomposition of natural gas; high-temperature thermochemical water-splitting cycles
	DOE Office of Nuclear Energy, Science and Technology	Initial research on high-temperature thermochemical production of hydrogen

Table 2.1: Thermochemical R&D Activities **[30, 31]**

2.1.2 Electrolytic Production

Electrolytic hydrogen production methods split water into hydrogen and oxygen by using electrical energy. Until the 1950s. water electrolysis was widely used for hydrogen production. Today, it plays a much smaller role, mainly used to create small volumes of high-purity hydrogen and oxygen, but it still accounts for 4% of the world's hydrogen production. There has been significant renewed interest in the use of electrolyzers to create hydrogen for automotive applications, and research is continuing to integrate intermittent renewable resources, such as wind, for more efficient hydrogen production **[3]**. A list of the current R&D activities involving electrolytic hydrogen production is shown in Table 2.

DOE Major Electrolytic Hydrogen Production Activities (FY2004)		
Technology	**Organizations**	**Project Focus**
Hydrogen production from water via electrolysis	National Renewable Energy Laboratory	Renewable electrolysis integrated system development
	Idaho National Engineering and Environmental Laboratory	Improved methods for producing hydrogen via electrolysis
	Teledyne; Proton Energy Systems	Hydrogen generation from electrolysis
	Sandia National Laboratory	High-efficiency electrolysis materials
	Giner Electrochemical Systems	Low-cost, high-pressure hydrogen generator

Table 2.2: Electrolytic R&D Activities **[32]**

2.1.3 Photolytic Production

Photolytic extraction methods use the energy from sunlight to split water into hydrogen and oxygen, with photobiological and photoelectrolysis systems being the front-running technologies in that area. All current R&D on photolytic technologies can be seen at the end of this section in Table 3.

A photobiological system relies on microbes that produce hydrogen during their metabolic activities. By applying direct sunlight to these microbes, such as cyanobacteria and algae, hydrogen is produced and harnessed. But as more hydrogen is produced, more oxygen is produced as well which kills off the microbes and effectively kills the system. The U.S Department of Energy is currently working on a new algal photoproduction system which would produce more oxygen-tolerant microbes, as well as a metabolic switch (sulfur deprivation) to cycle the algal cells faster, producing more hydrogen. By utilizing these catalysts, photobiological systems could reach a hydrogen production efficiency of 24%, which is a vast improvement over all current photobiological systems.

Photoelectrolysis utilizes a light harvesting system that collects enough voltage to split water atoms using solar electricity. This technology is still in developing stages, but if scientists can get it to work, the theoretical yield would be approximately 42%. It would also eliminate the need for electrolyzers in the system, lowering overall cost and possibly increasing efficiency at the same time. **[4]**

DOE Major Photolytic Hydrogen Production Activities (FY2004)		
Technology	**Organizations**	**Project Focus**
Photobiological production of hydrogen	National Renewable Energy Laboratory	New strains of algae/systems with improved oxygen tolerance/Reactor design and development
	UC Berkeley	New strains of algae with improved electron transport
	Oak Ridge National Laboratory	New strains of algae with improved solar conversion efficiency (truncated Chl antenna size)
Photoelectrochemical production of hydrogens	National Renewable Energy Laboratory; University of Hawaii	Development of durable and cost-effective photoelectrochemical hydrogen production systems
	UC Santa Barbara; SRI International	High-throughput analysis to identify candidate materials for further study

Table 2.3: Photolytic R&D Activities **[33]**

2.2 Delivery Methods

Since hydrogen has a relatively low volumetric energy density, transportation of hydrogen from point of origin to point of use is still very costly. Hydrogen is typically either transported by liquefying it and carrying it in cryogenic tankers, or through pipelines **[5]**. However, pipelines are very few and far between due to the small number of hydrogen plants in the U.S. The U.S. Department of Energy has set up a Hydrogen Delivery Program with the goal of "developing hydrogen delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power."**[6]** Under the Hydrogen Delivery Program, they hope to reach the following goals:

- By 2006, define criteria for a cost-effective and energy-efficient hydrogen delivery infrastructure for the transition and long-term use of hydrogen for transportation and stationary power.
- By 2010, reduce the cost of hydrogen transport from central and semi-central production facilities to the gate of refueling stations and other end users to <$0.90/gge of hydrogen.
- By 2010, reduce the cost of compression, storage and dispensing at refueling stations and stationary power facilities to less than $0.80/gge of hydrogen.
- By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units to less than $1.00/gge of hydrogen**[6]**

All of these targets are based on a well-established demand for hydrogen in the transportation market, but they are still very feasible with the way hydrogen technology is progressing.

2.3 Hydrogen Safety

To most, the mention of hydrogen invokes images of the 1937 video showing the Hindenburg going down in flames. The fact is that explosion was caused by improper material selection and faulty installation, but because of Hindenburg-like disasters, hydrogen isn't widely thought of as a safe fuel, and without willing consumers there's no market. Hydrogen has many advantages over gasoline; it is less toxic and burns cooler. It also has a lower specific heat, higher ignition temperature, and lower explosion energy than octane. Gasoline has higher ignition energy, lower flame velocity, and a slower dispersion rate than hydrogen, but these "flaws", when properly analyzed, can become hydrogen's greatest safety attributes **[7]**.

As a gas, hydrogen is commonly pressurized to between 5000 and 10000psi. This allows for a smaller storage footprint as well as more volumetric energy. When stored as a high pressure gas, hydrogen is actually an incredibly safe energy source. A perfect example to demonstrate this is the EERE's fuel leak simulation **[8]**, performed in 2001. In the study, a leak was created in the gas tank of two vehicles, one containing octane, and the other containing pressurized hydrogen.

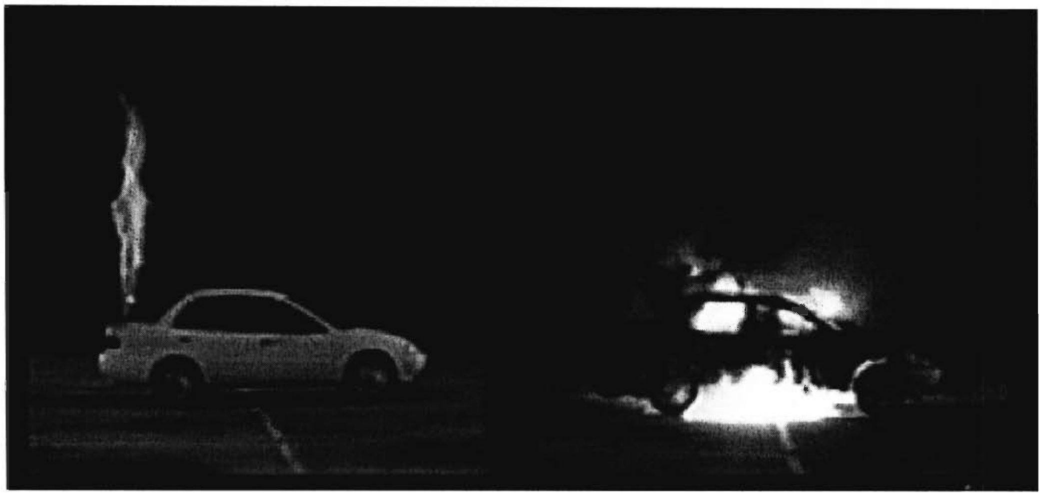

Figure 2.1: Photo from EERE Fuel Leak Simulation [8]

In the car with traditional gasoline, the slowly leaking fluid was ignited and the flame proceeded to slowly spread through the exterior and interior of the car. After about 3 minutes there was a series of explosions from the tires, gas tank, and the car was completely destroyed. In the case of pressurized hydrogen, the leak was ignited, and long flame jet shot out that lasted about 90 seconds before dying down. The car with the hydrogen remained perfectly intact; the only damage that may've been inflicted on the car would be a small area that needed to be repainted. In its gaseous form, especially at high pressure, hydrogen is less dense than air which allows it to rise up away from the leak and away from anywhere it can cause any real damage. Because it has such a quick dispersion rate, it is able to spread out into the air incredibly quickly, losing its combustibility. Any leak in a pressurized tank would have the gas expanding into the air, and raising up almost instantaneously.

