The Hydrogen Economy:

A Study on the Viability of Replacing Conventional Motor Vehicle Fuels with Hydrogen Technology

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Executive Summary:

Energy consumption is the single most important force driving the global economy. Without a steady supply of energy, economies and livelihoods would collapse. Currently, the world relies on fossil fuels as its primary energy source. However, fossil fuels are available only in finite quantities. Once these fuel reserves have been depleted, the citizens of the planet must be prepared with a form of renewable energy that will allow them to continue on with their ever-increasing energy-intensive lifestyles. Rather than simply waiting for fossil fuel reserves to diminish, it would be a prudent venture for citizens and governments to research and develop alternative fuel sources, and integrate them into their current energy economies. If an alternative energy source could gradually be developed and utilized by many sectors in the United States, eventually becoming more commonplace than oil, natural gas, or coal, then any potential future energy crises arising from the depletion of fossil fuels, could be significantly dampened, if not completely diverted.

While many alternative fuel sources, including solar, wind, and nuclear power, have become increasing more popular in recent years, they simply will not be able to replace the incredible energy demands currently being met by fossil fuels. Hydrogen technology is a fledgling alternative energy that many have touted as the solution to a future energy crisis. However, using hydrogen as a fuel source has many overlooked implications. Current hydrogen production methods are expensive, and still require the use of a fossil fuel, like methane, in order to create it. For this reason, and many others, hydrogen proves to be, at best, only a partial solution to the inevitable energy crisis looming in the near future.

Abstract:

The purpose of this report is to present a detailed analysis on the viability of hydrogen technology becoming a major factor in the United State's fuel economy, specifically pertaining to how it would affect gasoline consumption in the transportation sector. By providing an extensive background on energy consumption, natural resource limitations, and the current lack of efficient alternative energy media, this paper builds the case that the United States must be prepared for the point in time when it is forced to turn to alternative energy sources when fossil fuels become scarce. After discussing the well known faults of many over-hyped alternative energy technologies, this paper addresses the potential benefits and shortcomings of hydrogen use as a major fuel source. Lastly, the conclusion clearly explains that the hydrogen economy in the United States will not make a major impact on the imports of fossil fuels, unless there are major advances made in areas including hydrogen production, transportation, and integration of hydrogen-powered engines into gasoline-powered vehicles.

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Part 1: Introduction to Energy Consumption

1.1 World Energy Consumption:

Energy consumption by humans is growing at an alarming rate [1]. Consumption has nearly doubled over the past three decades, from approximately 280 quadrillion BTUs in 1980 to approximately 500 quadrillion BTUs today- an increase of nearly 50% (See Figure 1). Additionally, energy consumption is projected to increased by another 50% (to a total demand of approximately 700 quadrillion BTUs) by 2030[1].

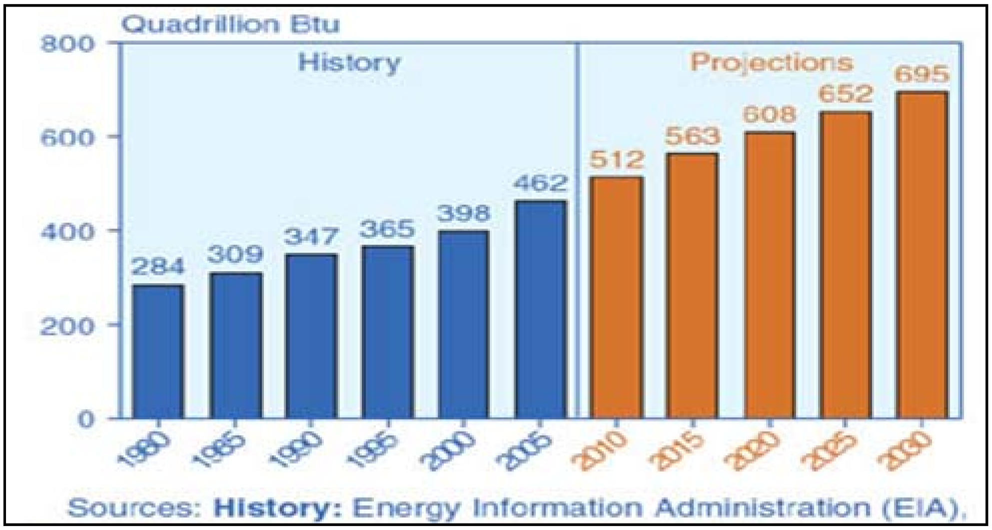


Figure 1: World Marketed Energy Consumption, 1980-2030

Source- http://wolf.readinglitho.co.uk/mainpages/oilproducts.html

This phenomenal increase in consumption results from massive energy needs by industrial countries like the United States and Russia, increasing demands by developing countries (namely China and India), and ever-increasing demands required by widespread energy intensive technology, which are all accentuated by a rapidly increasing human population. The world population is expected to increase by nearly 50% by 2040, increasing the world population from the current 6.7 billion to over 9 billion (See Figure 2), which will, of course, increase the amount of energy used each year [2].

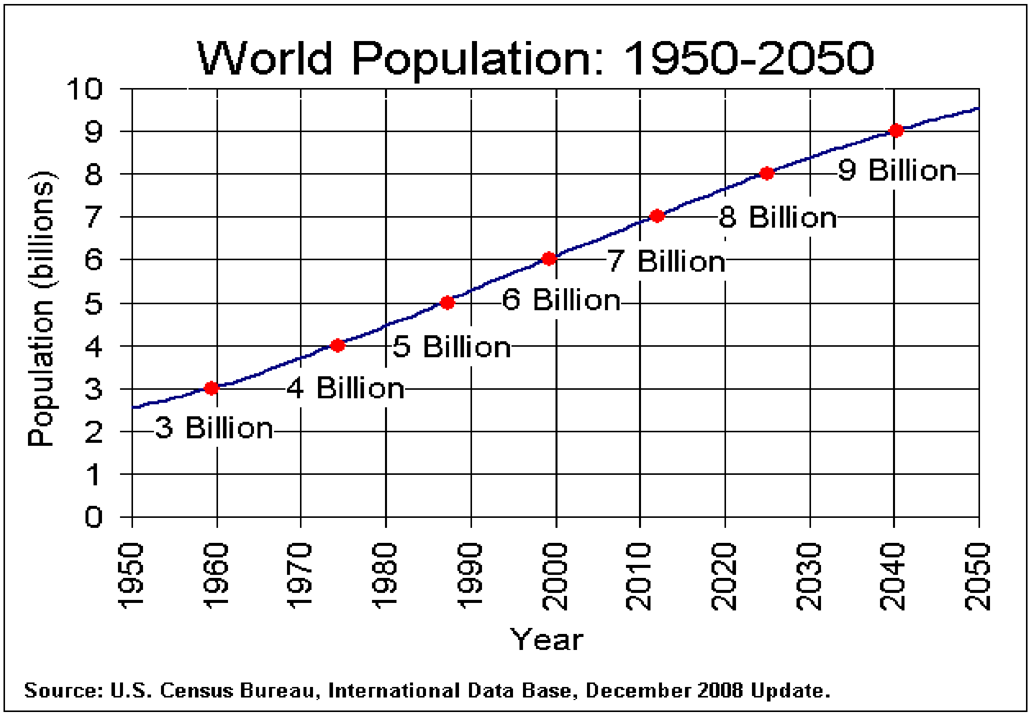
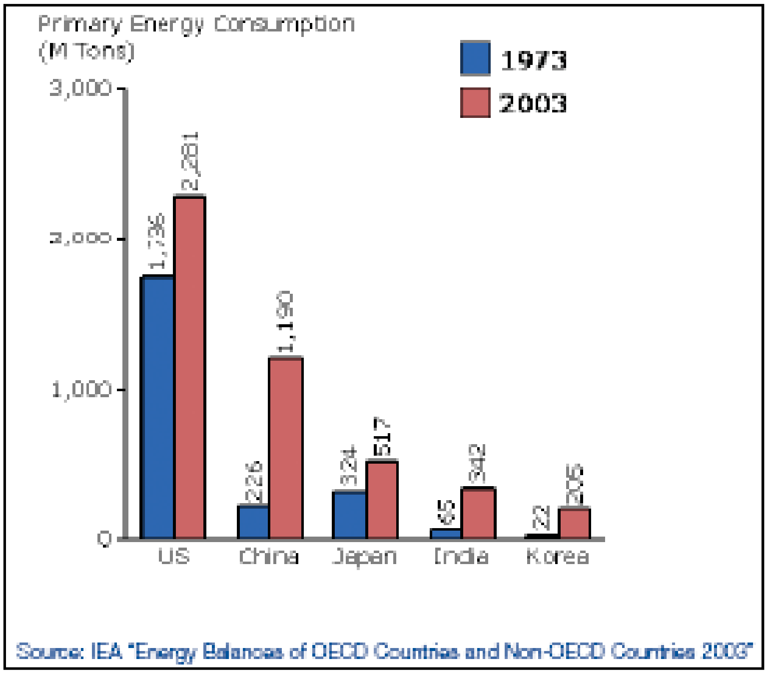


Figure 2: World Population: 1950-2050

In 1980, China and India's combined energy consumption was only 8% of total world consumption, while in 2005 they combined to account for 18% of the total world energy consumption. This figure has continued to grow, and is expected to more than double by 2030, giving these two countries a sizeable share (>25%) in the world's total energy consumption [1]. Figure 3 depicts the energy consumption of several industrial countries. It shows that China's energy consumption has increased by more than four-fold since the 1970's, while India's consumption has increased by a factor of more than 5.



Source: IEA "Energy Balances of OECD Countries and Non-OECD Countries 2003"

Figure 3: Energy Consumption Comparison, 1973-2003

The United States, on the other hand, already consumes approximately 22% of the world's energy on an annual basis [1]. Although the energy consumption of the United States is expected to rise significantly over the coming decades, its share of the world's consumption is projected to drop to about 17% [1]. This is due to the increasing number of industrialized countries, not to mention that most countries continue to increase their populations and standards of living, which will increase their total energy consumption.

Overall, worldwide per capita energy consumption has risen from 63.8 million BTUs in 1980 to 71.8 million BTUs in 2005, and it continues to rise as technology-dependent lifestyles become more prevalent, especially in countries where modern technologies are only just starting to become popular [5].The vast majority of consumed energy comes in the form of non-renewable resources (oil, natural gas, and coal) [1]. Because the world has only a finite quantity of these natural non-renewable resources, many researchers and scientists believe that humans will have depleted most of these resources before the century is half over [6]. Therefore, it is pertinent to consider the development of alternative energy technologies.

1.2 US Energy Consumption:

Since 1973, after its first major energy crisis due to the Oil Embargo, the United States has increased its total consumption by 33%, from 75 quadrillion BTUs to over 100 quadrillion BTUs in 2007 [1]. Since 1950, the United States' consumption of oil, coal, and natural gas has grown significantly.

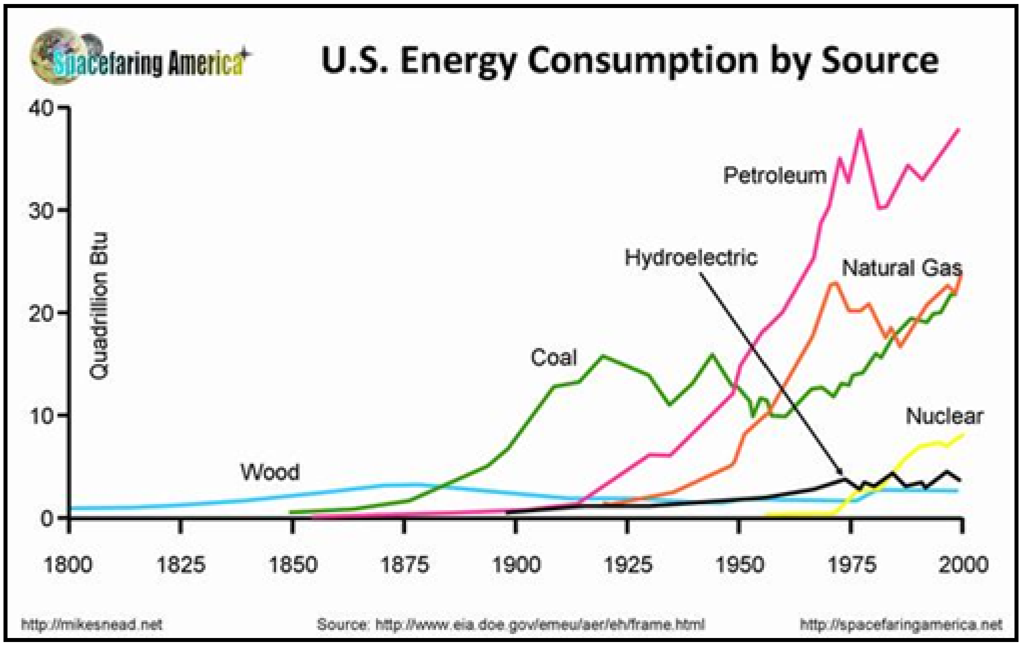
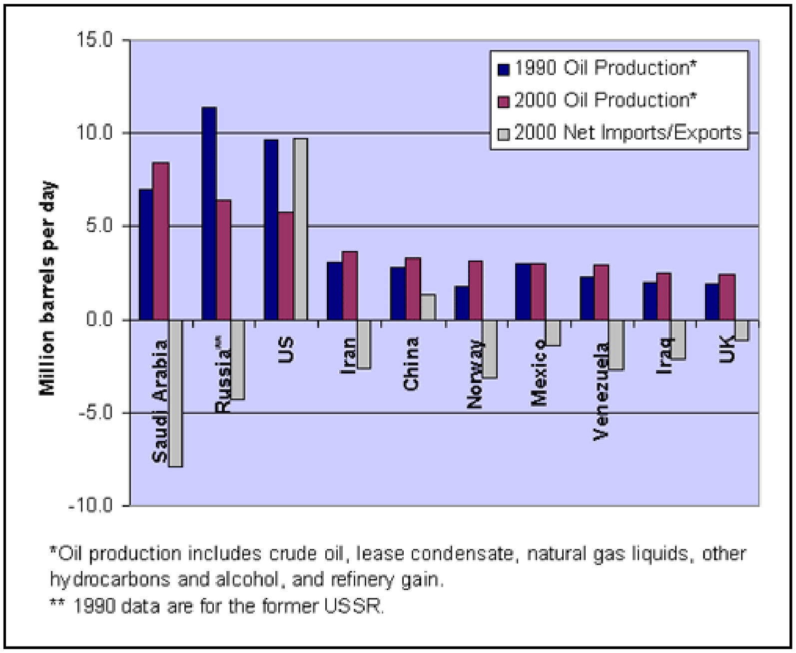


Figure 4: US Energy Consumption by Source, 2007

Source- http://images.quickblogcast.com/83512-73023/us_energy_consumption_by_source_600.jpg

However, that energy scare has not proven a viable warning that would cause Americans to decrease their energy consumption. This increase is largely due to increased industrialization of the nation, the advancement and widespread distribution energy-intensive technologies, and the need to travel to places of work, leisure, and other such places of necessity (hospitals, schools, grocery stores, etc). Per capita, energy consumption in the United States has actually decreased, dropping from 357 million BTUs in 1973 to 337 million BTUs in 2007 [2]. This drop is largely due to the development of energy-saving devices and higher fuel costs, resulting in slightly more conservative energy use in the private sector. However, overall energy usage continues to increase, as a result of the rapidly increasing population, as mentioned in the previous section. This trend can be seen across the globe.

Regardless of any minor drops in overall energy consumption, the United States should be concerned with the fact that it is the #1 oil consuming and oil importing country in the world [3]. However, the United States is only the #3 producer of oil (Figure 5), so it cannot come close to supplying itself with enough oil to satisfy its demands. This results in the country's dependence on foreign energy imports. It is also important to note that the United States is the only country of the top 10 oil producing countries, other than China, that is also a net importer of oil (Figure 5). The other counties in this list, such as Saudi Arabia, Russia, and Iran, all produce enough oil to not only satisfy their own demands, but have enough extra resources to export to countries that require imports. China at least produces more oil then it imports, whereas the United States, in 1990, imported roughly the same quantity of oil that it produced, and imported roughly twice as much oil as it produced in 2000 (Figure 5)!



*Oil production includes crude oil, lease condensate, natural gas liquids, other hydrocarbons and alcohol, and refinery gain.
** 1990 data are for the former USSR.

Figure 5: Top 10 Oil Producing Countries

Source- http://www1.eere.energy.gov/vehiclesandfuels/images/facts/fotw194.gif

Because of this inequality in consumption and production of oil, the United States now imports 58.2% of its petroleum annually [4]. As the level of energy consumption continues to rise, the United States' dependence will continue to increase as reserves diminish, until the country becomes nearly 100% dependent on oil imports from other nations.

The United States currently uses approximately 21 million barrels of oil/petroleum products per day [1]. This equates to about 7.7 billion barrels per year. Of those 21 million barrels, roughly ~44 % (9.3 million barrels) is converted to gasoline to be used as fuel for transportation [5]. This equates to about 3.4 billion barrels of gasoline consumed per year. 70% of all petroleum goes towards the production of various fuels for the transportation sector (See Figure 6).

