"How a Shift Toward Hydrogen Fuel Cells as a Main Alternative Energy Source will Affect the Global Economy"

An Honors Thesis

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Hydrogen Fuel Cells in America:
Changing the Economic and Environmental Landscape

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Abstract

Even today, despite efforts by the former president to push for other sources of cleaner energy, the United States still heavily depends on the markets for fossil fuel imports that are dominated by OPEC nations like Saudi Arabia. To reduce our use of fossil fuels, this paper examines many of the advantages of hydrogen fuel cells. They are then examined to decide if they are a worthy candidate for a future energy source for America as compared to alternative sources of power such as natural gas, wind energy, and solar power. It is important to analyze all energy alternatives as they may not offer the most efficient methods of generating electricity and are not as safe for the surrounding environment. Another main issue that I address in the paper is America's current dependence on foreign oil, where our country is losing money to nations that can easily drive us out of the market because of their low oil prices. Then, it is discussed how the United States will be able to become energy independent by adopting hydrogen fuel cell technology rather than just transferring its reliance from one country to another to meet future energy demand. The United States will need to open more rare-earth mines that are required to produce fuel cells to reduce its reliance on various countries. One primary country is China, where they can limit the supply of rare-earths to any country at their discretion, or intentionally lower their prices to drive out emerging competitors. This issue is also evaluated using game theory, where it is explained why the U.S. should begin mining rare-earths again. If the United States does not attempt to mine the necessary resources for fuel cells, then our country will once again be in the back seat while other countries take control of the world's supply of rare earth metals.

I. Introduction

Oil became the United States' top used fossil fuel in 1951, and ever since the country has showed difficulty in decreasing its dependence on the energy source (McLendon, 2010). This is not a sustainable source of energy as we will eventually run out in the future. If there is no backup plan, our country will face an economic challenge when there are no longer enough fossil fuel resources to support growing energy demand. The United States is also losing money to countries like Saudi Arabia, which now produces thirteen percent of the world's supply. Russia and China also produce 12.4 and 4.9 percent of the world's supply respectively ("Crude Oil Production", 2015). To avoid these problems overall, it will be necessary for the United States to rebuild its infrastructure from the ground up and become more of an energy independent country.

There are many forms of energy out there today, such as hydrogen fuel cells, wind, and solar power, and there are a plethora of companies experimenting with these different forms of sustainable energy. Unfortunately, none of these forms of energy have taken off and become cheap enough so that the everyday consumer can have one of these forms of energy installed in their home. Affordable renewable energy would allow consumers to no longer rely on a power grid while also giving them money in the long run. Despite these alternative forms of energy still being in their infancy, I believe that once all of them have had the chance to mature, it will be clear that the hydrogen fuel cell will become the true innovation. It will completely change the way we live as well as completely changing the economic and environmental landscape. Throughout the paper this will be clear, as it will discuss many of the practical applications of hydrogen fuel cells, along with why rebuilding the country's infrastructure with hydrogen fuel cells in mind will be a worthy investment. Many of the chief competitors to hydrogen fuel cells

are evaluated to clarify why they should not be the primary choice for America's main source of energy in the future as well.

II. Hydrogen Fuel Cell Background

Before assessing how if the United States were to completely change its predominant source of energy to become a more independent nation, it is imperative to gain a strong understanding of how exactly hydrogen fuel cells began, how they work, what powers them, and their potential uses for the future. Hydrogen fuel cells have been around since 1839, where Christian Friedrich Schoenbein, a German scientist, is known for uncovering the fuel cell effect (Robinson, 2017). Schoenbein had noticed the current formed when oxygen and hydrogen were combined. Around the same, time another man by the name of William Robert Grove had also started examining the current formed when the two elements were put together. While Schoenbein worked on theory, Grove created the first fuel fell, initially named the gas voltaic battery (Robinson, 2017). The hydrogen fuel cell incorporated pairs of platinum electrodes that were partly encased in oxygen and hydrogen as well as being partly submerged into sulfuric acid. Finally, water was the only byproduct of the hydrogen fuel cell. (Robinson, 2017).

Today hydrogen fuel cells have advanced immensely, and thus have become much more complicated. Hydrogen fuel cells can be compared to that of a battery, where a fuel cell has a plethora of individual cells that are combined to create a fuel cell stack. Then within every single fuel cell there is an electrolyte layer along with a cathode and an anode. One of the main differences between a battery and a hydrogen fuel cell is that batteries store the synthesized energy that is converted into electricity within the battery, while a hydrogen fuel cell accepts chemical energy or hydrogen atoms from outside the battery (Lish, 2016). This chemical energy is kept within the hydrogen, which is eventually sent to the anode. The anode within the

hydrogen fuel cell is also covered in platinum, which is the catalyst that breaks down the atoms into electrons and protons. This is unlike a battery where electrons are discharged from the anode, essentially harming the electrodes in the battery overtime since they are changed during the chemical operation. In hydrogen fuel cells the electrodes are much more reliable as they are the catalysts during the reception or discharge of electrons. It is important to note that they are not changed chemically during this procedure either. ("What Is a Hydrogen Fuel Cell?", 2016). Eventually, the protons created in the anode from the hydrogen move through the electrolyte to reach the cathode, where the oxygen is provided. The protons then react with the oxygen. Finally, electricity is created and the only byproducts produced because of the reactions are heat and water, which are essentially quite useful as they can directly be used by people, rather than the carbon dioxide produced from fossil fuels. I have provided a figure to further illustrate how a hydrogen fuel cell works.