Pressurized hydrogen gas is not perfect; unfortunately, safety concerns arise when a leak happens in a closed area like a garage. If the gas had no or little area to escape, the leaking gas could build up and create a safety hazard. If there was an ignition force while the gas was still built up, results could result in property and personal casualties. To avoid problems like gas buildup in a garage, and prevent another large scale disaster like the Hindenburg would be a relatively simple task. New standards for material, installation could easily be put in place to prevent large scale errors. Hydrogen detectors could be placed in the household and could work in the same fashion that carbon monoxide detectors work. Simple precautions like these could go a long way in making hydrogen an even safer fuel than it already is.

Hydrogen also has the ability of being cryogenically liquefied by running it through a compressor at temperatures below -100˚F. Liquefied hydrogen allows more energy per unit volume, but also causes a series of safety concerns. When in its cooled liquid state, the gaseous vapor released from the liquid is no longer maintains its lighter than air density as if it were a gas. If the gas tank scenario played out above were to be re-enacted with liquefied hydrogen, the hydrogen car would suffer a fate similar to that of the gasoline car. The vapor being released would add a second explosive element to the liquefied fuel still in the tank. This would leave the car with high flamed velocity liquid inside the gas tank, and high flamed velocity gas around the exterior and base of the car. It's like a double edged sword in that it creates significant danger inside and outside of the vehicle. To take it even further the super cooled liquid would make the storage containers more susceptible to failure. The low temperature in a tank makes the surrounding walls more brittle allowing cracks and breaches to occur more easily. Another liquid hydrogen safety risk is due to the low pressure the fluid is stored at. Liquefied hydrogen is kept at pressures of around one-twentieth that of gas so the containment devices used to store it are designed to have less durability. The weaker walls are more subject to failure from normal wear and tear, and also make it more susceptible to explosion.

Explosions in a liquefied hydrogen tank can be cause by either a difference in pressure, or like its gas counterpart, some sort of ignition energy within the storage tank. To stay in its liquid form the tanks need to have constant refrigeration to keep it from turning into a gas. If there is ever a failure in the electrical or mechanical devices used to refrigerate the liquid, temperature would start to rise inside the tank. Because of the fixed containment volume and the pressure within, a phase change will not occur. Instead the liquid will keep rising to its boiling point. Any heat transfer above creates molecular density fluctuations. These fluctuations create air pockets which create sonic waves within the liquid. These waves could cause catastrophic explosions of the tank, although the probability of mechanical failure or even a surrounding fire highly unlikely. As appealing as liquefied hydrogen appears with its volumetric energy density, the safety risks involved with it may never let it get off the ground **[9]**.

Comparing the risk assessment of hydrogen in its liquefied form and pressurized gas form, the pressurized gas has a major advantage. As good as liquid hydrogen sounds, concerning the amount of storage space needed, the potential for safety disasters makes it highly unlikely to become a mass-marketed product. As a gas, however, hydrogen possesses all the safety traits one would want in a fuel for a car and transportation and most of these characteristics carry over to use in the home. Hydrogen gas is non-toxic before and after combustion, and in the event of ignition the fire would dissipate and burn itself out in a matter of seconds, as opposed to minutes. The likelihood of explosion would be near impossible, minimizing damage and harm to the surrounding area.

2.4 Production and Delivery Challenges

As with any new technology, there are almost always kinks and bugs to work out, and hydrogen is no exception. According to the EERE **[27]**, the main goal in the hydrogen industry is to keep working towards reducing the cost of hydrogen, but there are five other areas that need to be analyzed as well; the hydrogen infrastructure, feedstock trade-offs, system efficiency, electrolytic technologies and emerging technologies.

While there has been lots of talk about building a hydrogen infrastructure as of late, no one has actually done an in-depth analysis of what needs to be done to make it actually happen. Every minor detail and contingency would need to be evaluated and factored in to the building if necessary. The options and trade-offs of having central, semi-central, or distributed points of production need to be analyzed, as well as the effectiveness of delivery from well-to-wheel. None of these aspects are well understood yet, and before we can get any sort of plan in motion, this massive undertaking needs to be done by the EERE or the DOE.

With each different feedstock that is used for hydrogen formation, there are a number of advantages and disadvantages to each one. The common trend in each case seems to be that the more potent the feedstock, the more emissions and other side effects are released during the production process. Steam methane reforming and algal photoproduction are two perfect examples of both ends of this spectrum. SMR is one of the most efficient and potent hydrogen production methods around today, but during the production process it requires natural gas to be burned, releasing greenhouse gases and other harmful emissions into the air. Algal photoproduction, while not nearly as potent as SMR, releases no greenhouse gases or other emissions during the harvesting of hydrogen. Hopefully, scientists will be able to come up with a method that rivals the potency of SMR with the environmental friendliness of algal photoproduction, but until then we will have to keep on working with what we have.

System efficiency is another problem that researchers hope to overcome in the near future. As with the feedstock trade-offs, the trend in hydrogen production is that the more efficient a system is in producing hydrogen, the worse it is for the environment. Researchers are also hoping to improve upon all hydrogen system efficiencies, because current systems are nowhere near 100%, allowing huge amounts of the hydrogen that could be produced to go to waste. A perfect example of the efficiency trade-off is the use of electrolysis. Electrolytic systems utilizing electrolysis are currently one of the most efficient methods that we have available, but they are also the biggest polluters of any hydrogen technology.

The removal of electrolyzers from hydrogen production is a huge milestone that scientists hope to achieve within the next 10 years. While they are very capable of producing and harvesting hydrogen, they consume large amounts of fossil fuels and emit lots of greenhouse gases and nitrous oxides. This trade-off is not worth it in the long run because essentially we would still be very reliant on fossil fuels to produce the hydrogen and we would still be polluting the air in massive amounts near hydrogen production facilities. Scientists hope that with new, emerging technologies, the use of electrolyzers can be phased out completely to create a safer, greener technology.

Emerging technologies is a very key aspect in the world of hydrogen production. Universities and private corporations are always researching new possibilities to come up with the next big breakthrough in hydrogen production, so before anyone decides to invest large sums of money to a specific technology, they might want to wait a few years to see what evolves. Methods such as the use ceramic membranes or high-temperature thermochemical production just came out and have generated a lot of interest within the hydrogen community. This might explain why there has been such hesitation by large corporations to invest in hydrogen technology. As of late, the stock market has shifted towards the bears and away from the bulls, so while hydrogen is an up and coming technology, it also had the misfortune of being brought up in the middle of an economic slowdown. There aren't as many people out there willing to make a risky investment in new companies since the dot-com bubble burst a few years ago, so the funding that many hydrogen researchers need is not there. The U.S. government has already tried to generate interest in new, greener technologies by offering incentives, such as tax breaks, to companies that make efforts to reduce their pollution or switch over to environmentally friendly. However, in order to get investors to put more money into hydrogen research, the government could show initiative by investing into the technology themselves. More ideas on how the government can promote growth in the hydrogen industry can be found in section 3.6.