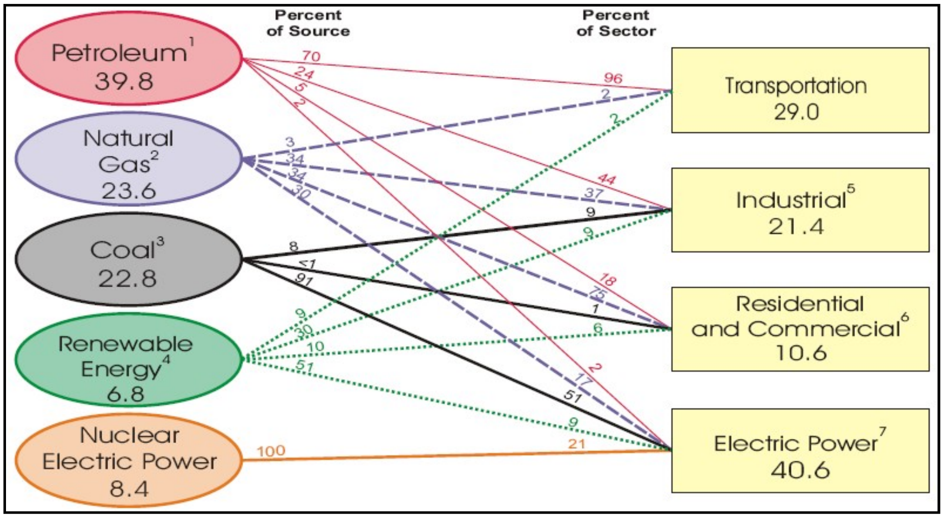


Figure 6: US Energy Consumption by Source

Source- http://www.eia.doe.gov/emeu/aer/pecss_diagram.html

This figure represents 96% of the total resources that contribute solely to the transportation sector (the remaining 4% being equally divided amongst natural gas and renewable energy) (See Figure 6). Therefore, it is clear that by creating alternative energy means to replace to the heavily petroleum dependent transportation sector, the United States could greatly reduce its status as a net importer of oil/petroleum from Canada, Mexico, and the Middle East (See Figure 7), and possibly return to a net exporter, as it was in the mid-1900s.

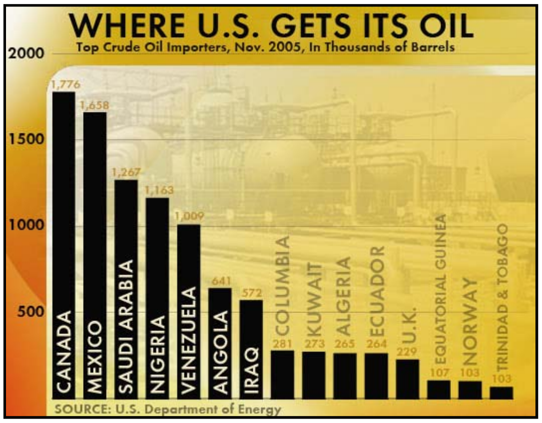


Figure 7: US Oil Imports By Country

Source- http://a.abcnews.com/International/popup?id=1566549

1.3 Gasoline Consumption:

One of the primary uses for oil is the production of “finished petroleum products”. These products include motor gasoline, aviation gasoline/kerosene, distillate fuel oil (mainly referred to as diesel fuel), lubricants, asphalt and road oil, and petrochemical feedstocks (used in the manufacturing of chemicals/rubbers/plastics). The petroleum product most familiar to Americans is gasoline. Gasoline is produced in oil refineries and distributed to local gas stations, where Americans fill their cars, trucks, lawnmowers, snow-throwers, and other machines containing combustion motors. More than half of the total finished petroleum products are motor gasoline [1], and gasoline accounts for 45% of all petroleum use by Americans [2]. Globally, the transportation sector consumes nearly half of all produced oil (also in the form of gasoline), and will continue to consume that amount through the year 2030, as seen below in Figure 8.

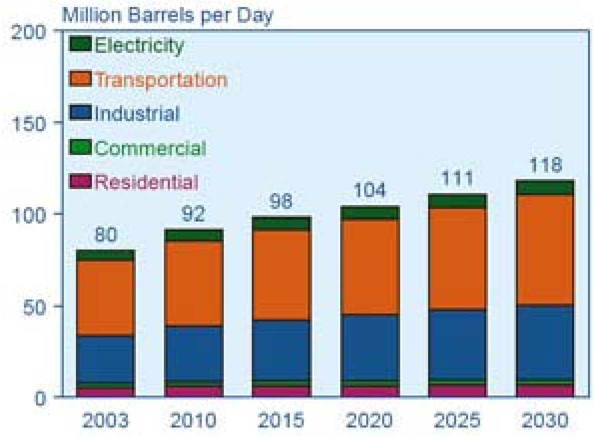


Figure 8: World Oil Consumption by Sector, 2003-2030

Source- http://www.llbbl.com/wp-content/uploads/2006/09/figure_26small.jpg

Since the turn of the millennium, the United States has used approximately 3.3 billion barrels of motor gasoline per year. This equates to over 9 million barrels (390 million gallons) of motor gasoline every day [1]. Gasoline appears to be the benchmark by which Americans judge the oil economy. When gas prices are low, people are content, but when prices rise, as they did in the summer of 2008, there is much resentment among people, especially the lower class, who must sometimes choose between filling up their vehicles with fuel or purchasing item of sustenance, like food or medicine. This is often a difficult decision to make, as most Americans rely on their vehicles to take them to their places of work, schools, and health centers. Per capita, Americans used about 470 gallons of gasoline in the year 2004 [5]. Since 2005, average national gasoline prices have consistently ranged from $2-3. Based on per capita gasoline consumption rates, that would mean that Americans spend roughly $940-1400+ per year simply to transport them to the places they need to go. Those who earn the national average salary of about $44,000 per year must spend more than 3% of their total income on gasoline [7]. Lower class Americans, which constitute 36% of the population (Figure 8), earn $25,000 or less per year, meaning that they must spend at least 5.6% of their income on fuel [7].

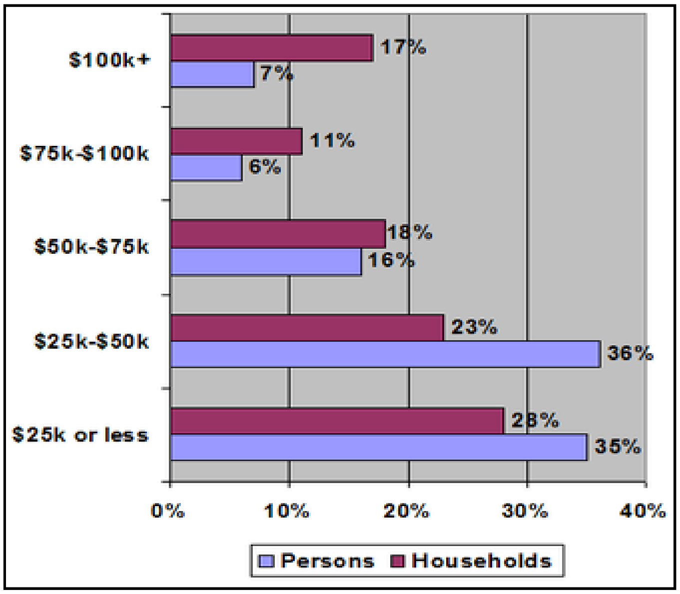


Figure 9: US National Average Salaries

Source- http://pubdb3.census.gov/macro/032007/hhinc/new06_000.htm

For many Americans, especially the lower class, motor fuel costs represent a substantial percentage of their total income. High gasoline prices therefore affect all Americans, save the very rich. In an attempt to make the inevitability of gasoline purchase more bearable, government mandates were made to ensure that vehicles met certain average miles per gallon criteria before released to the public. However, because of the general inefficiency of gasoline-powered motor vehicles and loopholes in these mandates, in addition to the higher number of vehicles on the road in recent years and decades, as well as an increase in miles driven per capita, fuel prices remain a burden on many [2]. In the future, as oil production decreases due to diminishing reserves, gasoline production will likewise falter. When this occurs, gasoline prices will likely soar to extreme highs. This will have a profoundly negative effect on lower and middle class citizens. A major revamping of the public/mass transportation system would be a short-term fix in order to ease the cost of transportations for those who can no longer afford personal transportation. According to the National Priorities Project Database, the state of California leads America as the most gasoline-efficient state in the union in 2001. Californians use a mere 0.974 barrel (43.1 gallons) of gasoline per capita during that year [3]. This is incredible when compared to the national average of 10 barrels (420 gallons) of gasoline per capita per year [3]. California also ranks as 10th lowest in overall oil consumption and 6th lowest in coal consumption per capita [3]. Not only is California efficient in its gasoline, oil, and coal consumption, it is also ranked the #1 most energy efficient state by The American Council for an Energy-Efficient Economy [4]. This organization attributes California's impressive energy efficiency to extremely strict building codes, and generous financial incentives for creating energy-efficient structures that exceed federal mandates [4]. That raises the question, if California can manage its energy efficiency at a level well above the baseline set by federal mandates, then why do the remaining 49 states not strive for similar results? Clearly, government regulations should be much stricter, as this would surely make the nation as a whole more energy-efficient, and in turn would reduce the country's energy demands, and thus reduce its dependence on foreign energy imports. Strict regulations on energy-efficiency would prove to be a truly beneficial piece of legislation, as all Americans would benefit from reduced energy consumption in their buildings and vehicles, which would, in turn, lower energy costs. In the long term, however, it is inevitable that a cheap and reliable alternative fuel source should be developed and made easily available to all.

1.4 Peak Oil/Natural Gas:

Peak oil is defined as the point in time when petroleum extraction in some region has reached its maximum rate. At that time, oil reserves will not be totally depleted; however, the oil production rate will enter a terminal decline, until the wells run dry. By observing the combined output of wells within a single oil field, or multiple fields, over time, geoscientists can estimate an approximate time when peak oil production will occur.

Marion King Hubbert, a notable geoscientist who worked for the Shell Oil Company during the mid-1900s, first created the Peak Oil theory in 1956. He predicted that the United States would reach its Peak Oil production between 1965 and 1970[1]. In 1970, the United States had indeed reached its maximum oil production, despite the continuous findings of small reserves [2]. Coinciding with this event, the nation experienced an oil embargo by the Organization of Arab Petroleum Exporting Countries (OAPEC) [3]. These two events resulted in the oil crisis of 1973, which threw the nation into a period of economic unrest [4]. These events began to display the great need for alternative energy sources, because foreign sources could not always be counted upon. Hubbert's model (see Figure 10) suggests that production rates of a resource with a finite reserve will follow a nearly symmetric curve, based on the ease of resource extraction and the current market demand. The initial rise in the curve represents the increasing production rates as demand increases over time, followed by a decrease in production rate as reserves are depleted, then finally reaching the peak of the curve which represents Peak Oil production, followed by a terminal decline as oil reserves diminish indefinitely until the point when they are completely exhausted [2].

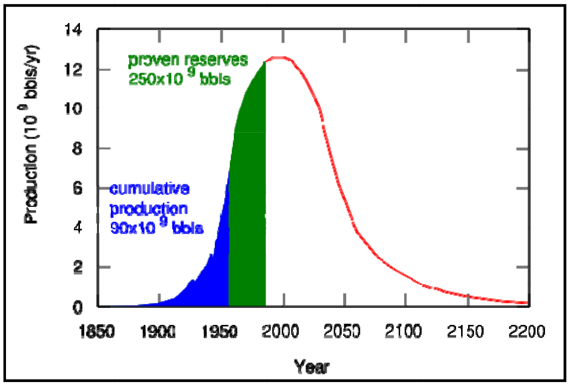


Figure 10: Hubbert's Peak Oil Prediction

Source- http://yalibnan.com/site/archives/2008/07/saudi_king_we_h.php

Oil quantities are finite, and subsequently so are oil-derived products such as plastics, fertilizers, and some forms of electrical energy. Yet, many Americans remain blissfully unaware of this, even despite the fact that gasoline prices reached their highest levels ever in the summer of 2008, topping out at a nationwide average of over $4/gallon [5]. These rising fuel costs have elicited the question of whether or not oil reserves were in peril of depletion, following the rule of supply and demand (as supply levels decrease, prices are driven up). These rising oil prices resulted in a surge of public interest in the field of alternative energy strategies that would combat rising fuel costs. High dependence on oil and oil products by modern industries combined with decreasing oil production will undoubtedly generate higher oil prices as shortages ensue, in accordance with the law of supply and demand.

Hubbert estimated that the world would reach its peak oil production between 1995 and 2000 [2]. Many modern scientists have placed their own Peak Oil estimation dates in a similar time frame. Some estimates are further in the future due to findings of additional oil reserves; however, most scientists agree that we have accounted for 95% of the known accessible oil in the world [9]. Because of this fact, the possibility of additional reserves must be considered negligible in determining a timeframe for the end of oil's use as a primary fuel source and hence for the development of alternative fuels. The Cambridge Energy Research Associates (CERA), a consulting company that advises governments and companies on energy markets and geopolitics, optimistically estimates that the global Peak Oil production will occur in approximately 2020 [7]. They state that this event should occur without a major crisis, assuming that substantial investments in alternative energies have been made to offset the inevitable inflation of oil prices [7]. Petroleum expert Kenneth Deffeyes, who worked with Hubbert and authored a book concerning their work together, gave a much less optimistic evaluation of the matter. He stated that the world reached its Peak Oil production in December of 2005. Many prominent researchers, including David Goldstein, professor of physics and Vice Provost at Cal Tech, A.M.S. Bakhitari, an Iranian oil executive, and M.R. Simmons, an investment banker, all concur with Deffeyes by providing their own estimates for the fast-approaching Peak Oil date. They agree that it will occur before 2010, and argue that regardless of when Peak Oil actually occurs, because it is impossible to determine exactly when oil reserves will be completely diminished, we need to be prepared by developing alternative fuel strategies before it is too late [8,18]. Exactly when this will occur is a hotly debated subject; however, it will likely happen in the near future. One thing is certain- that political and economic change must be brought about long before oil shortages and ensuing high prices occur. If legislation for the development of alternative fuels and an economic plan to reduce energy consumption are brought about only in response to the event of oil shortages and high costs, then it will likely be too late to make a difference. Once major oil-exporting countries realize that there is a worldwide shortage, they will likely reduce their exports in order to reserve oil for their own needs, resulting in massive inflation rates among oil-importing countries, and possible conflicts between oil-exporting and energy dependent countries [6].

Similar to the concept of Peak Oil, is the notion of Peak Natural Gas. This is the time that natural gas production reaches its maximum output, at which point production enters a terminal decline. Hubbert also made predictions regarding Peak Natural Gas in 1956. He predicted that the United States would reach its Peak Natural Gas production in roughly 1970, based on the expected future findings of natural gas fields in the Gulf of Mexico [11]. In 1973, Hubbert's theory seemed to be correct, as natural gas production began to enter a decline. However, a few years later, in 1977, natural gas productions began to rise again as a result of unexpectedly larger findings in the Gulf of Mexico than he had originally speculated [12]. Hubbert then revised his estimate, stating that Peak Natural Gas would occur around 1980 [13]. Once again, natural gas production began to fall, but in 1979 it rose again, and Energy Information Administration data showed that the United States had already produced far more gas then Hubbert had predicted the reserve quantity to be [14]. Many geoscientists find it difficult to place an exact date on Peak Natural Gas, due to constant findings of additional reserves, however, the EIA has estimated that it will occur in 2022 [15]. The EIA has also stated that they expect to see overall world natural gas production rise through 2030 [16]. Regardless of these predictions, it is an undeniable fact that we cannot forever rely on non-renewable resources. As such, it would be pertinent to research and develop alternative fuel sources immediately, before any type of energy crisis has the chance to wreak havoc on an unprepared global economy.

1.5 Estimations of Reserves:

In 2004, an Israeli renewable energy company called MST, founded by Dov Raviv, a prominent Israeli aeronautical engineer and energy advisor in the Israeli military, made some startling predictions concerning global energy consumption. MST was concerned with their country's total lack of natural energy sources, which causes Israel to be totally dependent on energy imports from foreign countries [1]. Since it was only a matter of time before natural resources became scarce and an energy crisis ensued, they knew that Israel would need to be prepared with alternative energy solutions, especially due to the nation's conflicts with the Arab countries in the region which control much of the world's oil and natural gas reserves. This prompted them to perform a study that would determine approximate dates for the total depletion of the three primary non-renewable energy sources, oil, natural gas, and coal. They did this so that they could set a timeline for the country to convert to other means of energy production so that they would not face disaster when worldwide supplies of fossil fuels ceased to exist [1].

Assuming that global oil usage remains constant at 26.9 billion barrels per year, the Israelis determined that the proven supply of oil reserves (~1017 billion barrels) will be completely depleted in a mere 34 years, in 2038. However, a more accurate estimate, based on the annual global increase in oil consumption of 2% per year in industrialized countries, shows that the world's oil supply will be depleted in only 24 years, in 2028 [2]. It is important to note, however, that the proven supply of oil does not represent all the oil present on the planet. In addition to accessible proven reserves, there is also unrecoverable oil, and heavy oil/oil shale, which are forms of oil that are incredibly difficult to process, and thus they are not regarded as a worthwhile fuel source [3].

After analyzing global natural gas consumption trends, the Israeli researchers once again predicted that if the current natural gas consumption remains constant at 92.8 trillion cubic feet per year, then the proven natural gas reserves of ~5450 trillion cubic feet [2] will be gone in 55 years, in 2063. Similar to their predictions of oil depletion, a more accurate estimate, based on a 5% annual global gas consumption increase, as well as factoring in an annual reserve increase of 10% of the annual consumption (based on the research of several fossil energy reserve studies), reveals that the world's natural gas reserves will be depleted after only 22 years, in 2030 [2]. More recent studies, including those performed by BP Statistical Review, Oil & Gas Journal, World Oil, and CEDIGAZ between 2007 and 2008, show slightly increased proven reserves, stating that oil reserves are available in a quantity of about 1100-1300 billion barrels, while natural gas reserves number 6200-6400 trillion cubic feet [4]. Despite the fact that these newer studies suggest that we have slightly higher available reserves of fossil fuels than the Israeli study showed, the inevitability that we will run out of oil and natural gas will be prolonged, optimistically, an additional decade. These timeframes are even more startling, especially when one considers that oil and natural gas combine (39% and 24%, -respectively) to provide a majority (63%) of the world's energy supply.