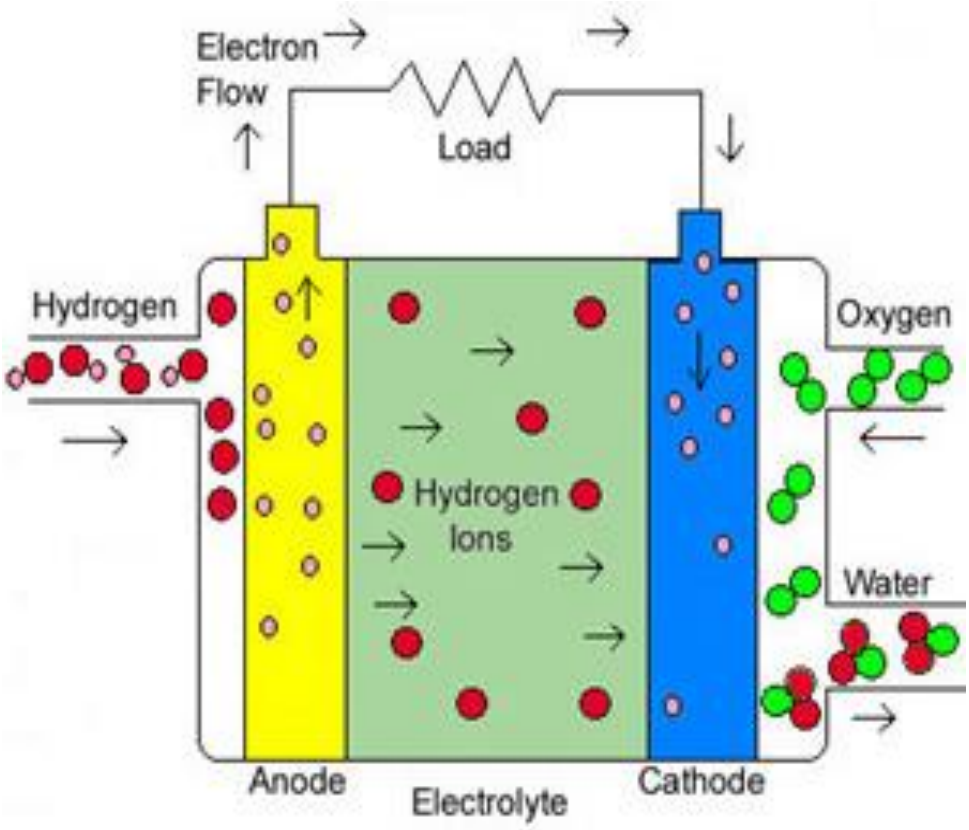

Figure 1. Diagram of how a hydrogen fuel cell works. This figure displays how hydrogen and oxygen enters the fuel cell to create the reaction to produce electricity. Adapted from Fuel Cells, 2008, Retrieved January 31, 2017, from http://americanhistory.si.edu/fuelcells/basics.htm.

III. Useful Applications of Hydrogen Fuel Cells

One of the main reasons hydrogen fuel cells should be America's main energy source is because of their useful applications that can enhance our society. One of the areas where hydrogen fuel cells benefit society the most are in vehicles. One of the primary reasons why hydrogen fuel cell vehicles should entice consumers is that they do not emit carbon dioxide, only water and heat. Water vapor is a less dangerous greenhouse gas as it does not solely dictate what the temperature will be. It is the addition of carbon dioxide, a non-condensable greenhouse gas, which controls the water vapor, making it increase the temperature. When non-condensable greenhouse gases are added to the atmosphere, the temperature rises, and the amount of water vapor in the atmosphere rises. The water vapor then absorbs the heat from the non-condensable greenhouse gases and creates even more heat. Water vapor only increases the Earth's temperature when a non-condensable like carbon dioxide is added to the atmosphere. When there are less non-condensable greenhouses gases, water vapor has less of an effect on the climate, and it doesn't increase the temperature at all if no non-condensable greenhouse gases are added (Shepherd, 2016). This should also satisfy new regulations from the Environmental Protection Agency (EPA) that is continuing to crack down on the auto industry with strict emission standards. As of right now though, extracting the hydrogen to put into the vehicles still leads to pollution. Despite this, the production of hydrogen is still only thirty percent of the pollution created by vehicles on the road today ("How Hydrogen Fuel Cell Vehicles Work", n.d.). It is also worth noting that California is developing renewable fuel cell standards, which could help lead the nation in even cleaner hydrogen production. Consumers would also most

likely choose FCVs over battery electric vehicles (BEVs) as they only take around three to five minutes to completely refill the car. BEVs, on the other hand, like a Tesla with a 120-kilowatt battery, still require nearly thirty minutes to completely charge (Cobb, 2015). FCVs also have the option to idle-off, which will turn off the car's engine while it is sitting in traffic or at an intersection to save fuel. Another great feature which fuel cell vehicles employ is regenerative braking, which obtains energy that is stored in the battery when the brakes are applied ("Hybrid Cars and Trucks", n.d.). Hydrogen fuel cell vehicles can be furthered depicted in figure 2 below.