3. TRANSITIONING TO A HYDROGEN ECONOMY

3.1 How to Begin the Transition

Looking at the progress of current hydrogen technology, in both production and delivery aspects, and where it is heading in the next five years, it can be assumed that the start of a full transition in the near future would likely flop. That being the case, there needs to be an alternative to ease hydrogen fuels into the consumer market in order to generate enough appeal and demand so that it will create widespread acceptance by the general population. A possible transition method would be to introduce it into one market, mostly private applications, and let technologies develop from there by offering incentives for further research, before introducing it to other markets. The transition can also be made by introducing hydrogen produced from fossil fuel, like from steam methane reforming or even nuclear energy. While this method is still environmentally unfriendly, due to the hydrocarbons and greenhouse gases emitted during production, it is a step in the right direction until the development of perfectly renewable resources matures.

There are several options as to what market to introduce hydrogen into first. The private domestic, private transportation and public transportation sectors are three of the best suited to enable hydrogen conversion. In the private transportation sector, the technology exists for a complete changeover to hydrogen. Honda has already created a hydrogen-powered car, the FCX, one of the first vehicles of its type that is able to be mass-produced. It looks and drives like a normal car, rather than a futuristic science experiment from the 1950s, unlike many other fuel cell vehicles (FCVs), giving it considerably more consumer appeal. However, the cost to purchase an entry level fuel cell vehicle is more than ten times that of what it costs to buy an entry level gasoline vehicle; it costs almost $200,000 to purchase a Honda FCX **[10]**. The car gets more than 60 mi/kg (the hydrogen equivalent of mi/gal) in city conditions **[11]**, but the advantages of having such great fuel economy would be negated by the high cost of hydrogen gas. If hydrogen were to enter the private transportation sector with prices still as high as they are, it would scare consumers away from the technology, at least for the near future, until prices were lowered appreciably.

Moves have already been made to introduce hydrogen and fuel cells in the private electronics sector. Companies such as SiGNa, based in Canada, have begun to market their hydrogen producing technology by collaborating with large electronics companies to introduce hydrogen fuel cells into small electronic devices like laptops, cell phones, and PDAs **[12]**. Cell phone prototypes have already been developed using hydrogen fuel cells to power them. In America, cell phones still serve as a status symbol, although nowadays most people have one. People are always searching for the most attractive, most feature-packed cell phone available, and if the industry can prove that hydrogen-powered cells last significantly longer in-between charges while remaining competitively priced, a major trickle-down effect would occur. Demand would take off, thereby forcing a need to increase the supply, which would lead to further improvements in technology and lowered prices. Unfortunately, there are still many aspects in this field, such as how to recharge the hydrogen fuel cell, that need to be fixed.

Another option for the introduction of hydrogen would be to follow in the way of Iceland's public transportation system. Iceland is leading the way in the transition to a hydrogen economy because its geothermal resources allow for more affordable and renewable hydrogen than countries without the same capabilities. The country plans to be completely hydrogen-dependent within the next 25 years. They have already started the transition to a full hydrogen economy with the conversion of their public bus system. Their current fueling infrastructure consists of hydrogen fueling stations at main bus hubs, with plans to expand the number and frequency of fueling stations in the near future. Starting the transition with larger vehicles like busses is a better idea than individual vehicles because fuel cells are still rather large and bulky, and cramming them in small, compact spaces with current technology creates more safety hazards. The size of systems affect the aesthetics of a product, thus affecting its consumer appeal, so until the cell size can be downsized, the idea is capsized. There are also two other major reasons why the United States can't make the jump as easily as Iceland. First, as was noted earlier, we are sorely lacking in geothermal resources compared to Iceland, meaning that we do not have the ability to produce perfectly renewable hydrogen on a large scale. Second, the sheer difference in the sizes of our countries makes conversion that much more of a problem for America. In a study by Wired Magazine **[13]**, they determined that if Iceland were to strategically place hydrogen fueling stations throughout their country so that a FCV could travel on a full tank load from one station to the next, it would take only 60 stations to cover the entire nation. If the same were to be done in America, it would require 1,440 stations, and considering that America had nearly 210,000 stations in 1992 **[14]**, the number that would actually need to be installed is considerably higher.

Regardless of which introduction method is decided upon, there would still have to be assistance to push it along. A likely assistant for this push would come from government funding. New technologies are usually not widely adopted, and in the past new landmark technologies have required brief government funding to initially make the technologies more affordable. The internet is a good example that required some extra government funding to start up the new technology, and now it has spread to the point where it's almost impossible to get along in school or business without having access.

3.2 Atmospheric Predictions and Implications

Hydrogen gas in its pure form is a naturally occurring trace gas that accounts for approximately 0.5ppm molecules of air, meaning that the Earth's atmosphere contains roughly 175Tg of H_2. Nearly half of this is produced in the atmosphere by photochemical oxidation of methane and other hydrocarbons, while the other half is the reaction from combustion and biogenic processes occurring on the Earth's surface. When hydrogen gas is consumed by a FCV, the exhaust doesn't contain any odd-nitrogen compounds (NO_X) that are typical of internal combustion engines. NO_X molecules are a key element in the formation of smog buildup. If we can perfect the production of hydrogen using non-fossil energy, then carbon dioxide emissions can be eliminated as well, making hydrogen a very viable solution for many major atmospheric issues. However, according to a study done by Prather **[22]**, while greenhouse gases may be eliminated, the influx of hydrogen may lead to new problems:

> "The chemicals that we dispose of in the atmosphere often return as unexpected environmental problems--witness the transport sector and local air pollution, halocarbon production and global ozone depletion, and fossil fuel use and global climate change. The seriousness of these problems was not discovered until after the technologies had been introduced, partly explaining the contentiousness of the public debate over remedying them. Given

> the growing interest in an H_2 economy, now is the time for assessing its environmental consequences."

The rise of the hydrogen economy has in fact already led to some studies about environmental and atmospheric impacts. Tromp *et al.* **[23]** concluded in one such study that the widespread use of hydrogen fuel cells could lead to unexpected consequences due to unintended emissions of H_2. The extra hydrogen molecules released would then combine with hydroxyl radicals in the air, theoretically causing an increase in the abundance of water vapor in the stratosphere, possibly as much as 1ppm. That increase of water vapor could lead to "stratospheric cooling, enhancement of the heterogeneous chemistry that destroys ozone, an increase in noctilucent clouds, and changes in the tropospheric chemistry and atmosphere-biosphere interactions."

Once H_2 has been released into the atmosphere, however, it doesn't just sit there and accumulate. It is broken down in one of two ways, either photochemically in the atmosphere, by combining with a hydroxyl radical to form water vapor, or biologically in the soil, being consumed by microorganisms. And while H_2 has been touted for years as an environmentally friendly gas, it turns out that it has been recognized as an indirect greenhouse gas, because of its photochemical breakdown. The H_2 molecule actually affects atmospheric chemistry similarly to carbon monoxide. When it combines with the OH radical, it takes away one OH and releases a H_2O radical into the air, and while the H_2O radical itself is harmless, it takes away the needed OH molecule which acts as an absorption material for methane, which would lead to an abundance of methane.