The Israeli study also mentioned that coal reserves, assuming no increase in either consumption rate of proven reserves, will be depleted in 245 years [2]. It is difficult to determine a more accurate figure, because there is a very high likelihood that coal technology will be advanced and thus used in place of the depleted natural gas and petroleum resources. Thus, coal consumption will greatly increase, in the absence of alternative fuels, as oil and natural gas reserves diminish. David Goldstein, professor of physics and applied physics at Caltech, has stated that using coal as a substitute for oil should be, at best, a last resort [5]. He argues that coal is an incredibly dirty energy source and that the magnitude of production that would be required simply to replace oil would be "on an absolutely unimaginable scale" [5]. Therefore, the magnitude of coal production to replace both oil and natural gas would be impossible to fathom. He goes on to mention that, should we be forced to take this route in the absence of widespread alternative energy when oil reserves are depleted, we could use a technique known as the Bergius Process to liquefy coal into an oil substitute [5]. This method was used decades ago during World War II in Nazi Germany, when they were forced to find a major fuel source due to their lack of oil reserves [6]. The Bergius Process works by grinding brown coal (lignite) into a powder, which is then reacted with hydrogen gas under high temperature and pressure. The resulting product is a synthetic petroleum substitute [6]. Regardless of this technique, coal is still a less efficient fuel source and would be more expensive to process and refine, and so Goldstein insists that our best options for oil substitutes are solar energy and nuclear power [5].

As was mentioned previously, the United States is the 3rd largest producer of oil, however, it has a relatively small quantity of proven reserves, about 22 billion barrels, compared to Saudi Arabia and Russia, which have proven reserves of 262 billion barrels and 60 billion barrels, respectively [7]. Countries which produce significantly smaller quantities of oil, such as Canada, Kuwait, and Iraq, have much higher known reserves of 179 billion barrels, 115 billion barrels, and 101 billion barrels, respectively [7]. Based on these facts, it is clear that the incredible consumption of oil by the United States will further increase its dependency on foreign imports as its reserves diminish. Thus, it is evident that the United States must pave the way for the rest of the world in a quest to relieve dependence on oil and other fossil fuels by developing alternative energy solutions.

By the time we have depleted our two main sources of energy, oil and natural gas, we will be in the transition phase between using fossil fuels as our primary energy sources and using renewable energy sources, which are still largely unexplored and in need of much technological advancement before they can fully replace their predecessors. It is clear that action must be taken immediately in order to ensure that the human race is prepared for the certainty that, within the next few decades, we will have depleted nearly all of the available oil and natural gas on the planet, with coal likely following suit shortly afterwards, as it would be the last remaining primary fossil fuel. If new energy conserving technologies and alternative fuels are not developed within the upcoming 20-30 years, it is likely that unprepared import-dependent countries will enter an economic quagmire, resulting in the downfall of their citizens' livelihoods.

1.6 Energy Independence:

The idea of energy independence was first embraced by Americans after the aforementioned Oil Embargo of 1973. The thought of living in a country that supplied all of its own energy was quite appealing. However, shortly after the Oil Embargo ended, Americans lost interest in the idea of energy independence, mainly due to the development of more energy efficient automobiles and an overall increase in worldwide oil production [1]. Despite these factors from past decades, the country is once again finding itself strongly attracted to the idea of energy independence through clean alternative energy sources. This is evidence by the popularity of wind and solar power, and hybrid vehicles. *Wired Science*, a popular authority on modern science developments, stated that investors allocated 5 billion dollars into the development of "green"-technology in the first 9 months of 2008 alone [4]. In fact, renewable energy technology was one of the focal points of the 2008 presidential election. Conversely, there are many prominent scientists and researchers who argue that energy independence is an unrealistic idea and an outright possibility. Robert Bryce, author of "Gusher of Lies: The Dangerous Delusions of Energy Independence", and editor of *Energy Tribune* magazine, states that energy independence sounds too good to be true because it is, in fact, simply too good to be true [2]. He says that "energy independence" is a popular buzzword because it gives people hope: hope that the nation will be able to overcome some of its biggest fears- the war in Iraq, Peak Oil, terrorism, oil shortages, and global warming- in a single effort [2]. He goes on to say that no matter how convincing studies or politicians may be, the energy business is "ruthlessly policed by the first and second laws of thermodynamics". These laws refer to the fact that energy cannot be created or destroyed, it can only change forms, and that the energy of a system can only increase if energy is actively added to the system [3]. He uses these laws to debunk popular ideas surrounding potential alternative energies and improvements in fossil fuel technologies, many of which seem to ignore these undeniable facts in order to promote energy independence. Bryce admits that nuclear energy may be the best route for the United States to take in the short run, but in the long term we will be no better off because uranium, the primary fuel for nuclear power, is just another non-renewable resource, thus it cannot be relied upon indefinitely.

Michael Grunwald, a prominent reporter for the Washington Post, concurs with Bryce on the topic on nuclear power, stating that "spectacularly expensive" nuclear energy is not the answer America is seeking, especially since electricity generated through nuclear power plants costs 500-2000% more per kilowatt-hour (1-3 cents per kilowatt-hour for conventionally generated electricity compared to 15-20 cents per kilowatt-hour for nuclear power-generated electricity) than electricity generated through more conventional means, such as through the burning of coal [5]. Grunwald also states that “we don’t need new drilling or new power plants. We need to get efficient!” [5]. He suggests that by implementing the widespread use of ultracapicitors in electronic devices, triple-layer glass windows, LED lights, better insulation in buildings, and other minor improvements in commonly used technology, the global energy demand could be cut by as much as 20% by 2020, which would be a great way to prolong the life of natural resources, granting more time for the development of alternative fuels [5]. Tom Reddoch of the Electric Power Research Institute agrees, stating that “a lot of simple answers are just sitting around waiting for us to execute” [5]. Energy efficiency is a common answer to energy independence, as well as lower energy costs, provided by those who oppose nuclear energy or other methods involving the improvement of current fossil fuel technology. Regardless of how efficient the current technology becomes, although it would be a progressive maneuver, the world must be prepared for the day when fossil fuels expire, and must be ready with alternative, renewable energy solutions.

1.7 Alternative Energy Solutions:

In the preceding sections in the Introduction to Energy Consumption, we have discussed how the world’s current rate of energy consumption, which is increasing rapidly as a result of skyrocketing human populations and the constant development of more energy-intensive technologies, combined with the knowledge of known fossil fuel reserves, have presented an effective timeline for the development of alternative fuel strategies in the world’s near future. This timeline stretches over only several decades, and even with the presumed findings of additional reserves, it cannot be expected to be extended by any considerable amount. Even the most optimistic figures pertaining to the findings of additional fossil fuel reserves cannot undermine the undeniable fact that fossil fuel reserves are finite, and will eventually run dry. This issue would not carry such enormous weight if it were not for the fact that oil, natural gas, and coal (the three major fossil fuels) combine to provide the world 80% of its annual energy consumption, as shown in Figure 11.

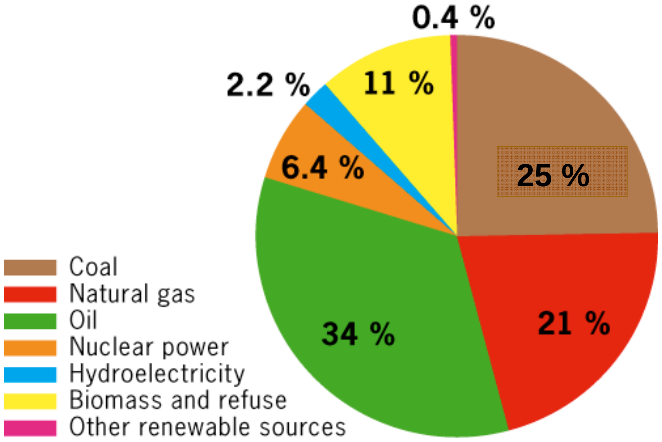


Figure 11: World Energy Consumption Distribution by Source

Source- http://www.npd.no/NR/rdonlyres/0AA583E1-955A-43DA-A2CD-2F06E9AD750F/15504/Figur61.gif

The situation is slightly worse in the United States, where fossil fuels make up 86% of the total consumed energy, as seen in Figure 12.

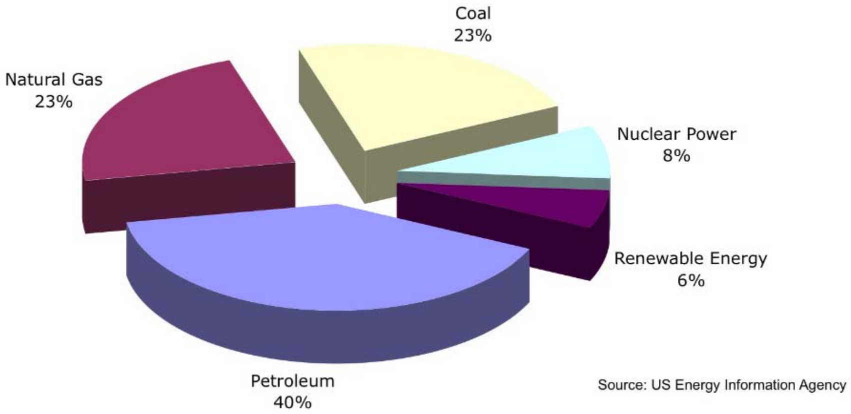


Figure 12: US Energy Consumption by Source

Source- http://gailtheactuary.files.wordpress.com/2007/03/fossil-fuel.jpeg

When the day comes when these fuel sources have been completely depleted, the countries of plant Earth must be prepared with alternative energy solutions; ones with traits including renewability, sustainability, efficiency, and cleanliness. If there is not a considerable level of development and widespread deployment of these alternative energies, prior to the event of fossil fuel depletion, then world economies, and hence all advanced modern societies, will certainly crumble.

1.7a Solar Power:

Robert Bryce is an outspoken opponent in his negative comments on some popular alternative energy solutions, namely solar power, wind power, and ethanol [1]. Bryce has dubbed solar energy the "1 percent solution", as it currently produces about 1 percent of the United State's total electricity. Solar panels are incredibly expensive; a luxury that most Americans cannot easily afford. They also tend to be large, unsightly systems (See Figure 13).

Figure 13: Solar Panel Array

Source- http://image.examiner.com/images/blog/wysiwyg/image/solar-power.jpg

In addition, their total rated electricity capacities are rarely met, due to limited sunlight intake during cloudy days and the winter season, and zero intake after sunset [1]. Bryce has estimated that his $22,445 solar panel system, even with a government subsidy that covered $15,000 of the cost, will take more than 20 years to pay for itself. Raymond James & Associates completed a report stating that electricity generated from residential units costs about 37 cents per kilowatt-hour, nearly 4 times the cost of electricity generated by conventional means [2]. The EIA has estimated that by 2030, solar energy will be providing roughly 5 billion kilowatt-hours of electricity per year. While this figure seems substantial, when put into perspective, it represents only a tiny fraction, 0.15%, of the expected 3,351 billion kilowatt-hours of electricity generated from coal-fired plants that will be consumed by Americans in 2030 [3]. To further demonstrate the insignificance that solar power will have in the future, the total electricity demand in the United States will be 5,478 billion kilowatt-hours. This means that by 2030, solar power will be responsible for generating less than 0.1% of Americans electricity need, ten times less than the 1% it is responsible for now. Additionally, high-density electricity storage technology does not exist, meaning that storing electrical energy from solar panels, or using it to power electric cars with comparative mileage ranges as those powered by fossil fuels, is not possible [1]. These facts, Bryce states, are the main reasons why solar energy will never become a significant solution to America's energy needs [1].

1.7b Wind Power:

Bryce's outlook on the viability of wind power becoming a major factor in America's energy production is equally bleak. The two primary reasons why he believes that wind power is overhyped are that wind power, like solar power, is not reliable, as wind is intermittent, and thus cannot be readily relied upon in the manner that fossil fuels can. Secondly, he states that very few people would want to live near massive wind turbines, nor do they want these devices tarnishing pristine regions of the country, labeling them eyesores (See Figure 14) [1].

Figure 14: Wind Turbines Obscuring a Serene Landscape

Source- http://www.tva.gov/news/files/buffmtn/turbines3.jpg

Bryce goes on to make the obvious point that even if a city had enough wind turbines to supply 100% of its electricity need during windy days, that the city would still require conventional electricity plants, powered by nuclear energy or the burning of fossil fuels, to power the city in the absence of wind [1]. He states that the cost of having to run these back-up plants at all times is extremely expensive, and negates any cost or cleanliness benefits of having a fleet of wind turbines [1]. Additionally, much of the United States, including nearly all of the Southwest, has little or no prospect for generating wind power, due to a general lack of wind in those areas. Also, the regions that would be good prospects for harnessing wind power are often many miles away from major cities, where the electricity is needed, and therefore would require extensive expensive additions to the electrical grid [1]. Some of the areas with the best prospects for placing wind turbines, such as Cape Cod, are consistently protested by politicians such as Senator Ted Kennedy, who lives in the area. Bryce calls this unwarranted protest the “NIMBY” (Not In My Backyard) syndrome, meaning that the only legitimate reasoning behind these politicians’ oppositions is the fact that they live in the area, and do not want their multi-million dollar estates disfigured with the unpleasant sight of many wind turbines [1]. The EIA has estimated that by 2030, America’s wind turbines will be capable of producing 64.5 billion kilowatt-hours of electricity per year. Once again, similar to solar power, this represents only a fraction of the electricity that will be produced by coal-fired plants, and will only contribute about 1% of the total 5,478 billion kilowatt-hours of electricity that Americans are expected to use each year by 2030 [1]. Bryce also goes on to mention that upkeep, additions to electrical infrastructure, and upgrades are expensive and often overlooked or unmentioned costs that, when factored into the so-called cost efficiency of wind power, further demonstrate the inability of this resource to become a major factor in American energy production without massive improvements in current technology.

1.7c Ethanol and Biodiesel:

Bryce’s most fervent opposition is to ethanol and biodiesel. He calls the ability for ethanol to become a major player in America’s energy game a “lie” and a “scam” [1]. In 2006, the United States produced 5 billion gallons of ethanol from corn and 250 million gallons of biodiesel, mainly from soybeans [4]. One thing to keep in mind with figures pertaining to ethanol is that it has an energy content worth only about two-thirds that of gasoline, so one gallon of ethanol equals about .66 gallons of gasoline. Therefore, when used in modern motor vehicles with typical engines, that 5 billion gallons of ethanol would have equated to only 3.3 billion gallons of gasoline. America uses 390 million gallons of gasoline per day, meaning that all the ethanol produced in 2006 would satisfy American motorists' thirst for fuel for a mere 8.5 days. Even without proper energy content conversions, that 5 billion gallons of ethanol equals about 119 million barrels of oil, which is only 0.015% of the country's total oil consumption of 7.7 billion barrels per year, and would satisfy little more than 5.5 days worth of oil consumption.

Dennis Avery, director of global food issues at the Hudson Institute, has calculated that it would take 546 million acres of cropland to produce enough ethanol to fully replace our gasoline consumption [5]. However, the United States currently has about 440 million acres of cropland (out of a total land area of about 2,300 million acres) devoted to all types of crops, not just the soybeans or corn that would be used for ethanol production [5]. That would mean that the United States would have to procure 100+ million more acres of cropland, and then replace all non-ethanol producing crops with those capable of being converted to the fuel. Therefore, 24% of the nation's total area would need to be dedicated solely to the production of ethanol-producing crops! This would obviously destroy America's agriculture business, cause the price of many foods to skyrocket, and leave many people, especially those in 3rd world countries that rely on the generosity of American food aid, starving [5].

David Pimentel, a leading Cornell University agricultural expert, is equally dismayed with the popularity of the idea of ethanol becoming a major fuel source. He has calculated that there is a net energy loss of 54,000BTUs for every gallon of ethanol, due to the fact that it takes 131,000BTUs to create, yet it yields only 77,000BTUs when burned [21]. His own estimations differ from Avery's with respect to the total area of the United States would need to be utilized as farmland for the growing of corn, which would be the primary ethanol feedstock. He has calculated that 97% of the total land area of the United States would be required in order to create enough ethanol to power all the automobiles in the nation [21]. The obvious impossibility of satisfying the cropland requirements, combined with net energy losses during production, should seal ethanol's fate as just another far-fetched, completely ludicrous alternative energy scheme.

In 2007, President Bush called for a target goal of 35 billion gallons of renewable and alternative fuel production, in order to help resolve what he called "America's addiction to oil" [1]. These 35 billion gallons of renewable fuel, say ethanol, would equate to the energy in about 23.1 billion gallons, or 550 million gallons of gasoline, and would be able to replace about 16% of America's annual gasoline usage (~3.4 billion barrels). By 2010, the United States is expected to be importing roughly 5 million barrels of gasoline per day, or 1.83 billion barrels per year [6]. This means that an increase in ethanol production from 5 billion gallons to 35 billion gallons per year would only cut gasoline imports by 30%, and since gasoline use continues to rise, ethanol production would have to continue to rise at an even faster rate just to continue to reduce gasoline imports by that 30%. As was previously mentioned, any substantial amount of gasoline replacement by ethanol would require a quantity of crops that would certainly destroy the nation's agricultural economy, and thus must be considered a completely unviable energy source. Bryce also goes on to note that one figure that will never be defined by alternative energy advocates is an acceptable level of decreased imports [1]. He makes the point that these figures are completely arbitrary, and will have no profound effect on overall energy consumption or imports.