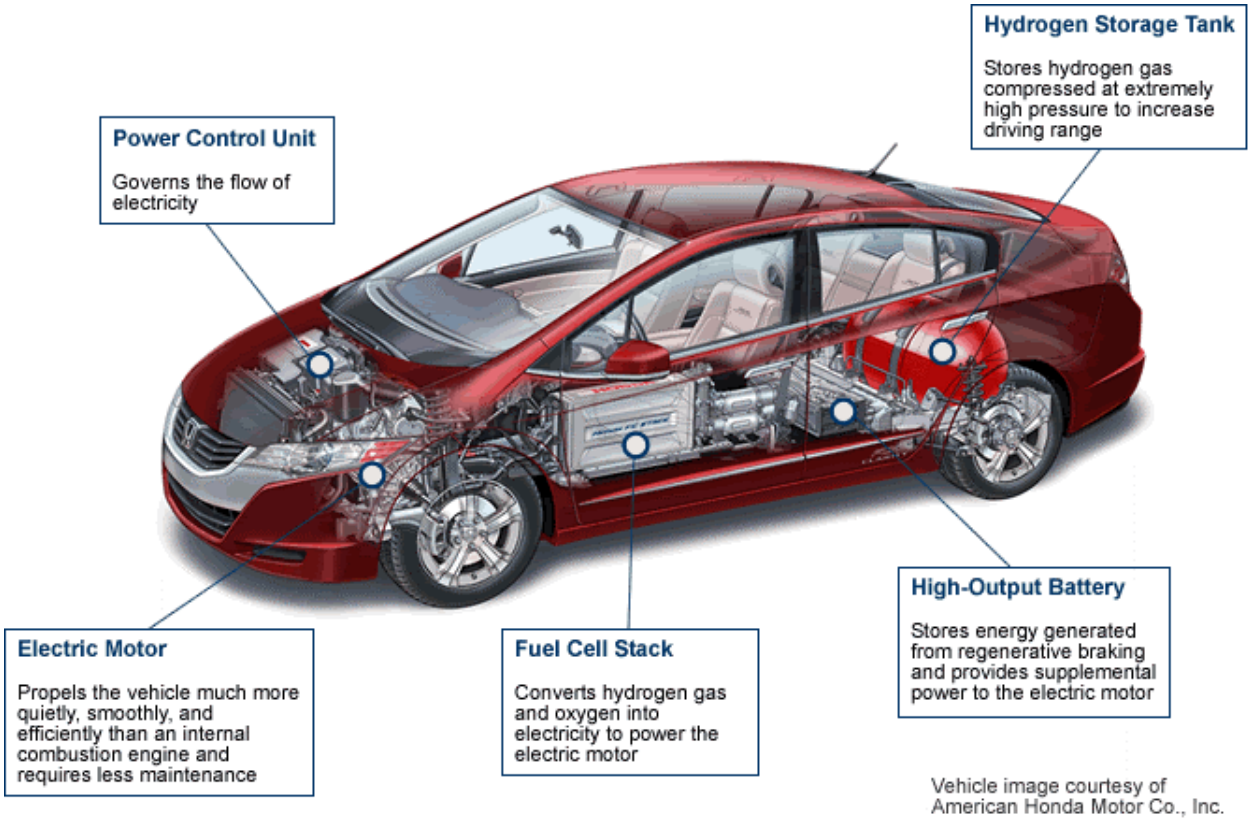

Figure 2. Diagram of what makes up a hydrogen fuel cell vehicle. This figure displays each component within a FCV and what role they play in the operation of the vehicle. Adapted from ComputerWorld, by L. Mearian, 2016, Retrieved January 31, 2017, from http://www.computerworld.com/article/3118724/car-tech/hydrogen-fuel-cell-vehicles-to-catch-electric-vehicles-report-claims.html. Copyright 2017 by IDG Communications, Inc. Adapted with permission.

Another key area where hydrogen fuel cells can be advantageous is in homes to allow people to rely less on the electrical grid, or go completely off the grid and never pay an electrical bill again. For a hydrogen fuel cell home to operate properly, the homeowner must first obtain

the hydrogen, in one of three different ways. The homeowner can have the hydrogen delivered, whereby the hydrogen is transported in gas cylinders or a tube trailer. The second method for obtaining the hydrogen is by having it reformed, where hydrocarbons are taken from mainly propane or natural gas and the hydrogen gas is created as it is restructured in a combustion compartment ("Fuel Cell Powered Home", 2015). The last and most efficient way to gather the necessary amount of hydrogen is by producing it on-site. This is also the best method if a homeowner is planning to go completely off the grid as you can take unused power, which would typically occur at night when power consumption is lowest, and use it to create the hydrogen by electrolyzing or splitting water ("Fuel Cell Powered Home", 2015). The hydrogen that is generated is then stored for later use, usually in propane tanks since they are capable of safely storing the fuel. Even if there was a leak in one of the tanks, there is no major need to worry as the flammable gas dissipates into the atmosphere quicker than any other gas (Biello, 2008). When the power is needed, the hydrogen can then be sent to the fuel cell stack, which as described earlier combines the oxygen and hydrogen to create electricity, along with water and heat as byproducts (Biello, 2008). This heat can be directed into an HVAC system to warm the home on colder days, and the water can simply be used to drink, shower with, or if there is enough, put back into the electrolyzer to create more hydrogen for future use.

One last use for hydrogen fuel cells involves NASA space shuttles where they are used to provide power to the electrical components within the spacecraft, creating only water as a byproduct, which everyone on board can drink ("Hydrogen Energy", 2016). Fuel cells were an easy choice to put on space shuttles because they weigh very little, and hydrogen is already on board as it is used as the fuel to launch the rocket, along with the oxygen necessary for the astronauts to breath (Robinson, 2017).

IV. **Moving Toward a New Primary Energy Source**

Although this paper analyzes hydrogen fuel cells, there are also many other alternatives to foreign oil. It is critical to analyze these alternative sources to prove why hydrogen fuel cells are better suited to power our nation. Earlier in the paper, the main benefits of hydrogen fuel cells have already been discussed, but a few other potential sources of energy for the future have not been thoroughly examined to properly evaluate why hydrogen fuel cells are the technology that the United States should move forward with in the coming years.

The first alternative fuel source is natural gas. There have been multiple estimates on America's natural gas reserves, and it is said to be between 1.5 and 2.5 quadrillion cubic feet, which amounts to a sixty to one-hundred-year supply (Ganos, 2012). If the supply could have the potential to last for nearly a century, why is it not worth moving to then? One of the main issues with moving to this technology is that the necessary infrastructure would need to be installed to create a network for supplying the natural gas, and the time estimated to create this network is ten years (Ganos, 2012). It would also take quite a bit of time to build the infrastructure needed for hydrogen fuel cells, specifically hydrogen fueling stations. But why waste a decade creating a network of pipelines when natural gas still pollutes our air and will eventually run out? If the country is going to take the time to create an entirely new framework for supplying a new form of fuel, then it may as well build the framework that supports a fuel such as hydrogen, which produces only heat and potable water as byproducts. Another major downside to natural gas is the fracking that is required to obtain the fuel. Fracking, without a doubt, takes a huge toll on our environment too. One prime example of this is the rash of earthquakes occurring in Oklahoma. Oklahoma had only three earthquakes from 1990 to 2008, but once the state added more and more fracking sites the earthquakes increased. There were

109 earthquakes in 2013, and in June 2014 that number rose to 238. There was an earthquake brought on by drilling that had severely damaged fourteen houses in Oklahoma City while wounding two people as well (Gibson, 2014). One last major problem regarding fracking is the fact that it leads to water contamination. There has been an alarming amount of surface spills, that involved two explosions at wells managed by EOG Resources and Chesapeake Energy, along with an 8,000-gallon spill of fracking fluid at a location in Dimock, Pennsylvania, which tainted the groundwater in the Marcellus Shale area (McGraw, 2016).

Another alternative form of energy is wind power. One of the main drawbacks to using wind energy is that it is simply not feasible to use wind turbines in some areas of the United States. Wind turbines will be rendered useless in some regions where the wind doesn't blow on a regular basis, and are only appropriate for coastal areas where there is a constant influx of wind to produce electricity ("Disadvantages of Wind Power", 2017). The use of wind power can also be a hazard to the wildlife nearby, especially birds as they can be killed when trying to pass through a turbine. Any animals living underground are also affected as wind turbines are required to be dug deep under the ground, inevitably disrupting habitats beneath the ground ("Disadvantages of Wind Power", 2017). Areas with frequent natural disasters, such as cyclones, tornadoes, and hurricanes will also prevent the use of wind turbines. The costly turbines can be severely damaged, taking more time and money to repair, as well as putting the lives of the employees that work on the wind farms at risk.