To prevent these scenarios from happening, improvements are needed on hydrogen storage units. As with any other gas, minor leaks are bound to occur here and there, and 100% containment of hydrogen is a definite impossibility. But with regulations and metering by the government and its agencies, hydrogen leakage can be monitored to prevent any long-term damaging effects, before it becomes too late like with fossil fuels.

3.3 Economic Predictions and Implications

In this section, we will review the possible futures of the energy economy based on today's leading methods. A breakdown of current day prices, as well as projected prices for the year 2025, for each technology is provided. From there, we projected how much it would cost annually to produce the hydrogen equivalent of petroleum and natural gas energy that will be consumed by Americans. A side-by-side comparison of all the methods and their respective projections can be found in Table 1 at the end of this section.

3.3.1 Petroleum

Based on projections done by the Energy Information Administration, a total of 85.89qn Btu of energy will be consumed by America in the year 2025, 54.42qn of that being petroleum products, and the rest (31.47qn) being supplied by natural gas. By the year 2025, petroleum is projected to have a price of $1.58 per gallon, due to a rapid exponential decrease in price of petroleum products. One barrel of a petroleum product contains 42 gallons of fuel which is capable of producing 5.8 million Btu. To produce 54.42qn Btu of energy it would require roughly 9.38 billion barrels of petroleum, or 394 billion gallons. At the modest price of $1.58/gal, it would cost approximately $622.5 billion dollars to keep up with the world's oil demands. However, given the present day gas scenario, a price of $1.58/gal seems a bit unreasonable. With gas prices hovering closer to $3.00/gal, it's safe to assume it will at least still be around that point in the future. At a cost of $3.00/gal, the petroleum costs inflates nearly half a trillion dollars, up to $1.18 trillion **[16]**

Again, based on the projections given by the EIA, natural gas will have a cost of $8.23 per thousand cubic feet in the year 2025. One-thousand cubic feet of natural gas is capable of producing 1.03 million Btu. For natural gas to produce the projected 31.47qn Btu, it would require around 30.52 trillion cubic feet. At a cost of $8.23 per thousand cubic feet, the total cost is about $251.2 billion annually to fulfill the predicted natural gas quota. When you add the two together, the annual cost for petroleum and natural gas products is approximately $1.431 trillion **[16]**.

3.3.2 Algal Photoproduction

At the end of the 2003 research year, the annual report given by the National Renewable Energy Laboratories (NREL) concerning current and predicted costs of hydrogen production using algal photoproduction. At the time of the presentation, the cost of producing one kilogram of hydrogen was $200, significantly down from $760 in the year 2000 **[17]**. Knowing that the energy output of hydrogen is 52,000 Btu/lb (114,640 Btu/kg) **[1]**, it would require approximately 744.3 billion kg of hydrogen to fulfill the 85.89 quadrillion Btu energy output predicted for the year 2025, which at a cost of modern day $200/kg would run about $149 trillion. However, researchers project that with further developments of the process, such as mutated hydrogenase enzymes in the algae and higher efficiency outputs, costs are predicted to decrease by a factor of nearly one hundred, all the way down to $2.34/kg (using land-based algal systems) and even as low as $1.40/kg (using ocean-based algal systems) **[18]**. The total costs of a hydrogen economy would range between $1.05 and $1.75 trillion within the next 20 years, but this all depends on whether or not scientists and researchers can meet and/or exceed their desired milestones. Assuming that algal production is split in half between land-based and ocean-based systems, the average cost of hydrogen production would be approximately $1.4 trillion annually, which is very competitive with the price of fossil fuels, putting hydrogen in a prime position to overtake fossil fuels.

3.3.3 Biomass

In 2005, the Gas Technology Institute gave a presentation at the 2005 DoE Hydrogen Review Board on hydrogen production technologies using biomass. They showed that biomass may reach a cost of $2.50/kg of hydrogen as early as the year 2010 **[19]**. As we have already reviewed, to completely replace natural gas and petroleum 744.3 billion kg of hydrogen is needed. At a price of $2.50/kg, it would cost approximately $1.86 trillion to replace both natural gas and petroleum. While this a bit more costly than fossil fuels or algal photoproduction, it is still a very viable alternative for the future of energy. As an interesting note, if biomass were used just to replace petroleum needs in the year 2025, it would require approximately 474 billion kg of hydrogen to be produced, at a cost of about $1.18 trillion. This would be roughly the same cost as petroleum (assuming the cost of $3.00/gallon) for total energy consumption, but the environmental effects would be much more desirable.

3.3.4 Electrolysis

Based on the presentations given at the Department of Energy Hydrogen Review by the NREL and Giner Electrochemical Systems, the DOE is requesting the price of hydrogen created through electrolysis be down to $2.85/kg in the year 2010. The NREL even predicts that by 2015 the price will be down to $2.75/kg **[20]**. With a price of $2.85/kg, it would cost around 2.12 trillion dollars to replace petroleum and natural gas, and around 1.34 trillion dollars to replace just petroleum. If electrolysis meets the projected costs by 2015 and remains the same until 2025, it would cost 2.04 trillion dollars to replace natural gas and petroleum, and 1.3 trillion dollars to replace only petroleum. Despite the enormous potency of electrolysis, the hydrogen industry plans to phase out electrolyzers due to their huge pollution emissions, but this is just another example of the competitive pricing hydrogen can bring to the table.

3.3.5 Steam Methane Reforming

Steam methane reformation is currently the biggest and cheapest hydrogen production resource in the United States. Based on a presentation given at the Department of Energy Hydrogen review by Air Products and Chemicals Inc, a kg of hydrogen produced through SMR can currently be obtained for $1.56 **[21]**. Assuming that cost will remain constant, it would total up to 1.16 trillion dollars to replace energy from petroleum and natural gas in the year 2025. The company H2gen has predicted costs to drop slightly to $1.50/kg in the next five years (by 2010) **[22]**. That estimate includes all the costs needed to make the hydrogen and get it shipped to the consumer. However, predictions have the price of availability dropping significantly down to nearly 58 cents per kilogram by 2025 **[21]**. Based on the estimated energy consumption in the year 2025, if all hydrogen in the United States was supplied through SMR, it would cost a mere 431.7 billion dollars to replace the energy provided by petroleum and natural gas, or 274.9 billion dollars to replace just petroleum.