1.7d Nuclear Power:

Ideally, the best alternative energy solutions would be those which are cheap for producers to create and for consumers to purchase, create little, if any, harmful byproducts, and are found in such abundance that there would not be any risk of depleting precious limited natural resources.

Currently, electricity in itself is the cleanest, most widespread, and cheapest energy carrier, when compared to other common energy sources, such as fossils fuels. However, the main disadvantage of electricity is that the majority (71.4%) of it is produced through the burning of fossil fuels, namely coal [7]. Coal is the dirtiest fossil fuel, producing many harmful byproducts, the major one being carbon dioxide, which has been dubbed the primary culprit in the recent global warming controversy.

The second largest electricity production method, nuclear fission, accounts for 20.7% of the total production [7]. Nuclear fission works by firing neutrons into the fissionable nucleus of an element, usually uranium, which causes the nucleus to split, releasing massive quantities of energy, neutrons, radioactive products, and more fissionable nuclei, which begins a chain reaction, as seen in figure 15 below.

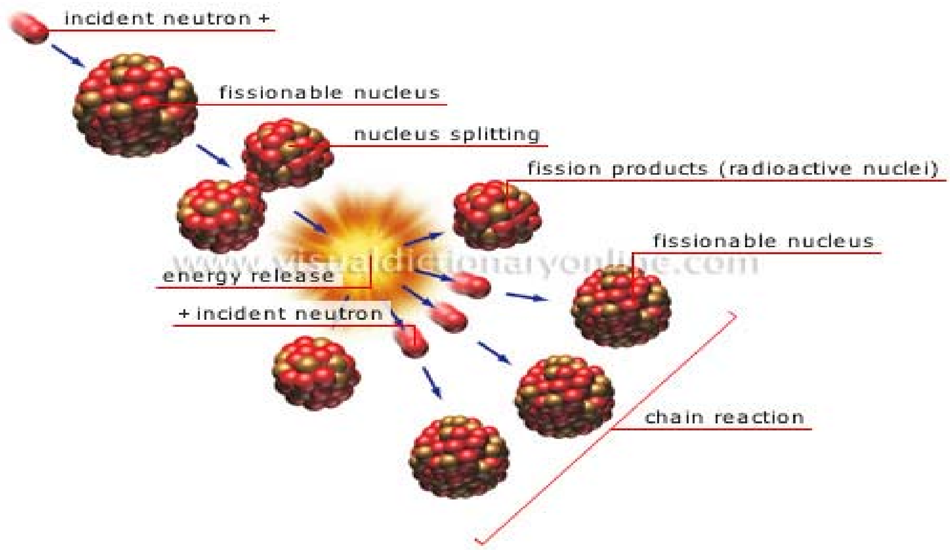


Figure 15: Nuclear Fission Chain Reaction Diagram

Source- http://visual.merriam-webster.com/images/science/chemistry/matter/nuclear-fission.jpg

Although the process of creating electricity from radioactive elements is relatively clean, there is still the matter of handling nuclear waste once the fuel rods are spent. When a fuel rod is decommissioned, it must be placed in an area where it can live out many half-lives without causing any negative impacts on the surrounding environment. The Yucca Mountain Repository, a proposed nuclear waste storage facility located in southern Nevada, is the hopeful future resting place of spent nuclear fuel rods [19]. The benefit of this facility is that all nuclear waste could be handled in one place, rather than at the current 121 sites nationwide. However, this facility is far from complete, and the long-term negative environmental impacts are impossible to determine [19]. Additionally, nuclear power can be extremely dangerous, most notably evidenced by the horrific meltdown in Chernobyl, Ukraine in 1986, shown in Figure 16.

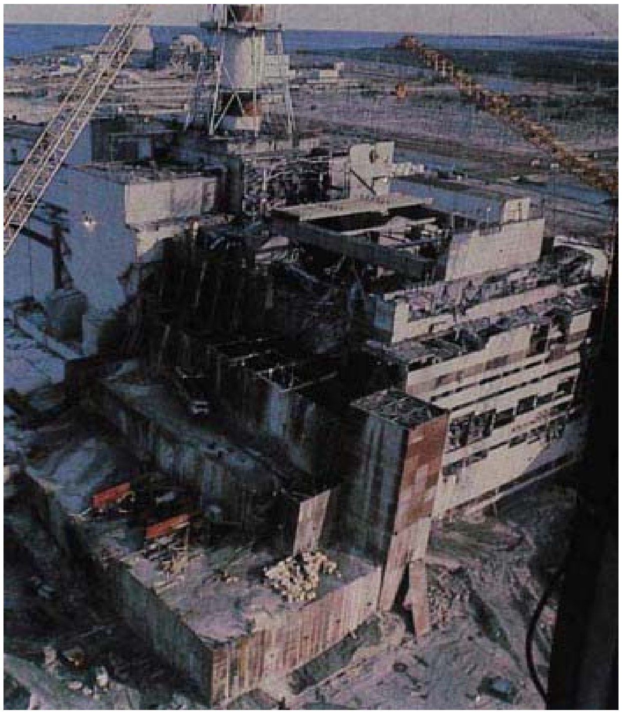


Figure 16: Aftermath of Chernobyl

Source- http://www.ourtimelines.com/hist/chernobyl.jpg

A similar disaster was averted at the 3-Mile Island nuclear facility, shown in figure 17, in 1979, however, this incident proved to be a massive detriment to the advancement and widespread use of nuclear power in the United States.

Figure 17: 3-Mile Island Nuclear Facility

Source- http://www.ohiocitizen.org/campaigns/electric/2004/ph_three_mile_island500.jpg

Still, there are those who embrace nuclear power as a safe means of alternative energy. The South Texas Project, shown below in figure 18, a nuclear endeavor that at first was viewed as a financial catastrophe, has paid for itself in energy savings that the city of Austin has made through decreased use of fossil fuels since it began operating in 1988 [1]. The city now obtains about 29% of its electricity from the dual-reactor power plant.

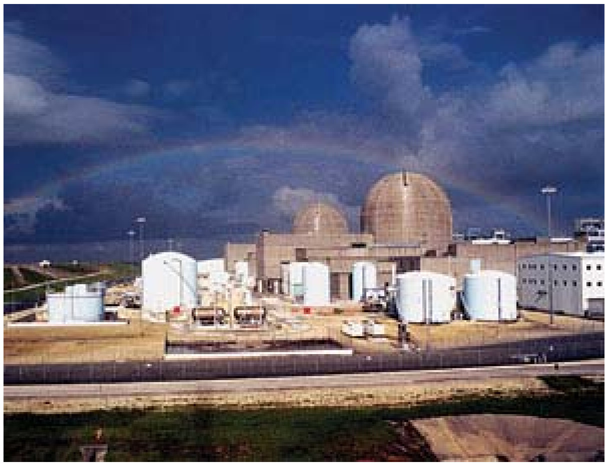


Figure 18: The South Texas Project Nuclear Facility

Source- http://pubs.acs.org/cen/_img/85/i40/8540notw3_rainbow.jpg

France is a country which generates over 75% of its electricity through nuclear fusion, and has never had any incidents which would cause the public to believe it to be unsafe [12]. In fact, large populations live in close proximity to nuclear facilities, and yet they completely embrace these power plants as an integral part of their country's economy and their lives. One of the most beneficial aspects of nuclear power is that it produces no or low-carbon emissions, which should appeal to any concerned with global warming and environmental pollution [1]. However, despite the relative cleanliness of nuclear power and the cheap electricity it provides, there is one major downfall. Robert Bryce points out in his book, "Gusher of Lies", that nuclear energy, while it has had many successes, is still in fact not a true alternative source of energy. He states that radioactive elements, namely uranium, are exactly the same as oil or any other fossil fuel, with respect to the fact that they exist only in finite quantities and will eventually, under widespread consumption, become depleted, leaving the world with just another energy crisis. He also points out that even if the United States promoted the use of nuclear power to the point where the country could obtain most of its energy needs, it would remain a net energy importer, with a simple shift from obtaining the majority of our oil from Canada, Mexico, South America, and the Middle East, to procuring uranium (the United States already imports 83% of its uranium, due to the collapse its uranium mining industry after the 3-Mile Island incident) or plutonium from countries which obtain large amounts of those elements, such as Australia, Russia, and Kazakhstan [1]. However, Bryce states that the country is much better off having the nuclear facilities that it operates, since these 104 commercial reactors combine to generate 20% of America's electricity consumed annually [8]. These reactors have helped reduce America's dependence on fossil fuel energy by 7% between 1973 and 2004 [9]. Additionally, the 442 nuclear reactors found worldwide generate 17% of the Earth's energy needs [20]. Just as in the United States, these reactors, which are only found in 30 countries worldwide, are extremely important in reducing the demand for fossil fuels. These reactors are also beneficial because they reduce carbon dioxide emissions (that would have been generated by fossil fuel-burning electricity plants) by 500 million metric tons per year [20]. Without that boost in electricity production, the country would rely even more heavily on fossil fuels, furthering foreign energy dependence and environmental pollution.

Another benefit of using nuclear reactors to create electricity is their potential for producing hydrogen. Nuclear reactors give off excessive amounts of heat due to the highly energetic fission process. If this heat energy were harnessed, it could be used to power the high temperature electrolysis process which is used to produce hydrogen. The International Association for Hydrogen Energy has stated that using high temperature electrolysis in nuclear power plants by utilizing their excess heat energy would be a superior improvement to the vastly used steam methane reforming, because of the minimal potential for global warming or acidification potential [12]. In fact, using high temperature electrolysis in nuclear power plants is comparable to using renewable energy sources, namely wind and hydropower, with respect to limited negative environmental impacts [12]. It would be prudent to develop technologies in which there is minimal energy waste, that is, excess energy should be harnessed and reused wherever it is cost-effective and plausible. Despite these benefits, with a worldwide increase in nuclear power, most notably in China, India, and Finland, nuclear power fuels, like uranium, will likely become an endangered resource, and will suffer the same fate as fossil fuels, eventually becoming depleted, leaving the world in need of a new major energy source [10].

1.7e Geothermal:

Geothermal power is power generated from steam or heat that is underground. With the use of power plants, this heat can be harnessed and used to turn turbines which generate power. The largest group of geothermal power plants in the world is located at "the Geysers" which are a geothermal field located in California [13]. The only countries in the world which produce significant amounts of energy through this process are the Philippines and Iceland. Both these countries produce between fifteen and twenty percent of their nation's electricity through the use of geothermal energy [14].

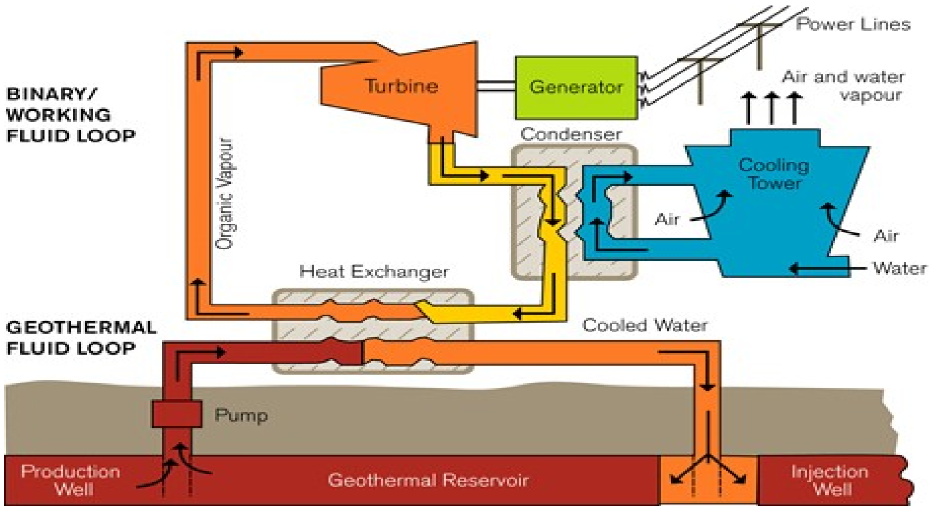


Figure 19: Schematic of a Typical Geothermal Power Plant

Source- http://www.greenearthenergy.com.au/images/clientupload/fullwidth/Fig13_small.jpg

Geothermal plants require almost no fuel, meaning that there is very little in the way of emissions [15]. The capacity factor is relatively high, almost 90%, because there are no transient sources of energy. This means that the theoretical capacitance versus the actual is only a 10% difference. It is also a highly sustainable energy source. The sheer magnitude of energy available inside the earth means that we could harness energy for hundreds, if not thousands, of years, without ever seeing any change in the level of energy being produced. This is in sharp contrast to fossil fuel extraction, as evidenced by Peak Oil. There have been operational power plants in Italy since 1913, New Zealand since 1958 and California since 1960 [16]. Geothermal plants do not necessarily take up a lot of space, only about 1-8 acres per megawatt versus a nuclear power plant which is 5-10 acres per megawatt and coal power plants which are 19 acres per megawatt [17]. Depending on how much energy is needed, the size of the factory can be reduced or enlarged. For example, a power plant needed to supply enough energy to a small town would be tiny in comparison to a larger plant that would be needed to power a large city [15].

The largest downside to this production method is that it cannot be used everywhere. It is necessary to find a structure near the surface of the earth, such as a geyser, hot spring, which has a large amount of geothermal energy potential, to build the power plant around. This is the main reason that only one percent of the earth's energy is produced in this manner. There simply are not enough geysers or geothermal activity to provide energy for the entire world. Geothermal energy can also be harnessed by drilling into the Earth's crust, between 4 and 10 kilometers deep. This would place geothermal power in the same category as solar and wind power; intermittent energy sources. However, the costs associated with this endeavor are phenomenal, and so geothermal power is really only useful in regions where it is readily available near the surface of the earth. So while it is a cheap, clean, and efficient energy source if you live in the right place, such as Iceland or the Philippines, elsewhere, it is currently not a plausible alternative energy source [18].

1.7f Hydrogen:

Lastly, there is the topic of hydrogen. Hydrogen is one of the most hotly debated forms of alternative energy in the United States, and around the world. In the remaining segments of this paper, pertinent issues will be extensively discussed in order to reveal the possibilities of integrating hydrogen as a major fuel source in the United States economy. Specifically, the potential of the hydrogen economy to replace petroleum in the area of the transportation sector will be discussed. These discussions will consist of the evaluation of the feasibility of the hydrogen economy after reviewing important topics, including hydrogen production, current imports of the United States as well as the current gasoline economy, current uses, limitations, storage, transportation, required technologies, and other relevant issues. Through extensive research, the practicality of the hydrogen economy, applied to the transportation sector in order to reduce the United States' dependence on foreign oil, will be presented.

Figure 20: Future Hydrogen Economy?

Source- http://www.wmo.int/pages/prog/arep/gaw/images/Hydrogen.economy.sys_integration_circle.jpg

Part 2: Hydrogen

2.1 What is Hydrogen?

Hydrogen is the simplest of all the elements found in the universe. It has an atomic number of 1, representing its simplest structure consisting of a single electron-proton pair. Hydrogen can also exist as an ion, where it can take either a positive or negative charge, by either losing its electron or gaining another, respectively. The vast majority of hydrogen exists as a stable isotope known as protium, while a minute portion of all hydrogen comes in the forms of deuterium or tritium isotopes. Hydrogen gas exists as a diatomic element, meaning that it is bonded to another hydrogen atom for stability, due to its extremely reactive nature. At any atmospheric pressures and temperatures found on earth, molecular hydrogen would exist as a colorless, odorless, tasteless gas. This attributes to the dangerous nature of hydrogen, as humans are incapable of noticing leaks or even burning hydrogen since it burns with a clear flame. Hydrogen makes up approximately 75% of the total elemental mass of the universe [1]. A massive hydrogen cloud, capable of creating thousands of stars, can be seen below in figure 21.

Figure 21: The Smith Hydrogen Cloud, 8000 light years from the Milky Way Galaxy

Source- http://www.bibliotecapleyades.net/universo/cosmos05.htm

Despite its common universal abundance, elemental hydrogen, meaning hydrogen existing by as H_2, and not bonded with another atom, is nearly non-existent on earth; therefore, it must be produced. Primary production methods include steam methane reforming and the electrolysis of water. There are also many less commonly used processes, and hypothetical processes that are currently being researched. Hydrogen is the most reactive, and therefore, most dangerous energy carrier known to man [4]. (It is important to note that hydrogen is an energy carrier and not an energy source, because it takes energy from one source and carries that energy, in a manner similar to electricity [2]). Because of the lack of abundance in its molecular form on earth and the difficultly and expense in its production, hydrogen-based technological development has been slow. By weight, hydrogen provides a significantly higher energy content than gasoline (three times higher energy content by mass), or any other fossil fuel. However, it has the lowest energy content by volume [2]. Because of the incredible amount of energy that hydrogen carries for its weight, the United States and many other countries are extensively researching it as an alternative fuel, most notably as a replacement fuel for automobiles. The Hydrogen Fuel Initiative was one of several pieces of legislation meant to hasten transition from simply theoretical ideas behind hydrogen's viability as a possibly alternative fuel into actual working technologies [1].

2.2 Hydrogen Production:

Before considering the plausibility of using hydrogen as an alternative fuel, it is important to note whether or not it can be efficiently manufactured. Currently, approximately 45 million tons of hydrogen are used annually for industrial purposes worldwide [1]. Nine million tons are produced in the United States alone [2]. Most of the hydrogen produced today contributes to the petroleum and fertilizer industries. These uses can be seen in Figure 22 [1].