One last form of energy worth noting is solar energy. While harnessing power from the sun is a fantastic and innovative idea, it is not the most efficient method when attempting to supply enough energy to an entire nation. Like wind turbines, solar panels will only be effective in certain geographic areas that receive plenty of sunlight. In areas where there are many clouds

or the skies are always overcast the efficiency of the solar panels can be reduced. The National Renewable Energy Laboratory estimates the sunlight gathered under low-cloud or foggy circumstances is only ten percent of what is normally acquired on a day with clear skies (Gromicko, 2017). It is also obvious that solar panels are of no use during the night, unless a homeowner has purchased a large quantity of batteries to store the electricity gathered from the sun during the day.

Additionally, solar panels are not very efficient. An immense solar array is needed to power a building, and a large automated structure is usually necessary to allow the panels to turn, following the sun as it moves throughout the day (Gromicko, 2017). The technology is slowly improving to harness more energy from the sun though. Engineers at Massachusetts Institute of Technology (MIT) have come up with an instrument that increases the efficiency in solar panels by taking advantage of specific wavelengths of light that were once unable to be collected by solar panels. The instrument involves a high-temperature material that includes a two-layer absorber-emitter mechanism, which is then installed on the photovoltaic cells. This device absorbs the light and converts it into heat, where the heat is then transferred to the layer with silicon dioxide photonic crystals whereupon the emitter turns the heat into light than can be captured by the photovoltaic cells to generate electricity. Right now, the testing is in its early stages and has only reached an efficiency of 3.2 percent, but with more trials they hope to reach twenty percent efficiency (Giges, 2014). Solar panels can also be severely damaged by the sun overtime as well as from other acts of nature such as dirt, rain, snow, wind, and hail. This means that the panels will inevitably need to be replaced overtime as they slowly lose their efficiency to capture enough sunlight to convert into electricity. This is unlike hydrogen fuel cells where they do not lose much of their effectiveness overtime, because of how the electrodes operate as

catalysts in the reception or discharge of electrons and are not altered chemically during the procedure ("What Is a Hydrogen Fuel Cell?", 2016).

Even though it may seem as if solar panels are not affiliated with any pollutants, they are involved in quite a few ways of creating pollution. A necessary component of solar panels is cadmium, which is a carcinogen. Although this toxin is sealed within the panels, it can eventually leak as the panel ages which can cause serious harm to the environment. This also means that solar panels cannot simply be thrown away, they must be responsibly discarded so that carcinogens do not seep into the ground or water (Gromicko, 2017). To hold a charge, solar panels also need batteries as described earlier, but the ones necessary for solar panels are usually deep-cycle, lead-acid batteries. These batteries are comprised of sulfuric acid and lead, which are extremely toxic, especially with regards to aquatic life (Gromicko, 2017). After considering the main disadvantages to these sources of energy it is evident that hydrogen fuel cells should be America's future source of energy as the emissions are harmless, and the technology can be used in a variety of environments.

V. Current State of American Dependence on Foreign Oil

It can be argued that America will not reach its growth potential unless it can separate itself from its heavy dependence on oil. In a report from 2009, it was discovered that the United States is spending nearly one billion dollars every day on foreign oil, rather than putting the funds back into our economy (Lefton & Weiss, 2010). Even in 2008, America used twenty-three percent of the world's crude oil, where fifty-seven percent of it was imported. A more recent study has shown that oil imports have steadily decreased over the years though, where the United States is now producing more oil domestically than it is importing. In fact, the country produces around sixty percent of its own oil now, meaning that imports are now around thirty percent

(Santiago, 2015). However, the U.S. Energy Information Administration mentions that oil will still be our primary source of energy through 2040, even as the country's use of it steadily decreases (Patton, 2016). The United States should not wait another twenty-three years to pick a clean energy source.

It is also alarming how we import this oil from unstable countries which threaten our safety, such as Syria, Pakistan, Saudi Arabia, and Iraq. The figures below help portray how we are essentially strengthening the economies of dangerous nations while at the same time weakening ours. We are not taking the time to rebuild our infrastructure to become a more energy independent nation, which in turn would help create jobs along the way. The United States could fund projects such as hydrogen fuel cell stations for cars, hydrogen fuel cell vehicles, and hydrogen fuel cell homes, which can be powered without having to be connected to an electrical grid, which acquires its power from resources that create pollution.