	Petroleum		Natural Gas	Algal Photoproduction		Biomass	Electrolysis	Steam Methane Reforming
2025 Projections								
Price per Unit	$1.58	$3.00	$8.23	$1.40	$2.34	$2.50	$2.75	$0.58
Total Units Needed	394 Billion		30.52 Billion	744.3 Billion		744.3 Billion	744.3 Billion	744.3 Billion
Projected Annual Cost	$622.5B	$1.18T	$251.2B	$1.05T	$1.75T	$1.86T	$2.04T	$431.7B
Total Cost of Fossil Fuel	**$873.7B**	**$1.431T**						
Total Difference				**-$381B**	**$319B**	**$330B**	**$609B**	**-$999B**

Table 3.1: Side-by-side fiscal comparison of energy sources

3.4 Consumer Appeal

A transition to a hydrogen economy will never be able to occur if there aren't desirable hydrogen products to bring it into the mainstream. With Western culture so heavily obsessed with image and aesthetics, it may not be the easiest thing to do, proposing a serious challenge for hydrogen fuel cells. People buying a new car want something that reflects their personality, and many people do not think of themselves as a giant brick on four wheels. Drive trains and fuel cell sizes are considerably larger than conventional gasoline engines, forcing designers to get more creative with the lines they use to sculpt a FCVs exterior. Some automakers have already succeeded in masking the technology. Looking at a Ford Focus FCV **[24]**, nobody would be able to tell anything was different, except for the fact that they are completely covered up with fuel cell stickers and decals because they are still in the testing phases. Ford's designers succeeded in making a car that looks normal, but even at first glance you can tell there is something just not right with the proportions. At the very least, this shows promise that there will be a market for fuel cell cars that are appealing. As for performance, the horsepower these cars are capable of isn't that impressive yet, but there is enough torque to make the cars feel plenty quick in everyday driving conditions. FCVs also have an incredible fuel economy of 60-plus mi/kg in the city, more than making up for the lack of speed. However, if the consumer still wants to fulfill their need for speed, there is also the option of hydrogen internal combustion engines.

Hydrogen internal combustion engines (ICE) aren't as environmentally friendly as fuel cells; they still release some greenhouse gases and they don't get as good fuel economy as a FCV. The technology, however, is not much different than modern day engines. Hydrogen ICEs are roughly the same size and weight as modern day gasoline engines, so fitting them into cars we already like won't be a problem.**[25]** The engines are able to produce a considerable more amount of horsepower than fuel cells, giving it a better chance for a market in the already massive tuner industry. You can already buy a reproduction of a Shelby Cobra powered by a hydrogen internal combustion engine.**[26]** Though no horsepower or torque numbers are given for the vehicle, anything carrying the Shelby name will undoubtedly be incredibly fast and powerful.

Other consumer markets, such as hand-held electronics and domestic items, are considerably more marketable for a number of reasons. The mechanical complexity of products in these markets doesn't come close to that of the auto industry, making bulkiness less of an issue. The transition to hydrogen-powered products would be for the most part unnoticeable, because aesthetically and performance-wise they are very similar to products already on the market. Cell phone and laptop hydrogen battery lifetime are comparable to traditional batteries, if not better. Electric and heating bills would be lowered, because the higher energy potential of hydrogen requires less of it to complete the same tasks as other energy sources. The consumer appeal is already there because it has been proven with traditional products, their hydrogen counterparts just need to make their way off the drawing board and into reality.

Hydrogen products are made more desirable by environmental benefits. American society has woken up to the fact that we need to help save the environment, and an increasing number of celebrities are advocating this cause, promoting hybrid cars and shunning gas-guzzling SUVs. Even if some of these products enter the market at a price higher than what we're used to, there will still be a large group of spenders willing to take the hit in the wallet if it means saving the environment. A good example of this is with the Toyota Prius. The half-electric, half-gasoline powered car entered the market at a price nearly twice that of the baseline Toyota model. The car became an instant status symbol when stories of big celebrities driving the car were all over the news. With greater environmental benefits from hydrogen, an even larger explosion of hype could be expected.

3.5 Transition Obstacles to Overcome

Despite all the great advances in hydrogen technologies, there are still many setbacks to overcome before the dreams of a hydrogen economy can be achieved. The cost of hydrogen is still very high compared to gasoline and other energy carriers, but with the Hydrogen Delivery Program, the Department of Energy hopes to bring the overall cost of hydrogen production down to $2.34/kg of hydrogen by 2010.**[18]** One kilogram of hydrogen contains approximately the same amount of energy as one gallon of gasoline, so if this goal is reached, it would bring a huge relief to the skyrocketing prices of gasoline and other fossil fuels.**[1]** Another huge cost standing in the way of mass hydrogen production is the use of electrolytic technologies. While these systems are fairly efficient, they are also incredible costly and emit a large amount of greenhouse gases still, which is the antithesis for why we are switching over to hydrogen fuel in the first place. Better developments in technology and system integration with low-cost, emission-free electricity sources are needed in order to be competitive with conventional fuels. **[27]**

The largest obstacles to overcome when considering a transition to hydrogen as an energy carrier are the delivery and storage aspects. A common form of fuel transport these days, even in domestic situations, is by way of tanker trucks. However, due to the incredibly low density of hydrogen, it would require 3 truckloads to of liquid hydrogen to deliver the equivalent energy output of one truckload of oil or petroleum **[28]**. By pressurizing the hydrogen gas somewhere between 5,000-10,000psi (the pressure at which automakers are hoping to store it in their vehicles) to increase the volumetric energy density is one possible solution to this problem. However, the process of compressing the gas to this level requires approximately one-third the amount of energy that the payload is capable of producing, which makes it an economically unwise decision. Another possible solution is through cryogenic liquefaction of the hydrogen gas, but transporting and storing liquid hydrogen is more of a safety hazard than in its gaseous form. The higher cost and safety risk of using refrigerated trucks, as well as the energy and capital it requires to produce liquid hydrogen is again more energy than its worth. This essentially leaves the only option being small, on-site hydrogen production plants.

There are many different options that can be considered when thinking of on-site energy production. In an ideal world, it would be possible for every domicile to have its own power plant. If that were to happen, a household would pay one flat fee for essentially infinite energy for their home and cars, only having to pay for maintenance after that. However, an energy station that could be used to power the average home typically costs upwards of $30,000, and most people aren't willing to pay that much, let alone be able to afford it. Also, most homeowners wouldn't want to compromise the aesthetics of their house by adding fairly large, unsightly structures in their garages or backyard, assuming they had room to fit one in the first place. A more viable solution is to have bigger production plants at fueling stations or dedicated power plants. From there, the hydrogen can be shipped directly to the consumer's home via a pipeline system that could be piggybacked onto the already existing gas mains, where it can be stored in underground tanks until it is consumed. In that situation there would still be the economic benefit of competition between several fueling stations, which would keep hydrogen prices in check.

3.6 Government Backing for a Hydrogen Economy

In order for a hydrogen economy to get off the ground, the U.S. Government would really need to step up and push the American people to get the job done. In 2003, President Bush asked Congress to allocate $1.2 billion in funding for the "Freedom Car" program, a program put in place to design a revolutionary "pollution-free" automobile **[38]**. Of that $1.2 billion, more than half of it is earmarked for automakers and the already booming oil industry. The oil industry giants have already realized their future downfall, and so in order to secure their futures as energy suppliers, the oil companies have begun investing in hydrogen technologies. Companies like Texaco, ExxonMobil, and Shell have taken the initiative by investing in promising companies and university research. The funds supplied by these companies total up to approximately $400 million **[34, 35, 36]**. These contributions will most likely increase over time to ensure these oil companies have a greater market share of the hydrogen technologies. However, the funding from these companies may start veering the technology in the wrong direction. The companies are pushing hard to ensure future hydrogen production will still mainly come from fossil fuels like natural gas and oil. Similar pushes can be seen in the Energy Policy Act of 2005 (public print) **[37]** where increased use of coal, natural gas, and nuclear power are all encouraged for hydrogen production with generous appropriations (Sections 401, 902, 104). However, it is in society's best interests that the economic and environmental benefits of hydrogen are brought to their full potential. If we want to see significant increase in both these aspects, renewable energy sources need to be taken off the back burner by legislative representatives.