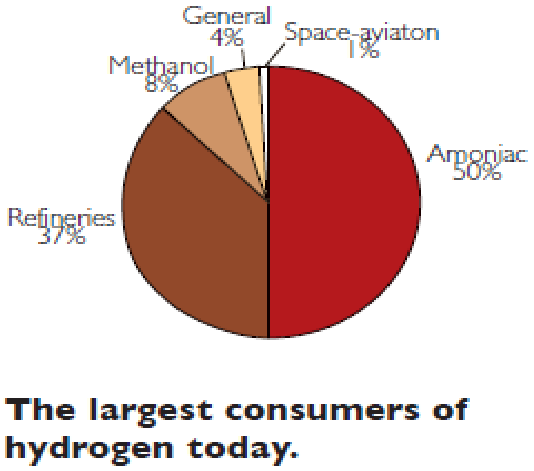


Figure 22: Uses of Hydrogen

Source- http://bellona.org/filearchive/fil_Hydrogen_6-2002.pdf

Because hydrogen is not found in abundance in its natural diatomic form, it must be procured from other molecules. The most common methods or hydrogen production are steam methane reforming and the electrolysis of water. There are also several theoretical methods of production that have, as of yet, not been used in the mass production of hydrogen. They include biomass gasification and photoelectrolysis, as well as photobiological and photoelectrochemical processes [3]. All of these methods may someday be necessary if hydrogen becomes a major alternative fuel, however, for the purpose of this paper only steam methane reforming, electrolysis, and biomass will be discussed.

2.2a. Steam Methane Reforming

The most common method of producing hydrogen, known as steam methane reforming (SMR) or syngas, accounts for 95% of the hydrogen produced in the United States and 48% globally [4]. A schematic for this process is depicted below in figure 23.

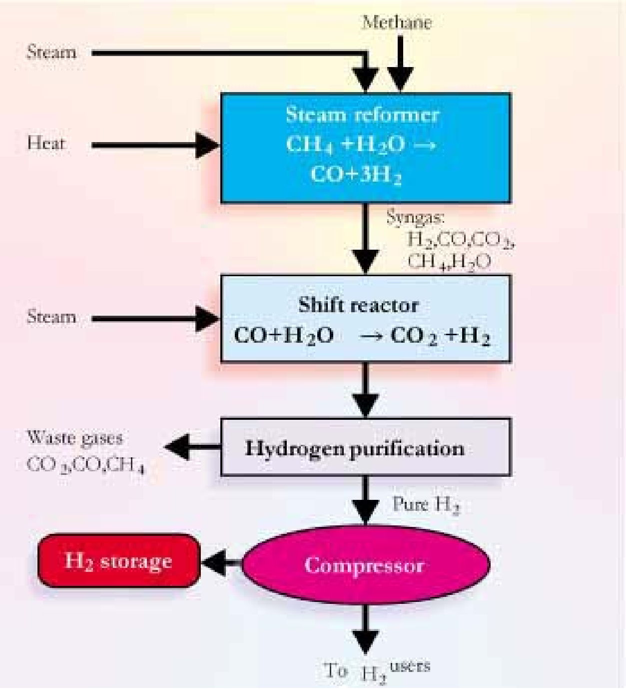


Figure 23: Steam Methane Reforming Process

Source- http://scitation.aip.org/journals/doc/

The rest of the globe uses steam methane reforming to a lesser degree, because other countries may have a natural abundance of raw materials that can be in hydrogen production. In addition to producing hydrogen from natural gas, it is possible to produce it from other fossil fuels, such as coal or oil [5].

Natural gas consists mainly of methane (≥75%), some heavier hydrocarbons, such as propane and butane, and carbon dioxide (CO_2) [6]. Steam methane reforming uses high temperature steam to cause catalytic oxidation reactions in natural gas releasing hydrogen and carbon oxide [4]. At high temperatures, 700-1000º C, natural gas and a catalyst, such as nickel, will facilitate the reaction between the steam and the methane, creating carbon monoxide and hydrogen. The reaction is depicted below;

$$CH_4 \text{ (methane)} + H_2O \text{ (steam)} \rightarrow CO \text{ (carbon monoxide)} + 3H_2 \text{ (hydrogen)} \qquad (1)$$

Following this reaction is a low temperature gas shift reaction, meaning that the reaction between steam and carbon monoxide will produce more hydrogen. This results in the final products being hydrogen and carbon dioxide, as shown below [3].

$$CO + H_2O \rightarrow CO_2\text{(carbon dioxide)} + H_2 \qquad (2)$$

Comparing mole ratios, for every hydrogen molecule that is created, 0.25 carbon dioxide molecules are made [4]. When equations 1 and 2 are combined, the result is shown below.

$$CH_4\text{(methane)} + 2H_2O\text{(steam)} \rightarrow CO_2\text{(carbon dioxide)} + 4H_2 \qquad (3)$$

Further purification is necessary to remove impurities (such as non-reacted carbon monoxide that was left over from the low temperature gas shift reaction) depending on the desired use of the hydrogen. In the case of hydrogen fuel cells, pure hydrogen is required and it is necessary to remove nearly all impurities. Hydrogen gas which contains small amounts of carbon oxides could cause catalyst poisoning and membrane failure in fuel cells. More advanced steam methane reformation plants use a pressure swing absorption unit, or PSA. This separates elements in a mixture based on their molecular characteristics. This technology currently allows for the production of 99.99% pure hydrogen [4].

Steam methane reforming, although it is currently the best method for producing hydrogen, still has many drawbacks. For one thing, the main reactant, natural gas, is available in finite quantities, and many researchers predict that it will be completely depleted within the next several decades. It is estimated that natural gas reserves will be depleted before midcentury, based on ever increasing consumption rates due to population increases, energy intensive technologies, and the industrialization of developing nations [7]. Furthermore, producing hydrogen with this method costs two to three times more than producing gasoline from crude oil not including the cost it would take to sequester the carbon dioxide [8]. This means that the steam methane reforming production method would not be a permanent, or sustainable, method to produce hydrogen. Essentially, if our primary energy source were to switch from oil to hydrogen, our dependence would simply change from oil to a dependence on natural gas for producing hydrogen fuel.

An additional drawback is the amount of carbon dioxide byproducts that are created during hydrogen production. Although hydrogen is hailed as a clean fuel, it is only as clean as the methods used to produce it. Therefore, if hydrogen is produced using steam methane reforming, it will not truly be clean, because it will release large quantities of greenhouse gasses, specifically carbon dioxide, into the atmosphere. There are hydrogen production methods being developed to separate and sequester the carbon dioxide, but no long term studies have been carried out to show if this is beneficial, or even possible. Also, sequestering carbon dioxide in the ocean is controversial because it could have impacts on the aquatic life, due to the fact it may increase the pH of the water [4].

Despite these drawbacks, there are some benefits to steam methane reforming. This process is the oldest method of hydrogen production and as such is the most well understood. Therefore, with enough investment, this technology could very well be made much more efficient and environmentally friendly, however, as Bryce mentioned, the laws of thermodynamics still apply, which puts a limit on the maximum efficiency of this process. Although steam methane reforming remains the cheapest method of hydrogen production currently being used, it is still not creating cheap enough hydrogen to effectively replace gasoline as the primary fuel for motor vehicles [4]. Moreover, the creation of hydrogen through steam methane reforming is simply not sustainable in the first place, as methane is a limited natural resource.

The efficiency of the process is approximately 65-75% [1]. Efficiency is the comparison of output energy to the energy input. Therefore, if it takes one unit of energy to create a certain amount of hydrogen, then that quantity of hydrogen will only contain an energy content equal to 65-75% of the original unit of energy that was used. Steam methane reforming is currently the least expensive method of hydrogen production in large quantities, costing from one to five dollars per kilogram of hydrogen [10]. However, this hydrogen is still more expensive to produce than gasoline, and assuming the producers will want to make a profit, it will cost significantly more than gasoline currently does. For these reasons, hydrogen production technology must become more efficient before it can be considered a viable replacement for gasoline in the United States.

2.2b. Electrolysis & High Temperature Electrolysis

Another method of hydrogen production is electrolysis of water. In this method, an electrical current is passed through water, which breaks the molecular bonds holding the water molecules together, resulting in hydrogen and oxygen. Because the only material required for this process is pure water, electrolysis it is able to produce 99.9995% pure oxygen and hydrogen [10]. This can be seen in the equation below.

$$2\ H_2O + 2\ e^{-} \longrightarrow H_2 + 2\ OH^{-} \qquad (4)$$

The process of electrolysis is the opposite of what happens in a fuel cell. In a fuel cell, hydrogen is burned which causes it to react with oxygen. The resulting products are simply water and energy in the form of heat [1].

Electrolysis is responsible for 4-5% of the hydrogen produced today. Most of this hydrogen is a byproduct in the production of chlorine. This equation is shown below [10].

$$2\ NaCl + 2\ H_2O \rightarrow Cl_2 + H_2 + 2\ NaOH \qquad (5)$$

In a perfect world, 39 kWh of electricity and 8.9 liters of water are required to produce 1 kg of hydrogen at 25°C and 1 atmosphere pressure [10]. The process of electrolysis is 56-73% efficient [6]. This figure is somewhat less than the efficiency of steam methane reforming, which is 65-75%.

The process of electrolysis was discovered by William Nicholson and Sir Anthony Carlisle shortly after Alessandro Volta invented the electric battery. As hydrogen use became more and more prevalent in the 1920's and 1930's, it gradually made the transition from being produced by electrolysis to steam reforming due to the lower cost involved. Currently, with the rising cost and eventual total depletion of natural gas reserves, electrolysis of water has become a viable hydrogen production replacement technology for steam methane reforming. Of course it is still the more expensive route to hydrogen production, and so methods of modifying the process are being researched.

Such methods include high temperature electrolysis. High temperature electrolysis, also known as steam electrolysis or HTE, is more economically efficient than the traditional room temperature method because it produces more hydrogen in the same amount of time as compared to the standard electrolysis process. However, it remains simply a non-feasible process, as it is still highly expensive, and produces hydrogen that cannot compete with gasoline or other common fuels on a price-per-unit level. However, this technology is constantly being improved upon [1]. The diagram shown below in figure 24 depicts a schematic of the electrolysis process. Steam enters the reaction chamber and its molecules are broken apart as an electrical current is passed through. Then, the hydrogen and oxygen molecules are attracted to opposite sides of the chamber due to their electrical attraction to either the porous cathode or anode. The downside to this production method is that a highly specialized and extremely expensive facility is necessary in order to produce large quantities [11].

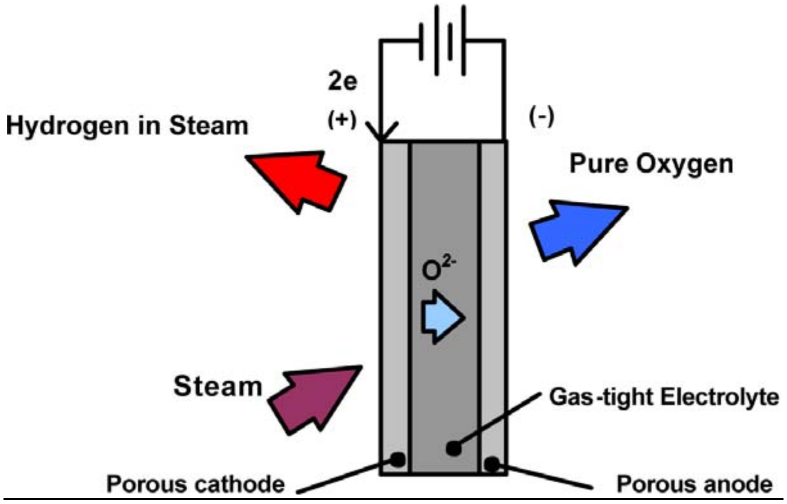


Figure 24: Schematic of Electrolysis of Water Process

Source- http://www1.eere.energy.gov/solar/pdfs/doctor.pdf

2.2c. Biomass

With the limitations on both steam methane reforming and electrolysis, it is evident that another large-scale production method would prove useful. Currently, steam methane reforming and electrolysis of water, along with the gasification of coal, are the only methods used for the industrial production of hydrogen. There are many theoretical methods for the production of hydrogen. An example of one of these processes would be hydrogen production through the utilization of biomass [12].

Biomass is mass produced from what was once living tissue. Examples of biomass would be agricultural crops and their waste by-products, lignocellulosic products such as wood and wood waste, waste from food processing and aquatic plants and algae, and effluents produced in the human habitat. Some dried mass can be burned directly as fuel, such as wood residue, wood scrap and urban garbage. Water-containing biomass such as sewage sludge, agricultural and livestock effluents, as well as animal excretions, all require the use of microbial fermentation in order to derive some sort of energy that can easily harnessed and used.

There are several theoretical processes to create hydrogen from biomass. The most practiced and practical route is thermo chemical gasification coupled with water gas shift [12]. Thermo chemical gasification is essentially a high rate chemical decomposition of a condensed substance by heating, or pyrolysis [13]. The equation for the reaction is shown below [12].

$$\text{Biomass} + O_2 \rightarrow CO + H_2 + CO_2 + \text{Energy} \qquad (6)$$

Like all of the processes stated, biomass has both positive and negative aspects associated with it. Biomass is a renewable energy source, and so would not run out like the fossil fuels. A drawback to biomass is the large amount of land necessary to produce the fuel. Biomass can never match the current demand for fuel, simply because there is not enough free, useable land to produce biomass [14]. Also, using all the available biomass, such as trees, would lead to massive deforestation which would have many negative impacts on the world, as well as take many years to grow back [15].

2.2d. Nuclear Power Plants Used During Off-Peak Hours:

Another possibility for the creation of hydrogen is the use of nuclear power plants at night during off-peak hours. There are currently 104 operational nuclear power plants in the United States [16]. Off-peak hours refer to the period of time when the demand for electricity is low, typically between 12AM and 6AM [17]. The proposed method of producing hydrogen in these nuclear reactors involves using electrical energy produced during off-peak hours and the current electrolysis of water process [17]. High temperature electrolysis and thermochemical water splitting cycles are more efficient processes compared to normal electrolysis, however, the temperatures (700-1000°C) required to operate them are too high for the currently used light water nuclear reactors and advanced light water nuclear reactors [17]. However, a new type of reactor, the generation IV nuclear reactor, which is current being developed and should be ready by the year 2020, will operate of high enough temperatures to provided sufficient heat energy to run both the high temperature electrolysis and the thermochemical water splitting processes [17].

The benefit of using nuclear reactors during off-peak hours to create hydrogen is that there are no emissions that would be harmful to the environment, such as carbon dioxide or sulfur dioxide. Additionally, the hydrogen produced through electrolysis is extremely pure (as opposed to the impure hydrogen created through steam methane reforming which requires purification) which is necessary in order to avoid corrosion in fuel cells [17]. Despite these benefits, many obstacles stand in the way of more widespread nuclear-power generated hydrogen, including incredibly strict safety regulations, waste storage, long-term hydrogen storage, and a lengthy siting and development process required for new facilities [17].

Hydrogen production via nuclear power may be the best method of production available today, and in the future. Nuclear energy is already a proven viable, primary energy source, with relatively limited emissions other than radioactive waste. Future technologies proposed by the Department of Energy that will increase the output and efficiency of nuclear facilities will allow hydrogen to be produced and sold at a price that is competitive with gasoline [17].

2.3 Hydrogen in the Transportation Sector:

In recent years, hydrogen has been touted as a renewable and viable replacement fuel for automobiles. There has been much anticipation of this new technology throughout the country, but few are aware of all the factors that must be considered before this fuel source could actually be deemed a viable fuel source. Assuming that hydrogen could be created efficiently without harmful byproducts, and could be safely stored and transported, there are still many flaws in using it as a major fuel source. The first problem is hydrogen's low volumetric energy density. According to a 1995 study by Stanford University faculty member John McCarthy (Professor Emeritus as of 2001), while hydrogen contains nearly 2.6 times the energy of gasoline in terms of mass, it still requires nearly 4 times the volume (of compressed hydrogen) of gasoline to produce an equivalent quantity of energy [1]. A typical gasoline-powered automobile utilizes a 15 gallon tank. A hydrogen-powered automobile would require a 60 gallon tank in order to have the same energy content as a gasoline-powered automobile. Although the weight of the fuel in a hydrogen-powered vehicle would only be about 34 pounds (compared to about 90 pounds for 15 gallons of gasoline), the massive tank size would require new vehicles to be much larger, and hence even more inefficient, and older vehicles would require massive overhauls in order to hold the larger fuel tank, which would likely be a costly venture, not affordable my most Americans [1]. Another issue is that of the safety in using hydrogen. Hydrogen burns with an invisible flame, and ignites when released into air [2]. The Hindenburg disaster in 1937 is an example of the dangers of using hydrogen that has contributed to the essential paralysis of the development of widespread hydrogen technology [3]. For this reason, it would be necessary to ensure that any vessels which store or transport hydrogen are completely impervious to leakage. While hydrogen leakage in open spaces may not prove as dangerous, as the escaping gas would quickly disperse and burn up, leaks in confined spaces could prove extremely dangerous. A leaking vehicle fuel tank within a garage could level a home, and an accident in a confined area, such as tunnel, could cause catastrophic damage not only to the structure itself, but also to any nearby motorists or pedestrians. Therefore, it would be necessary to develop technology that would allow for completely safe and accident-proof hydrogen storage containers.

The main advantage in burning hydrogen is that the only byproduct, other that energy in the form of heat, is water [1]. This would be especially beneficial in the case that global warming becomes a major problem. However, as mentioned in the Hydrogen Production section, the primary method of hydrogen creation is through steam methane reforming, in which the hydrogen molecules are stripped from methane, resulting in carbon dioxide release. This process renders the clean burning of hydrogen completely useless, since the same byproduct that it is preventing the release of through its burning is still being generated in its production, either directly through steam methane reforming, or indirectly through the generation of coal-fired electricity. If hydrogen could be made in large quantities with a method that did not involve the burning or cracking of fossil fuels, such as high-temperature electrolysis of water, then it would present a beneficial method to reduce carbon dioxide and other harmful byproducts into the environment. Even if it could be made cheaply and efficiently, and without the release of harmful byproducts in its production, it would still not make sense to convert conventional-fuel vehicles to hydrogen as long as fossil fuels are still readily available in large quantities, because these are still cheaper to produce.