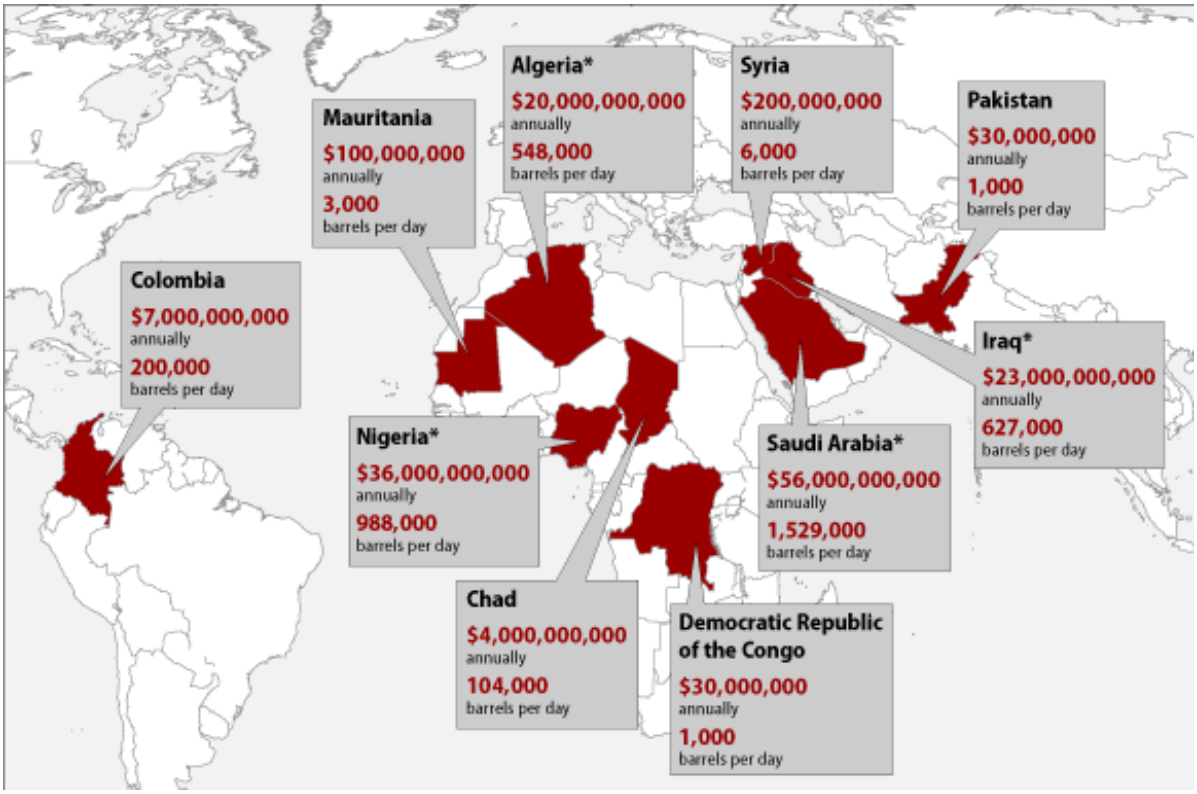

Figure 3. Map of which countries the U.S. receives oil from. The illustration also displays how much money each country receives annually, as well as the barrels per day which we import from each country. Adapted from Center for American Progress, by R. Lefton and D. J. Weiss, 2010, Retrieved January 31, 2017 from https://www.americanprogress.org/issues/green/reports/2010/01/13/7200/oil-dependence-is-a-dangerous-habit/. Copyright 2017 by Center for American Progress. Adapted with permission.

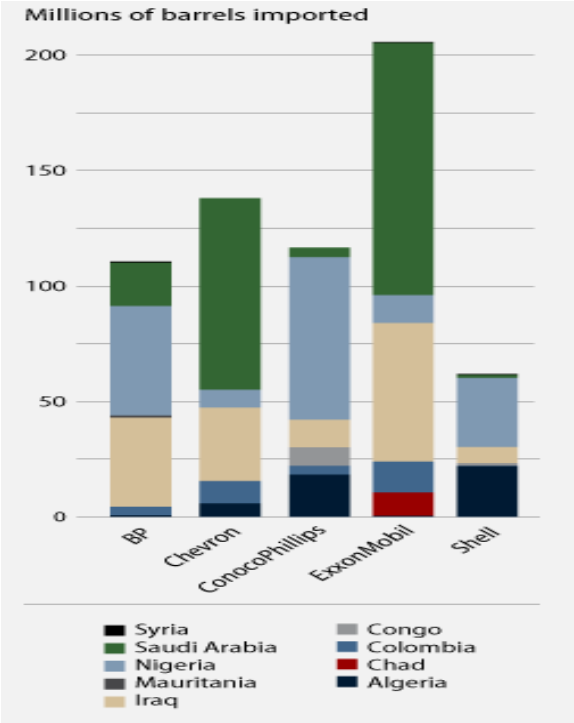

Figure 4. Chart displaying five of the largest corporations importing oil from unstable countries. Each country is color coded so that you can see the number of barrels by the millions that each company receives from them. Adapted from Center for American Progress, by R. Lefton and D. J. Weiss, 2010, Retrieved January 31, 2017 from https://www.americanprogress.org/issues/green/reports/2010/01/13/7200/oil-dependence-is-a-dangerous-habit/. Copyright 2017 by Center for American Progress. Adapted with permission.

America also has a moral obligation to avoid using foreign oil. It is helping to keep money in the pockets of these countries, where they seldom reinvest their profits in promoting and developing other forms of industry, which can lead to job creation and economic prosperity. This is also in part because many of these countries have corrupt political systems that attempt to seize nearly all the revenues gained from oil production (Stiglitz, 2012). There was also evidence where the State Department notes that in places like Nigeria, violence associated with petroleum is a serious issue. There were over fifty-four national oil workers who were abducted at oil sites since January 2008. (Lefton & Weiss, 2010). There were also attacks on the U.S.

army in places such as Iraq. This type of violence and terror, is what causes instability or uncertainty in the markets, which is why if the United States were to push for the use of hydrogen fuel cells, this type of violence may decrease as the funds going to these countries will steadily decline, thus eventually taking away their ability to cause chaos around the world.

It is also wise for America to stop the use of traditional fossil fuels to avoid competition from countries such as Saudi Arabia. Saudi Arabia in particular makes it rather difficult for America to compete as they intentionally create lower prices to gain a larger share of the market (Buchele, 2014). It is imperative that we leave fossil fuels behind as our production is much costlier than other countries such as Saudi Arabia, because it is costlier and more time consuming to acquire. This also makes it extremely difficult to keep prices low (Taft, 2016). It is also increasingly more important for these countries to maintain the type of market share that they are used to as it has become increasingly difficult in an economy where demand for oil is on the decline (Buchele, 2014). In the end, it is best to produce our own substitutes for foreign oil such as hydrogen, allowing us to diminish our use and imports of the fossil fuel (Taft, 2016).

VI. How the Economic Landscape Will Change

It is also essential to evaluate how America can gain energy independence, while recognizing how other nations may be able to strengthen their economies as they supply some of the resources and components necessary to construct a hydrogen fuel cell. If the United States moved to hydrogen fuel cells as a main energy source, we would drastically decrease our dependence on foreign oil. It is important to note however, that the country would be increasing its dependence in rare-earth elements unless action is taken. One of the main rare-earth elements that a hydrogen fuel cell requires is platinum, which as previously described, is the catalyst that breaks down the atoms of hydrogen into electrons and protons (“What Is a Hydrogen Fuel

Cell?", 2016). We already require the use of rare-earth elements for devices like phones, which are continually produced in larger quantities year after year, and with vehicles requiring the use of a rare-earth element we will need to further increase our reliance on countries such as China, Russia, South Africa, and Canada (Lifton, 2014). If the United States invested in its infrastructure to create a zero-emission source of fuel, then its citizens would no longer have to rely on the electrical grid and have cleaner air.

At the same time, however, we would be giving more money to countries, and some of them do not have the best relations with the U.S. Then, as an unintended consequence, we would be strengthening their economies. If nothing is done about this issue, we will become more dependent on them for the supply of the rare-earth elements which we so desperately desire and where they can basically set the prices if there is no other competition. China has even been guilty in the past for manipulating the international supply chain, creating a considerable strategic issue (Adams, 2015). China has cornered the market by overproducing rare-earth elements through illegal mines, which has in turn allowed them to set the price to keep any other company or country from attempting to enter the market (Adams, 2015). Platinum can also be costly, which is why many engineers have been working on a way to create a cheaper catalyst, which is what scientists at Yale accomplished. They incorporated a catalyst for an alkaline fuel cell which did not contain any platinum by using palladium, a cheaper alternative, and fused it with silver (Gershon, 2013). While this creates a cheaper substitute, it does not completely solve the problem of needing to develop a catalyst that does not use any rare-earth elements.