To remedy this potential disaster of hydrogen future, members of Congress, as well as hydrogen watchdogs, need to start lobbying for a considerable increase in government and private funding now. There are emerging technologies for renewable energy that would be able to compete with fossil fuel methods, but they are lacking in capital and exposure. These technologies need to be continually brought to the attention of our government and the general public in order to receive significant funding, before they get left in the shadow of their hydrocarbon-producing siblings.

While acts such as the Freedom Car program may seem like a huge push for hydrogen conversion, in reality it is merely a pittance compared to what the government could be providing. Consider this, the war in Iraq and Afghanistan has cost the government a total of $314 billion so far, with predicted expenses of $450 billion over the next decade to clean up. **[15]** That's an average of $105 billion spent each year so far. According to an article in Wired Magazine, if America was to take that $105 billion spent each year and put it towards researching hydrogen production instead, the hydrogen dream could be achieved within the next decade:

> "With that investment, ($100 billion over the next 10 years), the nation could shift the balance of power from foreign oil producers to US energy consumers within a decade. By 2013, a third of all new cars sold could be hydrogen-powered, 15 percent of the nation's gas stations could pump hydrogen, and the US could get more than half its energy from domestic sources, putting independence within reach. All that's missing is a national commitment to make it happen.
>
> It'd be easy - too easy - to misspend $100 billion. So the White House needs a plan. The strategy must take advantage of existing infrastructure and strengthen forces propelling the nation toward hydrogen while simultaneously removing obstacles." **[13]**

The Icelandic government has already begun to set up a hydrogen infrastructure, and plans to be completely free of fossil fuels within a 30-year timeframe. They are leading the way into this new era, with many other nations intently watching their progress. The United Kingdom and China have also set plans in motion to convert over to a hydrogen economy, using Iceland's infrastructure model as a prototype to build off of. With many other countries already realizing that a global hydrogen economy is within sight, America really needs a huge government commitment in order to get in on the ground floor. Scientists have predicted that the Earth's wells of cheap renewable crude oil will be depleted between 2038 and 2050, so if America keeps shuffling its feet when it comes to hydrogen, then when the energy conversion becomes a necessity rather than an alternative, America will fall so far behind the other world superpowers. If Congress took actions in order to turn the United States into a hydrogen-producing powerhouse, the economic implications alone would be huge. More jobs would be created at the opening of hydrogen power plants and the building of the hydrogen infrastructure throughout the United States. There would also be significant economic growth because of the reliance on domestic energy sources, rather than foreign countries. However, none of this will happen unless the government and its agencies complete the task of analyzing and creating the basis of a hydrogen infrastructure here in America. As was mentioned earlier, the EERE noted that a major obstacle to the realization of hydrogen is that no one has undertaken the necessary steps to determine what type of production and distribution system would be the most advantageous in America. Without any set plans in place, it is no wonder that hydrogen companies are having a hard time finding adequate investments.

Right now, there is weariness about investing due to the fact there is no quick return from investing in hydrogen. There are still a lot of unproven aspects to hydrogen as well, making investors want to wait until there is more of a "sure thing." Even then, investing in hydrogen would take about 10 to 15 years before any sort of significant profit is made, and not many people are willing to take that big of a risk. By offering incentives to investors and private companies alike, the government can help to stimulate growth in the hydrogen economy. Congress could also lead by example, investing significantly more money into hydrogen research. If they were to invest the $100 billion over 10 years, as was suggested by Schwartz **[13]**, rather than the paltry $1.2 billion per year, it wouldn't only help the progress of research and development. It would show individual investors that there is a significant amount of confidence in hydrogen, and that it will be here for the long run. An initial investment that huge by the government could lead to more investments from private companies and corporations, leading to a snowballing effect of the amount of revenue in the hydrogen industry. The potential for hydrogen to be the next frontrunner in energy has been there for awhile, all it really needs is one big push.

3.7 Comparison with Diesel and Bio-Diesel

Other countries across the globe have already been dealing with the crisis of high oil prices for the last decade. In Europe prices are over $5.00 per gallon of gasoline, and in Japan the prices have been hovering around $4.00 a gallon **[40]**. These high gas prices have driven consumers and car companies to start investing in the most popular alternative fuels, such as diesel and hydrogen. Diesel cars now make up more than one-third of the cars in Europe, and that mark is quickly being approached in Japan. Diesel fuel tends to be 10-15% cheaper than regular unleaded gasoline in these areas, and has been proven to be upwards of 50% more efficient than their gasoline counterparts **[42]**. As promising as all these figures sound, however, diesel isn't a probable solution to the energy crisis to be faced in the United States.

Despite the fact there are diesel vehicles being produced and sold in the United States, they aren't nearly as popular here as they are in Europe and Japan. The reason for this is there are stricter emissions laws against the high sulfur emitting diesel exhaust. The majority of diesel automobiles sold in other countries cannot legally adhere to these laws, so they never make it to our shores. A solution may be possible in the year 2007, when laws allowing new low sulfur diesel come into effect **[43]**. However, the face-lifted diesel will be even more expensive than regular gasoline, making it more of a burden on consumers.

Diesel-powered cars may be able to be salvaged in America by its clean burning counterpart bio-diesel. With a soybean oil base, bio-diesel shares all the same efficiency benefits of regular diesel, but without the pollutant producing emissions. Another advantage of bio-diesel is it can be made by essentially anyone with easily obtainable equipment for very little money; but non-officially distributed bio-diesel voids warranties and consumer agreements of the cars it is used to power. Since voiding a car's warranty will turn most consumers away from home-made bio-diesel, consumers need to buy it from traditional gas stations that sell the special fuel.

As with buying regular diesel, buying bio-diesel at a gas station has its disadvantages as well. Bio-diesel purchased at a gas station can be as much as one dollar above regular diesel price per gallon, and that's only for fuel consisting of up to 20% bio-diesel while the rest is still regular diesel. Recent tax incentives have been put in place for consumers wanting to buy bio-diesel, but only cover diesel fuels up to 20% bio-diesel content. Anything more than 20% bio-diesel still faces the normal tax rates similar to traditional diesel. So if a consumer was truly environmentally conscious about their diesel use and wanted to go au-natural with 100% bio-diesel, they would find themselves paying up to $5.00 a gallon for the pure stuff over the government subsidized 20% bio-diesel, which still fetches a pretty penny of around $3.50 a gallon **[41]**.

While diesel already has an infrastructure setup in the United States, the high costs and amount pollutants that remain cannot be ignored. The parts of Europe and Japan that have embraced diesel for now will still run into the same problems that have arisen with gasoline in the future. Also, there are currently very sparse technologies for utilizing diesel and bio-diesel in the domestic sector, whereas previously demonstrated, hydrogen technologies have already gotten a foothold. The more universal aspects of hydrogen and predicted lower costs in the future make it a much more viable and appealing alternative for the future.