2.4 Hydrogen Legislation:

Hydrogen could very well become one of the major alternative fuels in the world, but it is only just beginning to see approval by the world's governments. The politicians of this world are not blind, and have seen the increased dependence on oil as a need to develop safe, clean, alternative fuels. Much legislation has already been put into effect to further the research and development of these alternative fuels. Some of this legislation is beneficial; however, much of it is simply waste of taxpayers' money.

An energy policy was first put in place by United States President Jimmy Carter in 1977. In a speech during the same year he stated that; "With the exception of preventing war, this [energy problem] is the greatest challenge our country will face during our lifetimes" [1]. This led to the creation of America's first national energy policy. This policy is responsible today for the development of solar energy, as well as the insulation of millions of American homes [1]. Carter was ahead of his time in the desire to eliminate the country's need for foreign oil. In fact, he wanted to remove the foreign oil industry completely from the United States Foreign Policy [2]. He was also a major proponent of other alternative energies such as wind and nuclear power. He created the United States Department of Energy, and was also responsible for introducing the United States to plant based fuels like ethanol. With his interest in alternative energy, Carter was leading the country towards an alternative energy-rich future.

After his four years in office, the nation's standing point on alternative energy had changed. The nation was no longer experiencing an energy crisis, and so the subsequent president, Ronald Reagan, began to cut funding for Carter's programs. Reagan cut the Department of Energy's alternative fuel and conservation budgets in half [2]. Spending on photovoltaic research was decreased by two-thirds. Energy tax credits for home owners were significantly reduced. He even went so far as to remove the solar panels that Carter had installed on the roof of the White House. In effect, he halted the forward motion towards a more energy-independent nation that the United States Government had only just begun to start [2].

This attitude of alternative energy ignorance continued to be prominent in the following administrations. President Clinton however, did work to change the energy sources in government buildings. He signed an executive order which stated that federal agencies "shall use off-grid generation systems, including solar powered lighting fixtures, steam powered turbines, small wind turbines, fuel cells, and other off-grid alternatives, where such systems have been life-cycle cost-effective and offer benefits including energy efficiency, pollution prevention, source energy reductions, avoided infrastructure costs, and expedited service." This did extend legislation on alternative energies, but did very little to end the United State's addiction to foreign oil [3].

President George W. Bush was the nation's leader during an energy crisis in 2008, in which gasoline prices reached the highest levels that the country had ever seen. Although he did not do much to reduce greenhouse gas emissions that cause global warming [4], he did take notice of the nation's dependence on foreign oil. Alternative fuels take on a whole new level when they appear to be the only option available. President Bush stated that, "In the long run, the solution is to reduce demand for oil by promoting alternative energy technologies. My administration has worked with Congress to invest in gas-saving technologies like advanced batteries and hydrogen fuel cells... In the short run, the American economy will continue to rely largely on oil. And that means we need to increase supply, especially here at home. So my administration has repeatedly called on Congress to expand domestic oil production" [5]. This exemplifies the type of attitude that will make the United States a leader in the alternative energy economy that will prepare the world for a future that is free of dependence on fossil fuels.

As of writing this paper, President Obama is only just beginning his first term as president, and as such has not had the time required to encourage legislation for the development of alternative fuels. He has, however, developed a stimulus plan to help stimulate the economy. Among his plans is the creation of jobs through the development of alternative fuel infrastructures, which will help in turning the country into a more "green" nation. Similarly, he places on increasing the production of proven alternative fuel methods, which includes, from what he has stated thus far, solar and wind power. He has mentioned Hydrogen Power and stated that it shows promise in the nation's future. However, as mentioned previously, the actual viability of hydrogen becoming a major player in the United States' fuel economy remains a hotly debated subject.

2.5 Hydrogen Economies of the World:

The United States of America is in no way a leading figure in terms of hydrogen research. Many other countries are far ahead of the United States in their research, development, and implementation an effective hydrogen economy. Countries such as Japan, Portugal, Iceland, Norway, Denmark, Germany, and Canada are leading nations toward a hydrogen economy.

Most notable of these countries is Iceland, which has committed to developing the world's first complete hydrogen economy by 2050 [1]. As discussed in the section on geothermal energy, Iceland has an incredible amount of available heat energy through its location over highly active thermal vents in the earth's crust, allowing it to run geothermal power plants that create electricity, which could also be used to create hydrogen. This is exactly what Iceland is attempting to do. The Shell Oil Company opened the world's first hydrogen fueling station in Reykjavik in April, 2003 [2]. Iceland also currently employs a small pilot hydrogen bus program, and it plans to run its entire fishing fleet on hydrogen power in the future [2].

There are many other uses of hydrogen fuel worldwide. The Munich Airport Hydrogen Project, which began in 1999, fuels cars and airport buses on hydrogen. The California Fuel Cell Partnership is working with the government to convert California's oil economy to one dominated by hydrogen [3]. Japan is also working diligently to eliminate its dependence on foreign fuel (which it relies on almost exclusively due to limited natural fossil fuel resources) by converting its fossil fuel-based energy economy to a hydrogen economy. They plan to have 50,000 fuel cell cars on the road by 2010 [4]. Canada plans on constructing a hydrogen highway, similar to the one proposed for California, from the Vancouver Airport to Whistler by the 2010 Winter Olympic Games [5].

The United States of America is clearly not the only country interested in hydrogen as an alternative fuel. Other countries are making similar research and development, and some, like Iceland, are far ahead of the United States in their quest towards an energy economy that is more clean and sustainable then the current oil-dominated energy economies of the world. Iceland, and other countries with renewable natural resources, such as geothermal energy, has the potential to create a sustainable method of producing large quantities of hydrogen through electrolysis of water. The timeframes these countries have generated for their future hydrogen economies display the reality that, even under the best circumstances, they will not be fully implemented for some time to come, largely due to the relative new interest in alternative energy and a lack of government funding for research and development. Even with the most optimistic timeframe, it will be at least 20 years before countries develop just a fledgling version of, what they hope to be, a fully functional hydrogen economy to reduce or completely erase the need for unsustainable fossil fuel economies [6].

2.6 Transition to a Hydrogen Economy:

A successful hydrogen economy does not simply have to do with the feasibility of using hydrogen as a major alternative fuel. While many hydrogen-related technologies have already been developed, and still more are under development, an even larger obstacle looms in our nation's hydrogen economy's future. One of the primary antagonists to a hydrogen economy would be the conversion required to change the current fossil fuel-intensive energy economy to that of one based on hydrogen technology. This conversion would require a complete overhaul of the current fossil fuel infrastructure, and will be discussed in detail in the following section.

Additionally, a plethora of other problems exist, and these will certainly slow the development of hydrogen economies worldwide. Issues including the production of hydrogen in massive quantities, the distribution of hydrogen, storage, and general safety practices in everyday use of hydrogen, would have to be resolved before a complete transition to a hydrogen economy could come into effect.

As mentioned previously in the hydrogen production section, there is already a large demand for hydrogen. However, these hydrogen demands are not caused by the need for fuel, but rather for its use in the fertilizer, chemical, and fossil fuel-enhancement industries. The quantity of hydrogen that would have to be produced would have to increase by a considerable factor in order to satisfy the world's energy demands, and will be discussed in the conclusion. Furthermore, the primary production method of hydrogen, steam methane reforming, employs the use of nonrenewable sources, which simply will not allow hydrogen to become a sustainable alternative energy of the future.

Hydrogen-powered vehicles have been in production for quite some time by several automobile companies, most notably, Honda Motor Company [1]. Regrettably, most of these vehicles are not ready for public use, as they are largely still in the developmental phase, and the ones that are available are simply too expensive for the average person to afford.

Figure 25: Honda FCX Hydrogen Car

Source- http://www.hydrogencarsnow.com/

The majority of hydrogen-powered vehicles, such as the Honda FCX hydrogen car, shown above in figure 25, on the road in the United States today can be found in California [1]. This is due to the large strides that California is taking to expedite creation of a hydrogen infrastructure. In 2005, Honda leased the first hydrogen powered car to a family in southern California [1]. California's governor, Arnold Schwarzenegger, has called for the creation of 200 hydrogen fueling stations along Californian highways by the year 2010 [1]. This would be a significant improvement, because as of 2004, California had a mere 13 pilot stations [2]. Despite this recent interest and the development of a hydrogen economy and infrastructure, both the Ford and Nissan motor companies have announced that they will be cancelling their research and development of hydrogen-powered cars in favor of other alternative energy-powered vehicles, such as electrical hybrids. They believe that there is more promise and interest in electricity-powered cars and hybrids than in hydrogen fueled cars, due to the fact that functional hydrogen technology is years away from being perfected, and based on the widespread availability, low cost, and popularity of electricity [3, 4].

Yet another obstacle that must be overcome before a hydrogen economy will be accepted by the public is the high price of both hydrogen and fuel cells. According to the United States Department of Energy, in order “To be economically competitive with the present fossil fuel economy, the cost of fuel cells must be lowered by a factor of ten or more and the cost of producing hydrogen must be lowered by a factor of four” [5]. These are considerable figures, and will require much additional funding for development before they can become a reality. Before the public will even consider the possibility of using hydrogen energy in favor of the readily available and relatively cheap gasoline, it must first reach the point where it can be produced cheaply enough so that it has a comparable cost. Without lower prices, the hydrogen economy simply does not stand a chance against the widespread gasoline-dominated motor vehicle fuel economy. Additionally, the current price of a hydrogen fuel cell automobile is roughly $100,000 [2]. This is almost 5 times higher than the average automobile cost of roughly $22,000 in 2006, as determined by the United States Department of Energy’s Energy Efficiency and Renewable Energy program [6]. Clearly, new widespread technologies must be funded and developed in order to ensure that the costs of both hydrogen fuel and hydrogen-powered vehicles become comparable to, if not cheaper than the current costs of gasoline and gasoline-powered vehicles.

Another major transition factor would be the delivery of hydrogen. As mentioned above, California does have a few hydrogen fueling stations, but delivering hydrogen to a small amount of fueling stations versus delivery to an entire national infrastructure of hydrogen is a very different task. The problems with delivery will be extensively discussed in the following section which pertains to the issues involved with constructing a hydrogen infrastructure.

Converting America’s widespread fossil fuel infrastructure to one capable of accommodating a hydrogen economy would be a monumental task. Although California has already begun its own transition, most of the nation, and most of the world for that matter, is lagging behind, as the idea of converting from a well-known and time-tested, albeit ultimately unsustainable fossil fuel economy to a relatively unknown, untested, and potentially unreliable hydrogen economy is a seemingly ludicrous endeavor. With such problems to overcome, regardless of the practicality of using hydrogen as a fuel source, it is debatable as to whether or not hydrogen is the alternative fuel of the future, or merely billions upon billions of dollars of wasted funding.

2.7 The Infrastructure Dilemma:

As previously mentioned in the Transition to a Hydrogen Economy section, one of the largest obstacles that would require overcoming in order to complete a fully functional hydrogen economy in the United States would be the construction of an infrastructure. Historically, infrastructures grew gradually and spread over many decades as the energy demands of cities and states increased. Eventually, over the course of many decades, extensive pipelines for transporting oil and natural gas, and vast power grids for the transportation of electricity were established. Just like oil or natural gas, hydrogen must be transported directly to either refueling stations or to homes.

Because hydrogen has such a low volumetric energy density (compared to oil or natural gas), the costs of transporting, storing, and delivering it would be much higher than transporting, storing, and delivering conventional fuels [2]. In order to combat the high storage cost of gaseous hydrogen, the Office of Energy Efficiency and Renewable Energy is experimenting with and evaluating high pressure/low temperature storage methods [2]. Regardless of whether or not this technology is perfected, it will still be a highly expensive storage technique, as it must be refrigerated at a temperature below -423.0°F (-252.8°C) in order to ensure that it is kept in its liquid phase [2], clearly impractical for a large-scale hydrogen pipeline system. The energy cost that would be required to keep hydrogen that cold would offset any potential gains in efficiency.

In order to establish an infrastructure for hydrogen, the country would need to completely modify the current 550,000 kilometers of natural gas pipelines, and possibly the 245,000 kilometers of pipelines which carry petroleum, mainly to prevent the metal pipes from becoming brittle and cracking (due to hydrogen embrittlement), and to seal all pipe-pipe and valve interfaces where hydrogen would leak [1, 2]. This modification, which would be incredibly expensive not only to complete, but also to maintain, is just one of the many previously mentioned obstacles that stand in the way of a fully functioning hydrogen economy in the United States, and in countries around the globe.

Part 3: Calculations

1. **What is the ratio of energy contents between hydrogen and gasoline per unit mass?**

The ratio of energy contents between hydrogen and gasoline per unit mass is 2.98:1

2. **What quantity of uncompressed hydrogen gas contains the equivalent energy content of 1 gallon of conventional gasoline, and what pressure would be required to compress that quantity of hydrogen so that it would fit inside a standard vehicle's 20-gallon fuel tank?**

2,715.7 gallons (10.28 cubic meters) of uncompressed, gaseous hydrogen would be required to replace a single gallon of gasoline, in terms of energy content.

101,796Pa would be the required pressure inside a standard 20-gallon tank to accommodate 2715.7 gallons of uncompressed, gaseous hydrogen.

3. **How much hydrogen would be needed to replace 100% of motor gasoline (by energy content) used in the US every year?**

390,692,007,000,000 gallons (146,220,000 tons) of uncompressed, gaseous hydrogen would be needed to replace 100% of the gasoline consumed in the United States in 2007, in terms of energy content. (9 million tons are currently produced annually in the US; page 46)

4. **What is the increase in hydrogen production that would be required to replace 100% of motor gasoline (by energy content) in the US every year?**

Hydrogen production would have to increase by approximately 1625% in order for quantities to be sufficient enough to replace 100% of the annually consumed motor gasoline in the United States.

5. **How much energy does it take to produce enough hydrogen to replace 1 gallon of gasoline?**

169,460,000 Joules (160,610 BTUs) of energy would be required to create enough hydrogen through steam methane reforming to replace 1 gallon of gasoline, in terms of energy content.

6. **How much energy would it take to produce enough hydrogen to replace 100% of gasoline consumption?**

2.58*10^19 Joules (2.445*10^16 BTUs) of energy would be required to create enough hydrogen through the process of steam methane reforming to replace 100% of the gasoline consumption in the United States, in terms of energy content.

7. **Compare the energy output between burning equal quantities of natural gas and hydrogen.**

The energy output of 1m^3 of natural gas is 39 MJ, while the energy output of 1m^3 of hydrogen is 51.82 MJ. Hydrogen contains 72.3% more energy than natural gas, per unit volume.

8. **What volume of hydrogen gas has an equal energy content compared of a given volume of natural gas?**

0.753m^3 of hydrogen has an energy content equal to 1m^3 of natural gas.

9. **Compare carbon dioxide emissions between burning equal volumes of natural gas and hydrogen quantities (produced through both steam methane reforming and electrolysis), taking into consideration the emissions produced in the creation of hydrogen.**

   1) Carbon dioxide emissions from burning hydrogen produced through electrolysis of water:

      Carbon dioxide emissions from burning hydrogen are zero, as the only byproducts are water and heat (energy). There is no carbon dioxide emission in the electrolysis of water production method, as the only byproducts are oxygen and hydrogen. However, the carbon dioxide emissions created in the production of hydrogen though electrolysis would be about 1000g/kWh [1].

      Carbon dioxide emissions from the burning of natural gas are 443g/kWh [2].

   Based on these facts, the burning of hydrogen that was produced through the electrolysis of water is infinitely cleaner than the burning of natural gas.

   2) Net carbon dioxide emissions from the burning of hydrogen total 664g/kWh when said hydrogen was created through the process of steam methane reforming [2].

Once again, the carbon dioxide emissions from the burning of natural gas are 443g/kWh [2].

Therefore, the burning of hydrogen that was created by steam methane reforming has a net carbon dioxide output, that, when compared to the carbon dioxide output from the burning of natural gas, is:
664g/kWh / 443g/kWh = <u>**1.499 times higher**</u>

10. What quantity of hydrogen would be needed to replace: 1) 100% of the natural gas usage in the country? 2) Half the natural gas usage? 3) 10% of natural gas usage? 4) 1% of natural gas usage? What increase in current hydrogen production would be required to meet these demands?

1) 4.916*10^11 cubic meters of hydrogen would be need to replace 100% of the natural gas consumed in the United States annually, and a 540% increase in hydrogen production from the current 9,000,000 tons produced annually to satisfy 100% of the annual natural gas demand.

2) 2.458*10^11 cubic meters of hydrogen would be need to replace 50% of the natural gas consumed in the United States annually, and a 270% increase in hydrogen production from the current 9,000,000tons produced annually would be needed to satisfy 50% of the annual natural gas demand.

3) 49.16*10^9 cubic meters hydrogen would be need to replace 10% of the natural gas consumed in the United States annually, and a 54% increase in hydrogen production from the current 9,000,000tons produced annually would be needed to satisfy 10% of the annual natural gas demand.

4) 4.916*10^9 cubic meters hydrogen would be need to replace 1% of the natural gas consumed in the United States annually, and a 5.4% increase in hydrogen production from the current 9,000,000tons produced annually would be needed to satisfy 1% of the annual natural gas demand.

11. <u>What volume of natural gas would be required to generate 1 cubic meter of hydrogen through the process of steam methane reforming?</u>

It would take 2.013 cubic meters of natural gas to create 1 cubic meter of hydrogen through the process of steam methane reforming.