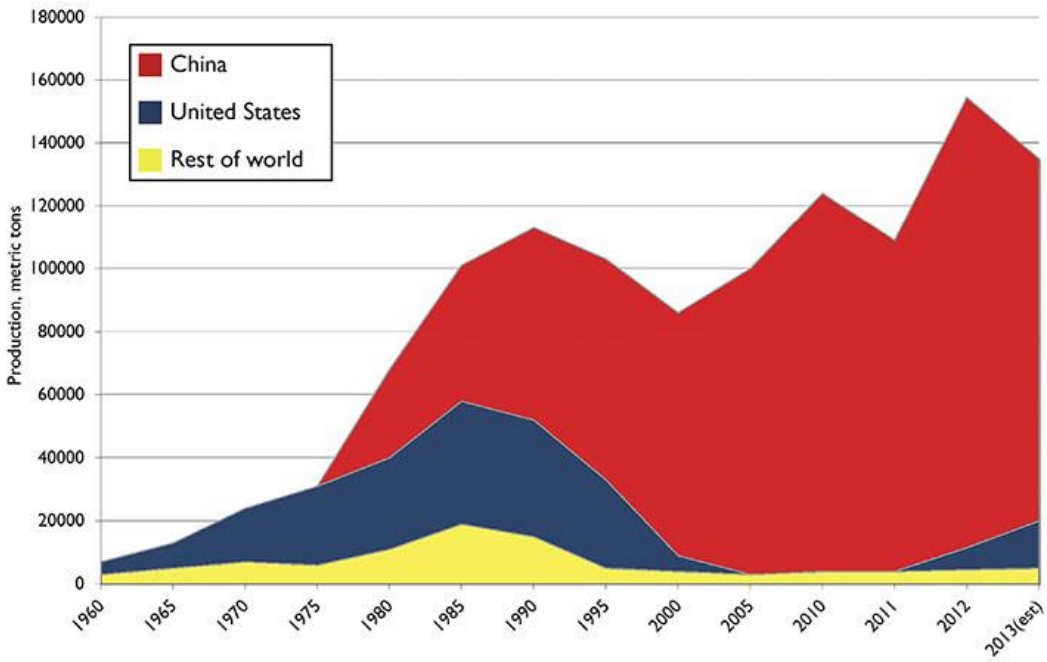

Figure 5. The chart above displays the production of rare-earth elements. The production is measured in metric tons. It is clear how China has captured over ninety percent of the market by keeping its prices lower than other competitors. Adapted from Center for Latin American Studies, by J. Klinger, 2013, Retrieved February 3, 2017 from http://clas.berkeley.edu/research/environment-rare-earths-lessons-latin-america. Copyright 2015 by The Regents of the University of California. Adapted with permission.

The only way to thwart this dependence on other countries for the rare-earth elements that we require is to start mining more of our own rare earth elements once again. America does have a rare earth mine located in California, known as the Molycorp Mountain Pass rare earth facility, which is in the Mojave Desert in California (Wiens, Chen, Snyder, & Fantl, 2012). It is interesting to note that in recent history, most of the rare-earths produced were mined at the Mountain Pass location (Wiens et al., 2012). Unfortunately, in 1998, there was a radioactive wastewater disaster at the mine, which ended up flooding the Ivanpah Dry Lake situated close to the Mountain Pass mine and inevitably slowed production. This also was around the time that China became a fierce competitor when it started to exponentially increase its mining of rare earth metals (Wiens et al., 2012). Eventually the competition from China became too fierce as their prices for the product were much lower than that of Molycorp, and they began mining over

ninety percent of the globe's rare-earth elements at the start of the twenty-first century. Eventually, Molycorp could no longer compete and had to shut down the facility in 2002 (Campbell-Dollaghan, 2015).

Despite the rough past that the Mountain Pass mine has dealt with in previous decades, it is finally beginning to see a resurgence thanks to more environmentally friendly technologies. This is fantastic news, because if the United States truly wants to rise as a leader in clean energy, it will also need to produce the resources necessary for products such as fuel cells in a clean and efficient manner with appropriate working conditions for employees. This is also an improvement from having to rely on countries such as Russia or China where their production of rare-earth elements is a filthy process leading to excessive amounts of pollution that will take years to clean. This would certainly be frowned upon in America because of our environmental policies. Molycorp became quite serious about producing rare earth elements again, and in July of 2010 the company decided to go public with an IPO of $394 million. Then in December of 2010, they acquired the necessary permits to begin constructing a manufacturing and mining complex to once again mine rare-earths (Wiens et al., 2012). Molycorp was also able to present good news to the public in 2011 when they uncovered another rare-earth deposit close to the existing rare earth mine, and were soon allowed to commence drilling.

It is also reassuring to learn that the government is for the reopening of the mine as they too realize that rare-earth elements are essential to produce the components necessary for clean energy, and that Molycorp can potentially be the strongest competitor against China, which controls much of the world's supply of rare-earths (Wiens et al., 2012). Unlike the polluted mines in other countries such as China, Molycorp has taken their time to position the Mountain Pass mine as one of the most environmentally friendly mines as they have obtained much of the

necessary and strict environmental permits. Molycorp has in fact invested billions of dollars to renovate the Mountain Pass facility, specifically in making sure all the mines were safe along with the replacement of the extraction systems. Once complete, Molycorp could begin mining for rare-earths. (Campbell-Dollaghan, 2015). The company is now beginning to use a procedure known as chloralkali which uses recycled water to isolate the ore, which had previously been done with harmful chemicals. There is still a fair amount of toxic waste after rare-earth metals have been mined though. Molycorp, however, is addressing this issue better than it has in previous decades. In the past they had continually dumped the waste into a pile of sludge located behind a damn, but now a high-pressure system will be used extract much of the water, leaving only a paste behind placed into ninety-acre landfill (Campbell-Dollaghan, 2015).