3.8 Final Word on Government

Looking at these other countries can serve as a look into where our country is headed. European gas prices had already surpassed the current gasoline prices in the U.S. over a decade ago. It was when prices got to this level that the evolution towards the more efficient and practical diesel had started. Shortly after, gas prices in Japan reached these high European benchmarks. Countries around the globe have proven to have a limit where oil use becomes just too impractical for the price. It is then they start progressing towards something newer and better. It's safe to say the same evolution will have to happen to our country when our financial frustrations with gasoline reach that limit. To progress towards a newer and more practical fuel like hydrogen we will need the help and guidance from our government. Unlike other countries, strict emissions standards put in place by national and local governments make it impossible for a transition to diesel on this scale. Because the government won't allow use of such an internationally supported alternative, it only seems proper that they be the ones to guide and support us in our transition towards the next fuel. Keen interest in the subject matter of hydrogen production and hydrogen applications has been fueling a number of researchers to get things started over the last few years. But with the projection of where research is going and where it's at now, Hydrogen won't be a plausible solution for everyday use for another at least another ten years. If the government wants an energy source for the economy to fall back on when we meet our financial frustration limit with gasoline, and want it to be a domestic product to help support the economy, they need to step up now and start appropriating the proper funds so we will be able to make a healthy progression towards hydrogen in the next five years instead of ten. Other things like tax incentives can be put on hydrogen to help get it off the ground. Tax incentives on bio-diesel and hybrid cars have attracted the consumerism of Americans, despite their shortcomings. If similar policies were to be enacted on the hydrogen market, it can be assumed that the same success would carry over as well. Current political turmoil in countries that supply a great deal of our oil leave many reporters an political analysts saying that oil prices are going to go absolutely through the roof. Instead of waiting for that to happen to give our society and government the extra kick needed to go to our own domestic fuel source, funds should be appropriated now so that when this does happen, we will be ready well in advance.

4. CONCLUSIONS

4.1 Conclusions

The potential for hydrogen technologies has far evolved from only a couple decades ago. As demonstrated by our economic analyses, the feasibility of a competitive hydrogen economy is within reach in the next 20 years. With the obvious environmental and economic benefits, the only transition obstacles left are to increase hydrogen accessibility and market it to consumers. However, none of this will be achieved unless a stable groundwork and greater incentives are provided for the hydrogen industry. With the pace that hydrogen technologies are moving, it may be too late before America makes the full transition. If the United States hopes to remain competitive with the rest of the world in the hydrogen market of the future, the effort to plant the seed needs to be made today. Congress has appropriated $1.2 billion for hydrogen R&D for the fiscal year 2006, but as shown by the study done by Wired, if Congress boosted that total up to $100 billion over the next 10 years, the transition would be nearly complete by 2016. This would put the United States well ahead of other world superpowers in terms of energy production. By becoming a hydrogen-producing powerhouse, we wouldn't be reliant on other countries for our energy, helping us out of our economic slump. Our energy independence would help rejuvenate the job market with the opening of new plants and more opportunities for domestic research and development.

The furthering of hydrogen technology hinges on how well the groundwork is laid out and adhered to by our government. Even with proper government funding, there are a number of milestones that need to be met. By maintaining closer supervision, the Department of Energy will be able to ensure their required capital goals are met on schedule. Researchers and developers need to be held closer to their economic predictions in both the production and delivery aspects. Research projects concerning current gas manes and their hydrogen carrying capacity need to be accelerated in case other delivery methods need to be developed. Decisions need to be made concerning hydrogen for home use, and whether it will be provided by individual household plants or mass supplied by a central plant. Many other vital details of the hydrogen transition such as these remain undetermined, but with proper focus and direction, they can all be resolved with relative promptness.

The shift away from fossil fuel-reliance has already begun, and will eventually be completed in due time. Ninety percent of current hydrogen technology still relies on fossil fuel, a number needs to be brought significantly within the next decade, otherwise all of the work that has been accomplished will be worthless once the oil supply is tapped. Unless more aggressive actions are taken by our government to get the ball rolling, we won't be able to get out of our own way in time and miss out on an incredible opportunity.

4.2 Suggestions for Future Work

Other things to consider when talking about alternative fuels are a comparison between other green fuels like solar power and bio diesel. All three have very different advantages. Bio diesel has technology that is very economically and commercially advantageous in present day. It's not as green an energy source as say hydrogen or fuel cells, but it may very well serve as a segue fuel in the hydrogen transition. Solar power has been around seemingly forever, but has never really reached the lime light as it was predicted to. Its transportation applications in present day aren't completely reasonable, but it serves as a worthy substitute for fueling a household with a fair amount of consistency. Like hydrogen, all it may need to go that extra step is some more funding. Some combination of these two, and possibly other alternative energy like nuclear power, could have more benefits over hydrogen as energy sources. Maybe some of the combinations could serve as a transition to hydrogen sometime in the future.

One thing that was never looked at was what industry would be the ones benefiting from a hydrogen economy. We were only able to find a few patents that are held by oil companies concerning hydrogen production, while most of the rest are held by government agencies and smaller independent research companies. If and when the technology enters the market, the money flow from energy may start going to new places. It was never found out if the patents held by the big oil companies may be used to try to protect their future as fuel providers as hydrogen stations, or to sit on them and prevent such a transition from ever happening. But in either case, right now it looks dubious that these oil companies will remain on top of the energy industry over the next 50 years.

At the rate the United States government is pushing researchers and product development; we have potential to be the first country to have a functioning total or partial hydrogen economy. If this were to happen, the possibility of a large economic boom could ensue. As the only country in the world with these capabilities there will be some technologies unique to our domestic manufacturers and consumers. Commercial interests in these technologies from other countries would leave open the possibility for a large economic boom. The larger the government investment to get things moving faster, the larger and more timely the investment turnaround could be.

REFERENCES

1. United States Energy Information Administration (www.eia.gov)

2. HFCIT Hydrogen Production and Delivery: Thermochemical (http://www.eere.energy.gov/hydrogenandfuelcells/production/thermochemical.html)

3. HFCIT Hydrogen Production and Delivery: Electrolytic (http://www.eere.energy.gov/hydrogenandfuelcells/production/electrolytic.html)

4. HFCIT Hydrogen Production and Delivery: Photolytic (http://www.eere.energy.gov/hydrogenandfuelcells/production/photolytic.html)

5. HFCIT Hydrogen Production and Delivery: Hydrogen Delivery Methods (http://www.eere.energy.gov/hydrogenandfuelcells/production/del_methods.html)

6. HFCIT Program, Multi-Year Research, Development and Demonstration Plan, Section 3, 37-54, (2003) (http://www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/delivery.pdf)

7. H.K. Abdel-Aal, "A new approach to Hydrogen as a safe fuel", *International Journal of Hydrogen Energy*, (in press)

8. M.R. Swain, "Fuel Leak Simulation", Proceedings of the 2001 DOE Hydrogen Program Review (2001) (http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/30535be.pdf)

9. Fotis Rigas, "Evaluation of hazards associated with hydrogen storage facilities", *International Journal of Hydrogen Energy*, (in press)

10. 2004 Honda FCX Specifications, Honda of America (http://automobiles.honda.com/info/news/article.asp?ArticleID=2003100837086)

11. D. Vanderwerp, "Honda FCX", *Car and Driver Magazine*, July 2005. (http://www.caranddriver.com/article.asp?section_id=3&article_id=9640)

12. SiGNa Chemistry (http://www.signachemistry.com)

13. P. Schwartz, D. Randall, "How Hydrogen Can Save America", *Wired Magazine*, **11.04**, April 2003 (http://www.wired.com/wired/archive/11.04/hydrogen.html)

14. J. Sugarmann, "More Gun Dealers than Gas Stations: A Study of Federally Licensed Firearms Dealers in America" (Washington, DC: Violence Policy Center, 1992)

15. J. Sterngold, "Casualty of War: The U.S. Economy", San Francisco Chronicle, 17 July 2005 (http://www.sfgate.com/cgi-bin/article.cgi?file=/c/a/2005/07/17/MNG5GDPEK31.DTL)