12. What quantity of natural gas would be required to create enough hydrogen to replace the current natural gas demand for 1 year, 1 month, and 1 day? How would this affect the current annual consumption rate of natural gas?

1) 9.896*10^11 m^3 of natural gas would be needed to create enough hydrogen through the process of steam methane reforming to replace the United States natural gas consumption for one year, in terms on energy content.

2) 8.247*10^10 m^3 of natural gas would be needed to create enough hydrogen through the process of steam methane reforming to replace the United States natural gas consumption for one month, in terms on energy content.

3) 2.712*10^9 m^3 of natural gas would be needed to create enough hydrogen through the process of steam methane reforming to replace the United States natural gas consumption for one day, in terms on energy content.

4) By using natural gas to create enough hydrogen, through the process of steam methane reforming, to replace the annual natural gas consumption, there would be a 51.57% increase in natural gas consumption per year.

13. What quantity of water would be required to create enough hydrogen, through the process of electrolysis, to replace the current natural gas demand for 1 year, 1 month, and 1 day?

1) 390,569,000m^3 of water would be need to produce enough hydrogen to replace the natural gas, in terms of energy content, consumed in 1 year in the United States.

2) 32,537,200m^3 of water would be need to produce enough hydrogen to replace the natural gas, in terms of energy content, consumed in 1 month in the United States.

3) 1,084,400m^3 of water would be need to produce enough hydrogen to replace the natural gas, in terms of energy content, consumed in 1 day in the United States.

14. How would annual oil imports be affected if the United States were to use steam methane reforming to produce enough hydrogen to replace 100% of its gasoline consumption, in terms of energy content?

If the United States were to use the process of steam methane reforming to create enough hydrogen to replace 100% of its annual gasoline consumption, then oil imports would decrease by 92.58%, as nearly the entire quantity of imported oil goes towards the creation of gasoline.

Part 4: Conclusions

Summary:

Energy consumption is an infinitely important aspect of the modern lifestyles enjoyed by even the poorest people on Earth. Without the extensive rates of energy consumption we as humans currently utilize, life as we know it would simply cease to exist. Everything we take for granted, including our automobiles, cell phones, air conditioners in the hot summers, heating systems in the cold winters, cooked meals, iPods, television sets, and virtually every piece of technology we own either requires energy to operate or consumed energy in its production. Additionally, as the human population increases, and as technologies become more and more advanced, thus yielding higher energy requirements, the worldwide energy demand will inevitably continue to grow.

While there is practically no limit to the amount of energy that could potentially be consumed, we must remain wary of the undeniable fact that the most commonly used energy sources on this small planet are finite in quantity. These limited energy sources, which primarily include oil, natural gas, coal, and their derivatives, will not last forever. In fact, most scientists and researchers agree that peak production rates for these fossil fuels have already been reached, which subsequently means that those production rates are now in a terminal decline, seeing less and less production potential as time passes. These leading authorities also estimate that oil and natural gas reserves will last less than a century, at best, while coal reserves may last approximately two centuries at the longest. There are simply not enough fossil fuels left in the earth to grant our progeny a secure future, in terms of energy availability. Furthermore, no matter how many additional fossil fuel reserves may be found, and no matter how efficient fossil fuel-dependent technologies become, these fuels will remain an unreliable source of energy due to the finite nature of their existence on Earth. Therefore, the only logical solution to the inevitable energy crisis that will occur in the near future is to develop alternative energy technologies.

While there have been many instances of attempts to create clean, alternative energies in recent decades, in reality, they have done little to arrest the overwhelming dominance of fossil fuels in the world's energy economy. Alternative energies, such as wind power, solar power, and hydro power, are renewable sources of energy that have been regarded as simple solutions to complete dependence from fossil fuels. However, these alternative energies will never be able to replace fossil fuels, mainly because they are not cost-effective, and because the energy that they harness is intermittent at best (solar energy is only available in large quantities during cloudless daytime hours, hydro power only being worthwhile when water flow rates are high, and wind power only being available on blustery days). Because of the intermittence of these alternatives, none could ever be relied upon as a primary energy source. In order for an energy source to become as main stream as fossil fuels, it must be as widely available and readily harnessed as they are. Other alternative energies, such as biodiesel and ethanol, while often touted as practical replacements to gasoline, are in fact, completely impractical and outright ludicrous notions. The very fact that it takes more energy to create a quantity of either biodiesel or ethanol than that same quantity can produce proves that these energy sources were illogical in the first place, and they will never amount to anything in terms of becoming a major player in the energy economy of the United States, or any other country in the world. Lastly, an alternative energy source, like geothermal power, is restricted to countries or regions with lie above areas of high geothermal activity. Therefore, it would be impossible for this type of energy to become a dominant alternative fuel in the absence of fossil fuels.

The world’s energy security in the future is largely uncertain. What is for certain is that fact that fossil fuels, which currently dominate the global energy economy, will indefinitely become totally depleted in time. The exact time at which this occurs is irrelevant, because the fact of the matter is that all nations must be prepared with cheap, readily available, renewable, and reliable alternative energy solutions that will be capable of replacing the heavy energy burden once carried by fossil fuels. In the event that countries worldwide are not prepared for the day when fossil fuels become extinct, there will most likely be an economic and societal failure of catastrophic proportions. Life as we have come to know it would become extremely difficult to maintain without the energy garnered from fossil fuels. For this reason, it is imperative that one or possibly multiple alternative energy solutions are developed and integrated into the global energy regime so that an easy transition will take place once the limited availability of fossil fuels becomes more apparent through decreased production and cost inflation.

The purpose of the introduction of this report, which was to present a detailed background of the energy consumption of the United States, as well as global energy consumption affects the United State’s consumption, have been fully discussed. Additionally, the flaws with currently used alternative energies have been revealed. Lastly, the largely new and hotly debated alternative energy, hydrogen, was presented. Topics ranging from hydrogen production, to current uses, to legislation regarding its use as a fuel, to its benefits and limitations were discussed in depth. Finally, we will determine whether or not a hydrogen economy is a viable replacement for the United State’s current fossil fuel-dominated energy economy, specifically pertaining to how it would affect gasoline consumption in the transportation sector.

The Viability of a Hydrogen Economy in the United States:

The question that this report set out to answer was whether or not hydrogen technology would prove to be a viable replacement for the fossil fuel-dominated energy economy of the transportation sector in the United States, specifically pertaining to gasoline. Hydrogen technology is praised as a clean, renewable energy that has the potential to solve the dilemmas of fossil fuel shortages and environmental pollution. However, these claims are generally unsupported by factual evidence. For this reason, we have set out to explore the complications involved in hydrogen production, as well as to complete an array of calculations that will allow the public to become more familiar with the facts behind hydrogen technology if it were to be used as a major fuel source in the transportation sector.

Based on the two primary hydrogen production methods currently available, steam methane reforming and electrolysis, the obvious conclusion is that they are simply not efficient enough to provide hydrogen at a cheap enough price to make it a viable replacement for gasoline and other commonly used fossil fuels. Not only are the processes not very efficient, resulting in a net energy losses, they are responsible for releasing harmful greenhouse gases which are of major concern to environmentalists. If the world was forced to shift to a hydrogen economy in the absence of fossil fuels and more effective alternative energies, then either the current production methods would need to be made more efficient or a new method of hydrogen production would have to be researched and developed.

Based on our calculations, we can see that hydrogen has the potential to greatly impact the United State’s dependence on fossil fuels for powering its transportation sector. If hydrogen production could be raised by 1625%, then it could replace all of the motor gasoline used in the

United States, and could drastically reduce foreign oil imports (over 90%, based on our calculations). However, the likelihood of this happening is very slim due to the impracticalities already mentioned, including astronomical costs, inefficient hydrogen production methods, lack of cheap hydrogen-powered vehicle technology, and an ineffectual hydrogen infrastructure, to name a few.

This is not to say there is no hope for a hydrogen economy, or at least an energy economy that relies partially on hydrogen, in the future. Many methods, currently only hypothetical propositions which are only just starting to be investigated, could be used to make hydrogen production more efficient and clean. Unfortunately, the shift to a different method of production, other than the dominant steam methane reforming and electrolysis processes, would be extremely costly. Additionally, the current infrastructure is based on the process of steam methane reforming, so it would have to be modified in order to accommodate a new type of production method. Furthermore, the calculations have shown that hydrogen production would need to be increased by more than 16-fold, which means that a substantial number of new production systems would need to be built, accentuating the enormous expense of developing a fully functional hydrogen economy. The aforementioned alternative hydrogen production methods are also, as of yet, untried and undeveloped. Although they may work in theory or on a small scale, much more research, development, and testing will be necessary if they are to supplant the current state-of-the-arts in the future. Unfortunately, this would take a very long time, and would be a costly expenditure. While monetary financing may not be an issue, every day that passes without the discovery of effective, large scale alternative energies brings the world a day closer to an energy crisis of epic proportions, due to the limited quantities of the fossil fuels which make up the majority of the world’s energy economy. The modern world relies upon peoples’ abilities to move about and complete tasks easily and quickly. Without massive quantities of energy, in one form or another, this would not be possible. While the human race would certainly be able to deal with an energy shortage, the quality of life would rapidly decline. This is why it is absolutely necessary to develop alternative energy technologies in the very near future.

Final Thoughts:

Based on our calculations, it is obvious that a hydrogen economy, with the intent of completely replacing the United State's gasoline economy, is currently impossible. As Robert Bryce said, thermodynamics cannot be beaten. In other words, no matter how much hydrogen technology improves, there will always be a net loss in energy as energy is converted from one form to another. However, hydrogen technology, should it be improved to increase its efficiency and cost-effectiveness, combined with a myriad of other alternative energy sources, has the potential to ease the world's future transition from a fossil fuel-based economy to a renewable resource-based one without suffering a major energy crisis.

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Appendices:

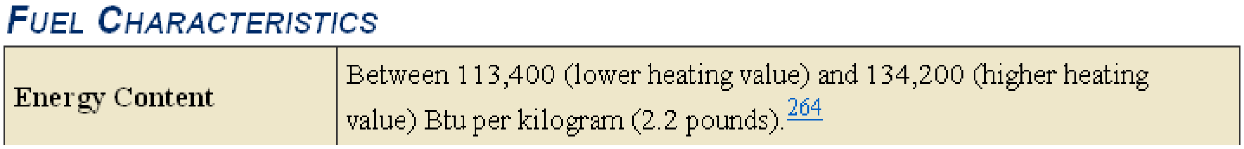
Calculations-

1. **What is the ratio of energy contents between hydrogen and gasoline per unit mass?**

According the Environmental Protection Agency, conventional motor gasoline has an energy content of 114,500 BTUs/gal [1].

Average Energy Content (btu per gallon)		
Summer	**Winter**	**Difference**
114,500	112,500	1.7%

According to the Executive Summary on the Hydrogen Energy Report from the Comptroller of the State of Texas, hydrogen has an energy content of 123,800 BTUs/kg (average of the higher and lower heating values) [2].



FUEL CHARACTERISTICS

Energy Content	Between 113,400 (lower heating value) and 134,200 (higher heating value) Btu per kilogram (2.2 pounds).[264]

1 US pound is equal to 0.4536 kilograms, and one gallon of gasoline weighs 6.073 pounds.

Therefore, one gallon of gasoline weighs: 6.073lbs * 0.4536 = 2.755kg

Therefore, gasoline has an energy content of: 114,500 BTU's / 2.755Kg = 41,560 BTUs/kg

When comparing the energy contents of hydrogen (123,800 BTUs/kg) and gasoline (41,560 BTUs/Kg), we can calculate that hydrogen has an energy content that is:
123,800 / 41,560 = **2.98:1 is the ratio of energy content ratio per unit mass between hydrogen and gasoline.**

However, the equivalent volume of hydrogen that would be needed to replace 1 gallon of gasoline is significantly more than 1 gallon.

2. **What quantity of hydrogen contains the equivalent energy content of 1 gallon of conventional gasoline?**

If one gallon of gasoline has an energy content of 114,500 BTUs, and one kilogram of hydrogen has an energy content of 123,800 BTUs, then it would take 114,500BTUs / 123,800BTUs/kg = 0.925 kg of hydrogen to equal the energy content of 1 gallon of gasoline.

Hydrogen has a density of 0.08988 g/L at standard temperature and pressure [1].

There are 1,000 liters in 1 cubic meter [1], therefore, there are: 1,000 * 0.08988 g/L = 89.88 grams of hydrogen per m^3

There are 1,000 grams in 1 kilogram [1], therefore, there are 0.08988kg of hydrogen per m^3

Therefore, 0.925kg of hydrogen would have a volume of: 0.925kg / 0.08988kg = 10.28m^3

There are 264.17 gallons in 1 cubic meter [1], hence, 10.28m^3 of hydrogen has a volume equal to: 10.28 * 264.17 = 2,715.7 gallons

From these calculations, we can see that it would take **2,715.7 gallons (10.28 cubic meters) of uncompressed, gaseous hydrogen** to replace a single gallon of gasoline, in terms of energy content.

In order for a standard 20-gallon motor vehicle fuel tank to accommodate 2,715.7 gallons of hydrogen, the gas would have to be compressed to: 2,715.7 / 20 = 135.8 => 1/135.8th, or 0.00736% of its original volume. In order for this volume of hydrogen to be compressed so that it would be able to fit inside a standard 20-gallon fuel tank, the required pressure would be:

Ideal Gas Law: PV=nRT => P=nRT/V

V= 10.28 m^3
R= 8.314 (m^3 * Pa) / (K * mol)
T(standard) = 273.15 K
n(moles) = 10.28 m^3 * 1000L/m^3 => 10280L * 0.08988g/L => 928.97g / 2.016g/mol => 460.8 moles of H_2

Thus: P= ((460.8mol) * (8.314 m^3 * Pa/K * mol) * (273.15K)) / 10.28m^3 = **101,796Pa** would be the required pressure inside a standard 20-gallon tank to accommodate 2715.7 gallons of uncompressed, gaseous hydrogen.

3. **How much hydrogen would be needed to replace 100% of motor gasoline (by energy content) used in the US every year?**

In 2007, motorists in the United States consumed 9,286,000 barrels of gasoline per day. This figure has been increasing by 30-100 million gallons per year since 2002 [1].

There are 42 gallons in 1 barrel, and 365 days in 1 year, and so there were: 9,286,000 * 42 * 365 = <u>142,354,380,000</u> gallons of gasoline consumed by Americans in 2007.

According to the previous calculation, it would take 2,715.7 gallons of uncompressed, gaseous hydrogen to replace a single gallon of gasoline, in terms of energy content.

Therefore, it would have taken: 142,354,380,000gal * 2,715.7gal/gal = **<u>390,692,007,000,000 gallons of uncompressed, gaseous hydrogen to replace 100% of the gasoline consumed in the United States in 2007, in terms of energy content.</u>**

An equivalent figure would be:
390,692,007,000,000gal / 264.17gal/m^3 = 1.4789*10^12m^3 of hydrogen
Density = 0.08988g/L = 89.99g/m^3 = .08988kg/m^3
1.4789*10^12m^3 * .08988kg/m^3 = 1.329*10^11 kg of hydrogen
1.329*10^11 kg * 2.2lb/kg = 2.9244*10^11 lbs of hydrogen
2.9244*10^11 lbs / 2000lb/ton = **<u>146,220,000 tons of hydrogen</u>** to replace 100% of the gasoline consumed in the United States in 2007, in terms of energy content.

4. **What is the increase in hydrogen production that would be required to replace 100% of motor gasoline (by energy content) in the US every year?**

The United States currently produces 9 million tons of hydrogen per year [1].

1 US ton (short ton) is equal to 907.18 kilograms.

Therefore, 9 million tons of hydrogen is equal to: 9,000,000 * 907.18 = <u>8,164,600,000kg</u>

As stated in a previous calculation, there is 0.08988kg of hydrogen per cubic meter, and there are 264.17 gallons in 1 cubic meter, therefore there are: 0.08988kg of hydrogen per 246.17 gallons.

This equates to: 0.08988 / 246.17 = .000365kg of hydrogen per gallon

1 kilogram is equal to 2.2 US pounds; therefore, 0.000365kg of hydrogen is equal to: 0.000365 * 2.2 = 0.000803lbs of hydrogen per gallon.

As previous calculated, the United States would need 386,591,790,000,000 gallons of uncompressed, gaseous hydrogen to replace 100% of the gasoline consumed in the United States in 2007, in terms of energy content.

This equates to: 386,591,790,000,000gal * 0.000803lbs/gal = 310,433,000,000lbs of hydrogen

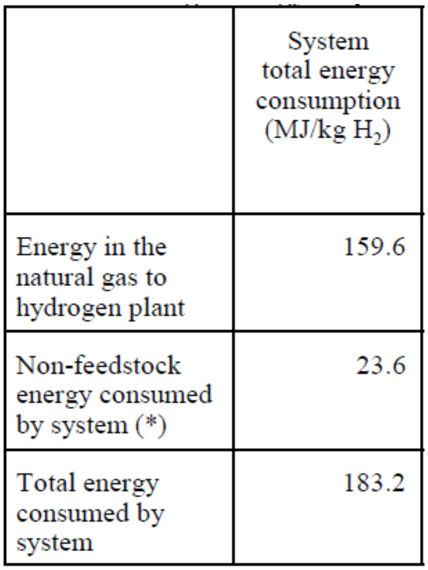
There are 2000lbs in 1 US ton, therefore, the US would need: 310,433,000,000/ 2000 = 155,220,000 tons of hydrogen to replace the gasoline consumed yearly, in terms of energy content.

This would mean that the United States would need to create an additional:
155,220,000 - 9,000,000 = 146,220,000 tons of the hydrogen annually in order to replace 100% of gasoline consumption.