Molycorp had also taken other steps to ensure its place in the rare-earth marketplace. The company finally reopened in 2012, and decided to expand after discovering another mine, and even planned to employ an additional twenty-five people each quarter until it reached its goal of hiring two hundred employees (Wiens et al., 2012). It seemed as if the United States could finally compete with other countries, such as China, which controls over ninety percent of the global supply (Adams, 2015). Unfortunately, in August of 2015, the corporation stated that it would halt production indefinitely and even earlier in June Molycorp filed for chapter 11 bankruptcy (Jamasmie, 2015). One of the biggest factors which lead to the fall of Molycorp started in 2010 when China had cutoff exports of rare-earth elements to Japan over a fishing quarrel close to islands that were under the control of both countries. In 2012, Molycorp thought it would be advantageous to reopen the mine in California to once again become a major competitor as they could finally sell rare-earth metals at a lower price since they were beginning to increase all over the world because China had decided to stop production to Japan. This

became very troubling to everyone who knew that if they were to enter a conflict with China, they would be able to do the same once again. It was not very long before China realized what the United States was up to so they began to produce rare-earths again, where prices dropped by ninety percent (Adams, 2015).

China also resembles a monopoly, where they control the production and pricing of rare-earths. This undoubtedly creates inefficiencies such as steep prices, or the ability to set prices at any desired level, with a limited supply. China even had the ability to cut off any country from their supply such as Japan, which caused prices for rare-earths to soar. Then they immediately dropped prices to keep the United States out of the market, which creates another inefficiency, stopping competitors from entering the market. This would have allowed for healthy competition, creating better prices for the consumer. The last inefficiency created from a monopoly is an excess of supply. Monopolists do not need to worry about producing at a minimum average cost, and almost always operate on an enormous scale, allowing them to produce an extensive amount of their product, far from an optimum level (Marjankhan, 2014). Monopolies also create deadweight loss, which comes at an expense to society because of market inefficiencies. The deadweight loss can be created from demand and supply not being in equilibrium, or when the price is too high from lack of competition. This causes consumers to either not buy the product, or if it is a necessary product, the buyer may have to go without buying other types of goods in a different market (Cooper & John, 2017).

As previously discussed, the United States must be able to cut itself off completely when having to rely on others for its energy, not just for foreign oil but for producing hydrogen fuel cells as well. When moving to hydrogen fuel cells, the United States no longer needs to rely on foreign oil from dangerous countries in the middle east, but it cannot simply transfer its

dependence from one country to another. History has shown us that when one country controls over ninety percent of the world's supply for rare-earth metals, they can corner the market and set prices to drive out other competitors. This already adds to the fact that mining for rare-earth metals is a costly endeavor despite rare earth metals not being that rare. The only reason why the cost of production is so high is because they are scattered in small numbers throughout the earth's crust, and are also known to be found within mineral deposits such as monazite and bastnaesite (Wiens et al., 2012). What if another country can overtake China and control most of the supply in the rare-earth metal market, such as Russia, with whom the United States has not had a stable relationship with over the years? It is not too late for the United States to arise as a leader in supplying rare-earth metals if it is to push for clean energy with the use of hydrogen fuel cells. Even though there is only one rare-earth mine in the United States, the country still has thirteen percent of the world's rare-earth reserves. Abundant reserves can be found in Alaska, California, Montana, Idaho, Missouri, and Montana (Adams, 2015).

VII. **Game Theory**

After discussing the importance for the United States to become a more independent nation in regards to securing more of its own resources for hydrogen fuel cell products, it is also critical to evaluate how the United States and China will react to one another as they both attempt to gain market share by using game theory. Game theory was originally created in 1944 by Oskar Morgenstern and John von Neumann (C. Chang, 2007). It is used to evaluate critical thinking and strategic decisions made based on players' predictions of the actions that their opponents will take as well as finding the best choice that will maximize their own benefits. This method for analyzing rational decisions has been used extensively in many different subjects such as politics, psychology, economics, and sociology (Myerson, 1997).

Perhaps the best example and explanation of how game theory is applied is through the prisoner's dilemma. It begins where there are two criminals who are being questioned for murder, and are also guilty of having illegal weapons. They each have the option to confess or not confess as displayed in the figure below.

		Player 2	
		Confess	*Stay silent*
Player 1	*Confess*	Life, Life	Free, Death
	Stay silent	Death, Free	1 year, 1 year

Figure 6. The matrix above clearly displays the options each player has along with their respective payoffs. Adapted from *Game Theory at Work* (p. 117), by J. Miller, 2003, New York City, NY: McGraw-Hill. Copyright 2003 by McGraw-Hill. Adapted with permission.

Each player is questioned in a separate room, so they do not know the actions of the other player; they can only try to predict what the other person will choose. If only one player chooses to confess, then he will be able to walk away free while the other criminal faces the death penalty. If both stay silent they each only receive a year in prison while both face life in prison if they both confess. After analyzing the options, it is in the best interest for each player to confess. If player 1 believes that player 2 will confess, then he will be forced to confess as well or else face the death penalty, and vice versa. If player 1 believes that player 2 will not confess, and even if player 2 somehow promised player 1 that he would not confess, it still benefits player 1 to confess as he will walk away with no jail time (Miller, 2003).

There is also another factor to note in this problem, and that is the Nash equilibrium. John Nash created the concept, and it is defined as the position each player is currently in where they can no longer benefit from a change in their strategy where it is understood that no other participant changes their position (K. Chang, 2015).

As previously stated, game theory has been used in a variety of different subjects such as economics, which is where it will be applied in this thesis, specifically in setting up the game between the United States and China. It has already been established earlier in the paper that China currently controls over ninety percent of the market when it comes to selling rare-earth metals (Yan, 2015). Moreover, the United States has been in a trade deficit with China since 1984 (Ghoneim & Reda, 2008). Our country has even ceased its own production on rare-earth metals, forcing us to rely on the largest producer of rare-earths in the world, giving the United States zero percent market share in relation to rare-earths.

The United States does have choices when it comes to the rare-earth market though. The United States could respond or simply not respond and continue with the status quo. If the United States were to respond, their best chances at increasing market share would be to propose tariffs on rare-earth imports coming from China while offering subsidies for companies willing to engineer their products so that they do not require rare-earth elements, decreasing dependence on rare-earths overall. There has even been a recent proposal by the president to put a forty-five percent tariff on imports coming in from China (Tan, 2016). Putting in place subsidies for companies would also help the U.S. gain independence from China, in fact some companies have already begun to design their products so that they are absent of rare earth elements. One company is Honda, which had responded to the increased prices of rare-earths from China by engineering an electric engine which no longer required two rare-earth elements that they had

previously used (Home, 2016). Tesla, has manufactured batteries for its vehicles that do not need rare-earth metals either, although the production of the cars is still demanding in terms of energy consumption overall and has room for improvement (Oremus, 2013). The United States could also help increase the development of rare-earth mines by offering subsidizes to the companies that own them. This would help create more competition, especially since China had subsidized their mines in 2012 when they lost market share after their prices for rare-earths increased (Els, 2012). Even though subsidies can help make the United States a competitor in the rare-earth market, they can create inefficiencies and deadweight loss if used unnecessarily in the long run. It is more expensive for a government to issue subsidies than the benefits generated from the subsidy for the supplier. It also comes at the expense of the taxpayers to provide the funds necessary for subsidies, and if subsidies are used for long periods they may keep businesses from finding more efficient methods to produce their goods. Subsidies for suppliers may also result in a surplus of supply, as the product is much cheaper to produce (Beggs, 2013). Nonetheless, by not responding to China's growing market share for rare-earths, the United States keeps with the status quo, keeping the country's production levels at zero.