16. Energy Information Administration 2004 Gas Predictions
(http://www.eia.doe.gov/oiaf/aeo/pdf/aeo_base.pdf)

17. NREL: Hydrogen and Fuel Cells Research – Hydrogen Production and Delivery
(http://www.nrel.gov/hydrogen/proj_production_delivery.html)

18. M. Ghirardi, M. Seibert, "Algal Hydrogen Photoproduction", NREL Program Review Meeting (2003)
(http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/merit03/42_nrel_maria_ghirardi.pdf)

19. S. Doong *et al.*, "Low Cost Hydrogen Production from Biomass Using Novel Membrane Gasification Reactor", 2005 DOE Hydrogen Program Review (2005)
(http://www.hydrogen.energy.gov/pdfs/review05/pd13_lau.pdf)

20. C. Cropley, "Low-Cost, High-Pressure Hydrogen Generator", 2005 DOE Hydrogen Program Review (2005) (http://www.hydrogen.energy.gov/pdfs/review05/pd23_cropley.pdf)

21. C. Chen, "Ceramic Membrane Reactor Systems for Converting Natural Gas to Hydrogen and Synthesis Gas" 2005 DOE Hydrogen Program Review (2005)
(http://www.hydrogen.energy.gov/pdfs/review05/pdp_15_chen.pdf)

22. F. Lomax, "Low-Cost Hydrogen Distributed Production Systems" 2005 DOE Hydrogen Program Review (2005) (http://www.hydrogen.energy.gov/pdfs/review05/pd9_lomax.pdf)

22. M. J. Prather, "An Environmental Experiment with H_2?" *Science*, **302**, Issue 5645, 581-582 (2003)

23. T. K. Tromp *et al.*, "Potential Environmental Impact of a Hydrogen Economy on the Stratosphere", *Science*, **300**, Issue 5626, 1740-1742, (2003)

24. Ford Motor Company – Ford Focus FCV
(http://www.ford.com/en/vehicles/specialtyVehicles/environmental/fuelCell/focusFCV.htm)

25. Ford Motor Company – Hydrogen Internal Combustion
http://www.ford.com/en/innovation/engineFuelTechnology/hydrogenInternalCombustion.htm

26. "Hydrogen Shelby Cobra Now Available", Green Car Journal, 28 June 2004
(http://www.greencar.com/index.cfm?content=news&ArticleID=26)

27. HFCIT Hydrogen Production and Delivery: Hydrogen Production and Delivery Challenges
(http://www.eere.energy.gov/hydrogenandfuelcells/production/prod_challenges.html)

28. U. Bossel, B. Eliasson, "Energy and the Hydrogen Economy" (2003)
(http://www.methanol.org/pdf/HydrogenEconomyReport2003.pdf)

29. Universal Industrial Gases, Inc. – Physical Properties of Industrial Gases and Common Industrial Chemicals (http://www.uigi.com/physical_prop_e.html)

30. HFCIT Hydrogen Production and Delivery: Fossil-Based Production (http://www.eere.energy.gov/hydrogenandfuelcells/production/fossil_prod.html)

31. HFCIT Hydrogen Production and Delivery: High-Temperature Processes (http://www.eere.energy.gov/hydrogenandfuelcells/production/high_temperatures.html)

32. HFCIT Hydrogen Production and Delivery: Electrolytic Hydrogen Production (http://www.eere.energy.gov/hydrogenandfuelcells/production/electrolytic_prod.html)

33. HFCIT Hydrogen Production and Delivery: Photolytic Hydrogen Production (http://www.eere.energy.gov/hydrogenandfuelcells/production/photolytic_prod.html)

34. About Shell – Shell Hydrogen (http://www.shell.com/home/Framework?siteId=royal-en&FC2=&FC3=/royal-en/html/iwgen/what_we_do/hydrogen/about_hydrogen.html)

35. Texaco Press Release – Texaco and Energy Conversion Devices, Inc. Form Hydrogen (2000) (http://www.chevron.com/news/archive/texaco_press/2000/pr10_31.asp)

36. G. Blumenstyk, "Greening the World or "Greenwashing" a Reputation?", Campaign ExxonMobil (2003) (http://www.campaignexxonmobil.org/news/News_ChronHigherEd_2003.html)

37. THOMAS – U.S. Congress on the Internet (http://thomas.loc.gov)

38. AAAS Analysis of R&D in the FY2006 Budget (http://www.aaas.org/spp/rd/prel06pr.htm)

39. CNN/Money: Gas Prices Around the World: (http://money.cnn.com/pf/features/lists/global_gasprices/price.html)

40. Fuel/Diesel/Petrol Prices Across Europe: (http://www.see-search.com/business/fuelandpetrolpriceseurope.htm)

41. USA TODAY.COM- Biodiesel, Other Alternatives Surge as Oil Price Soars (http://www.usatoday.com/money/industries/energy/2004-11-07-alternative-fuel_x.htm)

42. Diesel Multi-Client Study, Knibb Gormeza and Partners: (http://www.kgpauto.com/Initiatives/Diesel.htm)

43. Ultra Low Sulfur Diesel Home Page: (http://www.dec.state.ak.us/air/anpms/as/ulsd/ulsdhome.htm)

APPENDIX A – CALCULATIONS

Hydrogen energy equivalent of gasoline consumption $= 7.443 \cdot 10^{11}$ kg

<u>Petroleum</u>

Number of barrels $=$(total energy consumption)/(energy per barrel) $= \dfrac{54.42 \cdot 10^{15}}{5.8 \cdot 10^{6}} = 9.38 \cdot 10^{9}$

Number of gallons $=$(number of barrels)*(gallons per barrel) $= (9.38 \cdot 10^{9}) \cdot 42 = 3.94 \cdot 10^{11}$

Projected annual cost of petroleum $=$(number of gallons)*(price per gallon)

$$(3.94 \cdot 10^{11}) \cdot \$1.58 = \$6.225 \cdot 10^{11}$$

$$(3.94 \cdot 10^{11}) \cdot \$3.00 = \$1.18 \cdot 10^{12}$$

<u>Natural Gas</u>

Number of 1000 ft^3 $=$(total energy consumption)/(energy per 1000 ft^3) $= \dfrac{31.47 \cdot 10^{15}}{1.031 \cdot 10^{6}} = 3.052 \cdot 10^{10}$

Projected annual cost of natural gas $=$(number of 1000 ft^3)*(price per 1000 ft^3) $= (3.052 \cdot 10^{10}) \cdot \$8.23 = \$2.512 \cdot 10^{11}$

<u>Algal Photoproduction</u>

Projected annual cost of algal photoproduction $=$(number of kgs)*(price per kg)

$$(7.443 \cdot 10^{11}) \cdot \$1.40 = \$1.05 \cdot 10^{12}$$

$$(7.443 \cdot 10^{11}) \cdot \$2.34 = \$1.75 \cdot 10^{12}$$

<u>Biomass</u>

Projected annual cost of biomass $=$(number of kgs)*(price per kg)

$$(7.443 \cdot 10^{11}) \cdot \$2.50 = \$1.86 \cdot 10^{12}$$

<u>Electrolysis</u>

Projected annual cost of electrolysis $=$(number of kgs)*(price per kg)

$$(7.443 \cdot 10^{11}) \cdot \$2.75 = \$2.04 \cdot 10^{12}$$