This would require an increase in production of: 146,220,000 / 9,000,000 = 16.25 => 16.25 * 100 = **1625% increase in hydrogen production.**

5. How much energy does it take to produce enough hydrogen to replace 1 gallon of gasoline?

According to the National Renewable Energy Laboratory, it takes 183.2 MJ of energy to create 1 kilogram of hydrogen through the process of steam methane reforming, as seen in the table below [1].



	System total energy consumption (MJ/kg H_2)
Energy in the natural gas to hydrogen plant	159.6
Non-feedstock energy consumed by system (*)	23.6
Total energy consumed by system	183.2

1 MJ is equal to 1,000,000 joules. Therefore it takes: 183.2 * 1,000,000 = 183,200,000 joules of energy to create 1 kilogram of hydrogen.

Based on the previous calculation that 0.925kg (2715.7 gallons) of hydrogen has an energy content equal to 1 gallon of gasoline, we can see that it would take: 183,200,000 * 0.925 = **169,460,000 joules of energy to create enough hydrogen to replace 1 gallon of gasoline, in terms of energy content.**

This is equivalent to:

1 BTU = 1,055.1 Joules

169,460,000J / 1,055.1J/BTU = **160,610 BTUs of energy would be required to create enough hydrogen, through the process of steam methane reforming, to replace 1 gallon of gasoline, in terms of energy content.**

6. **How much energy would it take to produce enough hydrogen to replace 100% of gasoline consumption?**

Based on the fact that the United States would need to produce 310,433,000,000 lbs of hydrogen to replace 100% of the countries gasoline consumption, an equivalent weight would be:
310,433,000,000lbs * 0.4536kg/lb = 140,812,400,000kg

As previously mentioned, it would take 183,200,000 joules of energy to create 1kg of hydrogen. Therefore, in terms of energy content, it would take:
183,200,000J /kg * 140,812,400,000kg = **2.58*10^19 J of energy to replace 100% of the gasoline consumption in the United States, in terms of energy content.**

An equivalent figure would be:
2.58*10^19J / 1,055.1J/BTU = **2.445*10^16 BTUs of energy to replace 100% of the gasoline consumption in the United States, in terms of energy content.**

7. **Compare the energy output between burning equal quantities of natural gas and hydrogen.**

The gross heat of combustion of 1 cubic meter of natural gas is 39MJ [1].

The enthalpy of combustion for hydrogen is −286 kJ/mol [1].

1 m^3=1000 L

Hydrogen has an atomic weight = 1.0079g/ mol, and a density equal to 0.08988g/L.

H_2 = 2 * 1.0079g/mol = 2.016g/mol

1000L/m^3 * 0.08988g/L = 89.88g/m^3

89.88g/m^3 / 2.016g/mol = 181.2mol/m^3 hydrogen

181.2mol/m^3 * 286 KJ/mol = <u>51.82MJ/m^3 of hydrogen</u>

<u>The energy output of 1m^3 of natural gas is 39 MJ, while the energy output of 1m^3 of hydrogen is 51.82 MJ. Hydrogen contains 72.3% more energy than natural gas, per unit volume.</u>

8. **What volume of hydrogen gas has an equal energy content compared of a given volume of natural gas?**

From question 7, we learned that the energy output of 1m^3 of natural gas is 39MJ [1], while the energy output of 1m^3 of hydrogen is 51.82MJ.

Therefore, hydrogen and natural gas have an energy content ratio per unit of volume of:

51.8MJ / 39MJ = <u>1.328:1</u>

Hence, in terms of energy content, it would take:

39MJ / 51.82MJ/m^3 = **<u>0.753m^3 of hydrogen to equal 1m^3 of natural gas, in terms of energy content.</u>**

9. **Compare carbon dioxide emissions between burning equal volumes of natural gas and hydrogen quantities (produced through both steam methane reforming and electrolysis), taking into consideration the emissions produced in the creation of hydrogen.**

    1) Carbon dioxide emissions from burning hydrogen produced through electrolysis of water:

       Carbon dioxide emissions from burning hydrogen are zero, as the only byproducts are water and heat (energy). There is no carbon dioxide emission in the electrolysis of water production method, as the only byproducts are oxygen and hydrogen. However, the carbon dioxide emissions created in the production of hydrogen though electrolysis would be about 1000g/kWh [1].

Carbon dioxide emissions from the burning of natural gas are 443g/kWh [2].

Based on these facts, the burning of hydrogen that was produced through the electrolysis of water is infinitely cleaner than the burning of natural gas.

2) Net carbon dioxide emissions from the burning of hydrogen total 664g/kWh when said hydrogen was created through the process of steam methane reforming [2].

   Once again, the carbon dioxide emissions from the burning of natural gas are 443g/kWh [2].

   Therefore, the burning of hydrogen that was created by steam methane reforming has a net carbon dioxide output, that, when compared to the carbon dioxide output from the burning of natural gas, is:
   664g/kWh / 443g/kWh = **1.499 times higher**

10. What quantity of hydrogen would be needed to replace: 1) 100% of the natural gas usage in the country? 2) Half the natural gas usage? 3) 10% of natural gas usage? 4) 1% of natural gas usage? What increase in current hydrogen production would be required to meet these demands?

1) Volume of hydrogen need to replace 100% the natural gas consumed annually in the United States:

Natural gas used in the United States annually = 23,056*10^9 ft^3 [1].

1m^3 = 35.315 ft^3, therefore:

(23,056*10^9 ft^3) / (35.315 ft^3) = 6.528*10^11 m^3

From previous calculations, the equivalent energy content, per unit volume, of 1 cubic meter of natural gas is 0.753 cubic meters of hydrogen.

And so: (6.528* 10^11 m^3) * 0.753 meters^3 = **4.916*10^11 cubic meters** of hydrogen would be need to replace 100% of the natural gas consumed in the United States annually.

Increase in hydrogen production required:

491,610,000,000 m^3 * 0.08988kg/m^3 = 4.419*10^10 kg

4.419*10^10 kg * 2.2lb/kg = 9.721*10^10 lbs

9.721*10^10 lbs / 2000lb/ton = 48,605,000 tons of hydrogen, which would require a:

48,605,000 _/ 9,000,000tons = 5.40 * 100 = **540% increase in hydrogen production from the current 9,000,000 tons produced annually to satisfy 100% of the annual natural gas demand.**

2) Volume of hydrogen need to replace half the natural gas consumed annually in the Unites States:

(6.528*10^11 m^3) / 2 = 3.264*10^11 m^3

3.264*10^11 m^3 * 0.753 = **2.458*10^11 cubic meters of hydrogen**

Increase in hydrogen production required:

2.458*10^11 m^3 * 0.08988kg/m^3 = 2.21*10^10 kg

2.21*10^10 kg * 2.2lb/kg = 4.86*10^11 lbs

4.86*10^11 lbs / 2000lb/ton = 24,302,000 tons of hydrogen, which would require an:

24,302,000 tons / 9,000,000tons = 2.7 * 100 = **270% increase in hydrogen production from the current 9,000,000tons produced annually to satisfy 50% of the annual natural gas demand.**

3) Volume of hydrogen need to replace 10% the natural gas consumed annually in the Unites States:

(6.528*10^11 m^3) * 0.1 = 6.528*10^10 m^3

6.528*10^10 m^3 * 0.753 = **49,156,000,000 cubic meters hydrogen**

Increase in hydrogen production required:

49,156,000,000m ^3 * 0.08988kg/m^3 = 4.418*10^9 kg

4.418*10^9 kg * 2.2lb/kg = 9.72*10^9 lbs

9.72*10^9 lbs / 2000lb/ton = 4,860,000 tons of hydrogen, which would require a:

4,860,000 tons / 9,000,000tons = 0.54 * 100 = **54% increase in hydrogen production from the current 9,000,000tons produced annually to satisfy 10% of the annual natural gas demand.**

4) Volume of hydrogen need to replace 1% the natural gas consumed annually in the Unites States:

(6.528*10^11 m^3) * 0.01= 6.528*10^9 m^3

6.528*10^9 m^3 * 0.753 = **4.916*10^9 cubic meters of hydrogen.**

Increase in hydrogen production required:

4.916*10^9 m^3 * 0.08988kg/m^3 = 4.419*10^8 kg

4.419*10^8 kg * 2.2lb/kg = 9.721*10^8 lbs

9.721*10^8 lbs / 2000lb/ton = 486,000 tons of hydrogen, which would require a:

486,000 tons / 9,000,000tons = 0.054 * 100 = **5.4% increase in hydrogen production from the current 9,000,000tons produced annually to satisfy 1% of the annual natural gas demand.**

11. **What volume of natural gas would be required to generate 1 cubic meter of hydrogen through the process of steam methane reforming?**

For every 1 MJ of energy in the form of natural gas consumed through the steam methane reforming process, 0.66 MJ of energy in the form of hydrogen is produced [1].

Therefore: 1MJ / 0.66MJ = 1.515:1 is the ratio of energy from natural gas put into the steam methane reforming procedure to the energy content of the hydrogen that is created.

From question 7, we learned that the energy output of 1m^3 of natural gas is 39MJ, while the energy output of 1m^3 of hydrogen is 51.82MJ

Therefore:
1MJ / 39MJ/m^3 natural gas = 0.025641m^3 of natural gas
0.66MJ / 51.82MJ/m^3 hydrogen = 0.01274m^3 of hydrogen
It will take 0.025641m^3 of natural gas to produce 0.01274m^3 of hydrogen through the process of steam methane reforming. The ratio of natural gas into the reaction to hydrogen out of the reaction, in m^3, is 2.013:1

Therefore, it would take 2.013 cubic meters of natural gas to create 1 cubic meter of hydrogen through the process of steam methane reforming.

12. **What quantity of natural gas would be required to create enough hydrogen to replace the current natural gas demand for 1 year, 1 month, and 1 day? How would this affect the current annual consumption rate of natural gas?**

Natural gas used in the United States annually = 23,056*10^9 ft^3 [1].

First we will find the volume of natural gas consumed in 1 year, 1 month, and 1 day.

(23,056*10^9 ft^3/year) / (35.315ft^3/m^3) = <u>6.529*10^11 m^3 of natural gas consumed annually.</u>

(6.529*10^11 m^3/year) / (12 months/year) = <u>5.441*10^10 m^3 of natural gas consumed monthly.</u>

(5.441*10^10m^3/month) / (30.42 days/month = <u>1.789*10^9 m^3 of natural gas consumed daily.</u>

Next, we will find the volume of hydrogen needed to replace 1 year, 1 month, and 1 day's worth of natural gas, in terms of energy content. Keep in mind that we previously calculated that hydrogen and natural gas have an energy content ratio of 1.328:1, and 0.753m^3 of hydrogen has the equivalent energy content of 1m^3 of natural gas.

(6.529*10^11 m^3 natural gas) * (0.753m^3 hydrogen/m^3 natural gas) = <u>4.916*10^11 m^3 of hydrogen necessary to replace natural gas for a year.</u>

(5.441*10^10 m^3 natural gas) * (0.753m^3 hydrogen/m^3 natural gas) = <u>4.097*10^10 m^3 of hydrogen necessary to replace natural gas for a month.</u>

(1.789*10^9 m^3 natural gas) * (0.753m^3 hydrogen/m^3 natural gas) = <u>1.347*10^9 m^3 of hydrogen necessary to replace natural gas for a day.</u>

As we learned in Question 11, it would take 2.013 cubic meters of natural gas to create 1 cubic meter of hydrogen through the process of steam methane reforming. Hence, the quantities of natural gas that would be required to create enough hydrogen to replace the current natural gas demand for 1 year, 1 month, and 1 day are as follows:

1) (4.916*10^11 m^3 of hydrogen) * (2.013 m^3 natural gas/m^3hydrogen) = <u>**9.896*10^11 m^3 of natural gas would be needed to create enough hydrogen through the process of steam methane reforming to replace the United States natural gas consumption for one year, in terms on energy content.**</u>

2) (4.097*10^10 m^3 of hydrogen) * (2.013 m^3 natural gas/m^3hydrogen) = **8.247*10^10 m^3 of natural gas would be needed to create enough hydrogen through the process of steam methane reforming to replace the United States natural gas consumption for one month, in terms on energy content.**

3) (1.347*10^9 m^3 of hydrogen) * (2.013 m^3 natural gas/m^3hydrogen) = **2.712*10^9 m^3 of natural gas would be needed to create enough hydrogen through the process of steam methane reforming to replace the United States natural gas consumption for one day, in terms on energy content.**

4) This would result in an annual increase in natural gas consumption of:
   9.896*10^11m^3 - 6.529*10^11 m^3 = 3.367*10^11m^3 additional natural gas needed
   3.367*10^11m^3 / 6.529*10^11 m^3 = 0.5157 * 100 = **51.57% increase in natural gas consumption per year.**

Clearly, the act of using steam methane reforming to create hydrogen to use as a substitute for natural gas is insanity, as there is absolutely no logical reason why anyone would waste 51.57% more energy to create a supply of hydrogen for their needs when they could get the same energy content from burning natural gas directly.

13. What quantity of water would be required to create enough hydrogen, through the process of electrolysis, to replace the current natural gas demand for 1 year, 1 month, and 1 day?

As previously calculated, the natural gas demand in the United States is 6.456*10^11 m^3 /year, 5.38*10^10 m^3 /month, and 1.793*10^9 m^3 /day.

H_2O + energy -> H_2 + ½ O_2, and so there is a 1:1 ratio of H_2 produced per water molecule used in the process of electrolysis [1].

From previous calculations, we know that 0.753m^3 of hydrogen has the same energy content of 1m^3 of natural gas. So, the annual, monthly, and daily hydrogen consumption would be:

6.456*10^11 m^3 natural gas/year * 0.753m^3 hydrogen/1m^3 of natural gas = 4.862*10^11m^3 of hydrogen to replace a year's supply of natural gas.

5.38*10^10 m^3 natural gas/month * 0.753m^3 hydrogen/1m^3 of natural gas = 4.051*10^10m^3 of hydrogen to replace a month's supply of natural gas.

1.793*10^9 m^3 natural gas/day * 0.753m^3 hydrogen/1m^3 of natural gas = 1.35*10^9m^3of hydrogen to replace a day's supply of natural gas.

Now we will convert these volumes to moles:

(4.862*10^11m^3 * 1000L/m^3 * 0.08988g/L) / 2.016g/mol = 2.168*10^13 moles of hydrogen would be needed to replace a year's supply of natural gas.

(4.051*10^10m^3 * 1000L/m^3 * 0.08988g/L) / 2.016g/mol = 1.8061*10^12 moles of hydrogen would be needed to replace a month's supply of natural gas.

(1.35*10^9m^3 * 1000L/m^3 * 0.08988g/L) / 2.016g/mol = 6.0193*10^10 moles of hydrogen would be needed to replace a day's supply of natural gas.

We know that it takes 1 molecule of water to create 1 molecule of diatomic hydrogen, so we can also say that 1 mole of water will yield 1 mole of diatomic hydrogen (1mol of water = 18.01518g [2]). Therefore:

2.168*10^13mol * 18.01518g/mol * 1L/1000g * 1m^3/1000L = **390,569,000m^3 of water would be need to produce enough hydrogen to replace the natural gas, in terms of energy content, consumed in 1 year in the United States.**

1.8061*10^12mol * 18.01518g/mol * 1L/1000g * 1m^3/1000L = **32,537,200m^3 of water would be need to produce enough hydrogen to replace the natural gas, in terms of energy content, consumed in 1 month in the United States.**

6.0193*10^10mol * 18.01518g/mol * 1L/1000g * 1m^3/1000L = **1,084,400m^3 of water would be need to produce enough hydrogen to replace the natural gas, in terms of energy content, consumed in 1 day in the United States.**

To put these numbers into perspective, 168,000 cubic meters of water passes over Niagara Falls every minute [3]. So, the volume of water passing through the falls in 38.75 hours, 3.23 hours, and 6.45 minutes, would, respectively, provide enough feedstock for the process of electrolysis to produce enough hydrogen to replace the United State's natural gas consumption for 1 year, 1 month, and 1 day.

Discuss how this will affect natural gas imports.

14. How would annual oil imports be affected if the United States were to use steam methane reforming to produce enough hydrogen to replace 100% of its gasoline consumption, in terms of energy content?

According to the Energy Information Administration, for every barrel of crude oil that gets processed, about 19.6 gallons of gasoline is created. The remaining products include fuel oil, jet fuel, diesel fuel, and others [1]. The total volume of finished products is about 44 gallons, due to additives that enter the oil during processing. Assuming that the non-gasoline products from each barrel of oil will not be needed, then we can calculate that:

# of barrels of oil needed to obtain 1 barrel of gasoline:

42gal gasoline / 19.6gal gasoline/barrel of oil = <u>2.143 barrels of oil</u>

Therefore, it would take

9,286,000 barrels of gasoline/day * 365days/year = 3,389,390,000 barrels of gasoline/year

3,389,390,000 barrels of gasoline/year * 2.143 barrels of oil/barrel of gasoline = <u>7,263,463,000 barrels of oil would be needed to produce a year's supply of gasoline.</u>

The United States currently imports 10,031,000 barrels of oil per day, or 3,661,000,000 barrels per year [2]. If the country could replace its gasoline consumption with hydrogen, then it could reduce its oil imports by 100%, assuming that there would be no need for any of the other products that come from a barrel of crude oil. If we assume that 1 barrel of crude oil will yield 1 barrel of gasoline, then oil imports could be cut by:

3,661,000,000 barrels of oil per year - 3,389,390,000 barrels of gasoline per year = 271,610,000 barrels of oil

271,610,000 barrels of oil / 3,661,000,000 barrels of oil per year = 0.0742 * 100 = 7.42%

100% – 7.42% = **<u>92.58% would be the decrease in oil imports made by the United States if it were to use hydrogen to replace gasoline as the primary fuel for automobiles.</u>**

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