After the United States has chosen to respond or not respond, China will be compelled to come to a decision with how to increase their payoff with relation to the decision made by the United States. If the United States decided not to act at all despite falling far behind in market share, China could choose to simply not respond and hold a clear majority of the market for rare-earth production, or they could choose to drive out more competitors, in this case the U.S. If China were to choose to drive out competitors, their primary option should be to undercut the prices of all other rare-earth companies, which is how they effectively ran Molycorp out of business after they decided to reopen in 2012 (Heffernan, 2015). After offering cheap prices to

keep out the competition, it would be in the best interest of the country to institute tariffs on the exports of its rare-earth metals so that the government can acquire more funds. The potential tariff should be between fifteen to twenty-five percent, which is what they have done in the past (Ferris, 2015). The only change in China's previous strategy would be to not abuse their power and institute their tariffs for very long, as that was what had allowed the United States to enter the market once again in 2012.

The U.S. and China each have distinct options when choosing how to respond to one another, but their decisions do not become clear unless they can see how much market share they gain or lose based on their chosen strategy, as well as the one made by the opposing country. Currently, China has ninety-five percent of the market when it comes to the supply of rare-earths (Leotaud, 2016). If the United States chose to not respond to China's overwhelmingly large market share, and China chose to do nothing as well, then the payoffs for each country would neither decrease nor increase, China would stay at ninety-five percent, while the United States would remain at zero percent. However, if the response for China changed to driving out competitors, while the U.S.'s decision remained the same then China would most likely be able to increase its market share to ninety-seven percent, which was what the country had originally before the United States interfered after the price increase (Strauss, 2014).

Now if the U.S. changed its decision to respond while China chose to drive out competitors at the same time, then the U.S. would have the chance to increase its market share to 4.7 percent, while decreasing China's market share to eighty-six percent. Each country's market share would most likely reflect these numbers as this was where both countries stood in 2012 as China was attempting to drive higher prices while the U.S. was trying to undercut those prices at the same time (Scouras, 2013). It would also highly benefit the U.S. to respond to China's high

market share if they had decided to implement no new strategy. This would allow for the greatest improvement in market share for the U.S. where it could increase to twenty-five percent, while decreasing China's share of the market to 68.75 percent. These statistics reflect those in 1995 when the United States still had a decent percentage of the market while China was only beginning to increase production while considerably decreasing its prices when compared to other countries (Nusca, 2010).

		China	
		Drive out competitors	Do not respond
United States	Respond	4.7%, 86%	25%, 68.75%
	Do not respond	0%, 97%	0%, 95%

Figure 7. Payoff Matrix displaying each option the U.S. and China has at hand.

After reviewing the different actions which each country can take, and the market share which results in each decision made, it is important to find the best strategy for each country to always choose. This relates back to the Nash equilibrium, where no participant benefits from changing their strategy, while the strategies of all other participants remain constant. When looking at the options that the United States has at hand, they can choose to either not respond to China's growing market share, or they can choose to act to gain a portion of the market. After viewing the payoff matrix, it is not in the best interest of the United States to not respond. If the United States chose to not respond while China did not respond, the U.S. does not gain any market share, while China keeps its ninety-five percent of the market. When China chooses to drive out more competitors while the U.S. still does not respond, China gains two percent of the

market while the U.S. still stays at zero percent. If the U.S. chooses to respond, while China does not respond, then the U.S. gains twenty-five percent of the market, and even if China attempts to drive out its competitors, the U.S. still gains 4.7 percent of the market. This means that the United States should always choose to respond, which is a dominant strategy.

China's best strategy is to always choose to drive out more competitors. If the United States were to respond to China's large market share while China did nothing, then they would lose a significant amount of the market. Even if the United States did not respond, then it would still be in China's best interest to attempt to drive out more competitors as they would gain more market share than if they didn't respond. This means that there is a Nash equilibrium when the United States chooses to respond and China chooses to drive out competitors.

VIII. **Conclusion**

This paper has argued that hydrogen fuel cells are America's future for clean energy. Continuing to rely on fossil fuels will inevitably harm the environment. Our reliance on foreign nations for the supply is problematic as well, since we do not have peaceful relationships with some of them. Countries such as Saudi Arabia can lower prices beyond reason so that other nations like the U.S. cannot compete. They can also set the prices if there is not much competition such as Saudi Arabia has done. They even can lower their prices beyond reason so that countries like the U.S. cannot compete. It would also be irresponsible to move to another source of fuel which still emits greenhouse gases such as natural gas, which is even more harmful to the environment to produce than to use. It would not be worth our time to build a framework to support a fuel which has led to more earthquakes as well as groundwater contamination. Once the U.S. is finally able to make the switch to hydrogen fuel cells, it will be important that they do not simply switch their reliance from one resource to another to supply the

clean energy. Fuel cells require rare-earth elements, and currently China has control of this market as they can cutoff or limit the supply of certain countries such as Japan over a conflict. This in turn worried countries across the globe, causing prices to skyrocket, but then they immediately reduced prices on their supply to drive out new competitors like the United States. The U.S. does have significant rare-earth metal deposits, allowing the country to rely less on countries like China.

After analyzing each country's decisions through game theory, the U.S. should attempt to mine its own rare-earths while putting restrictions on the imports of rare-earths from China. It is also critical that our country realizes the importance of being able to supply its own resources, especially when moving to a new source of clean energy which we may use for centuries. If America quietly sits back, and lets other countries produce the resources essential to our way of life then we will not be able sustain our position as a global leader, and other nations will be allowed to manipulate the markets as they gain most of the control just as many have done in the past. Nevertheless, it will truly be interesting to see where the new technology can take us, and what nations will arise as new leaders in the future as some will inevitably gain a competitive advantage regarding the supply of the necessary resources.

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