Fuel Cells for Stationary Power Generation

A Comprehensive Analysis of Technology, Plant Construction, and Marketing Strategy for Small Buildings

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EXECUTIVE SUMMARY

The University of Oklahoma Fuel Cell Corporation (The OUFCC) proposes to build a fuel cell manufacturing plant in Wyoming to produce three types of 200-250kW stationary fuel cell units. The three types of fuel cells produced will be solid oxide fuel cells (SOFCs), phosphoric acid fuel cells (PAFCs), and proton exchange membrane fuel cells (PEMFCs). The target market is small commercial and government buildings such as hospitals, banks, police stations, and post offices. The fuel cells will serve as a constant supplementary power system or as an occasional emergency supply of electricity.

For the first year of manufacturing, it is predicted that approximately 74 PEMFCs, 42 SOFCs, and 60 PAFCs will be sold. The increase in fuel cell demand throughout the project lifetime (ten years) will be due to the acceptance of a new technology, an aggressive advertising campaign, and The OUFCC's reputation as established by previous customers.

The net present worth of the project is approximately $83.2 million and the rate of return is 23%.

In order to reduce incidentals at the on-set of production, only a minimum number of employees will be hired, and The OUFCC will produce fewer fuel cells than predicted by market demand. In subsequent years, The OUFCC will work with a financial planner and/or accountant to adjust the selling price of the product and with various engineers to optimize the number of employees and the manufacturing process so that all operating costs may be kept at a minimum.

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I. DESCRIPTION OF THE BUSINESS

The University of Oklahoma Fuel Cell Corporation (The OUFCC) will be operated by seven entrepreneurs who hold Bachelor of Science degrees in Chemical Engineering from the University of Oklahoma, and various Masters Degrees from other universities. The OUFCC is legally structured as a corporation, and for the first year control will be exercised solely by the seven founders of the corporation. After the first year, 51% of the control will depend upon stock ownership. During this time, control will be exercised through regular board meetings, the board consisting of the seven founders and the chief executive officer, and an annual stockholders' meeting. Dr. Miguel Bagajewicz will be the chief executive officer.

a. Business Objectives

The OUFCC will fill the need for a source of electricity that is:

- **Clean** and produces few toxic emissions, depending on the type of fuel used. If pure hydrogen is used, the only products of a fuel cell are electricity, water and heat.
- **Reliable** and not susceptible to black-outs or power surges. This is especially important for areas where the energy supply does not meet the energy demand, such as New York and California.
- **Independent of a power grid** for use in rural areas or in emergency situations. This is a benefit for businesses that are located far from power plants where the cost of renovations to connect to an urban power grid would be excessive.
- **Optionally dependent on fossil fuel** which helps cut dependence on foreign oil. Fossil fuels are used more efficiently today than in the past, but this is offset by higher demand and increased population. Many people are looking for alternative energy resources. The OUFCC is able to supply these customers a fuel cell that will run on a variety of fuels, from fossil fuels such as natural gas to pure hydrogen that may be extracted from renewable energy resources such as sunlight, water, or biomass.

The business will serve to supply the continental United States with proton exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), and phosphoric acid fuel cells (PAFCs) that each supply approximately 200-250kW of power for use in commercial and government businesses (including, but not limited to, hospitals, banks, police stations, and post offices). The stationary fuel cells will serve as a constant supplementary power system or as an occasional emergency supply of electricity.

b. Customer Benefits

The customer that buys a fuel cell from The OUFCC will benefit in the following ways:

- **Tax credits and incentives** provided at a federal and state level.[1] The main agencies that grant these credits and incentives are the Database of State Incentives for Renewable Energy (DSIRE) and the Department of Energy (DOE). One such incentive is the DSIRE's Renewable Energy Systems and Energy Efficiency Improvements Program. Businesses that want to purchase a fuel cell can apply for a grant from $10,000 to $500,000.[2] Since our plant is located in Wyoming, DSIRE's Renewable Energy Sales Tax Exemption applies.[3] This means that there will be no sales tax for fuel cells sold from the Wyoming plant. Also, if the customer decides to sell electricity back to the power grid, DSIRE's Renewable Energy Production Incentive (REPI) applies. In addition to what the business makes for selling the electricity, the REPI promises them 1.5 cents per kWh.[4]
- **Higher Efficiency** of the fuel cell will reduce utility costs. Fuel cells operate at approximately 60% efficiency, and may operate at up to 85% efficiency with the implementation of cogeneration. Mainstream power generation methods, for example combustion turbines, operate at only 20-45% efficiency.[5]
- **Quiet Operation.** This is especially beneficial to businesses such as banks that require communication with the customer. Utilizing a back-up fuel cell rather than a generator would provide quiet operation that would not disrupt business in the building. In the event that a generator is used for back-up power generation, this could be noisy and possibly cause the business to lose customers.
- **Cogeneration** that will produce both electricity and thermal energy and therefore lower utility costs. This thermal energy may be used for any purpose from heating the building to providing hot water.
- **Fewer maintenance costs** when compared to mainstream power generation methods. Fuel cells have no moving parts, and therefore rarely require maintenance. The only scheduled maintenance is the replacement of the catalyst, which usually occurs 6 to 10 years after implementation of the fuel cell. Usually at this time, the fuel cell unit is replaced.

Also, the consumer may be assured that a fuel cell purchased from The OUFCC will be a quality product manufactured by qualified chemical engineers and supplied at a reasonable cost. By manufacturing three specific, yet widely-utilized, types of fuel cells, The OUFCC limits the operating costs while assuring that the consumer is buying the product that best fits the individual business's needs.

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[1] Website Source: http://www.eere.energy.gov/consumerinfo/refbriefs/la7.html

[2] Website Source: http://www.dsireusa.org/library/includes/incentive2.cfm?Incentive_Code=US05F&State=Federal&currentpageid=1

[3] Website Source: http://www.dsireusa.org/library/includes/incentive2.cfm?Incentive_Code=WY04F&state=WY&CurrentPageID=1

[4] Website Source: http://www.dsireusa.org/library/includes/incentive2.cfm?Incentive_Code=US33F&State=Federal&currentpageid=1

[5] Website Source: http://www.energy.ca.gov/distgen/equipment/equipment.html

c. Product Options and Incentives

The customer has the option of purchasing one of three types of fuel cells. The customer has a choice of the type of fuel to use: natural gas, pure hydrogen, alcohols (methanol or ethanol), or petroleum(gasoline), and the customer may choose a fuel cell that operates at a high temperature so that cogeneration is used. In order to help the customer with this decision, The OUFCC offers the following services with the purchase of at least one fuel cell:

- **On-site consultation** to determine the consumer's individual advantages of purchasing a fuel cell. The OUFCC will help the customer decide which type of fuel cell, if any, will best fit the needs of his/her business. The OUFCC will also help the customer choose a reformer for the fuel cell unit.
- **On-site consultation** to determine what, if any, additions and/or changes should be made to the existing electrical infrastructure in order to incorporate a fuel cell system (incorporating these changes is not the responsibility of The OUFCC).
- **Delivery** of the fuel cell system to the purchaser.
- **Trial-period of one year** beginning upon date of installation when the fuel cell may be returned to the manufacturer in the event of dissatisfaction of performance. All costs will be reimbursed to the purchaser, minus the costs of shipping.
- **Warranty period of two years** beginning upon the date of installation during which The OUFCC will perform on-site consultations in the effect that the fuel cell is not performing as promised.

d. Legal Documents

Patents[6]

The OUFCC will file a utility patent to cover our manufacturing process for fuel cells. It will last from the date of grant to 20 years from the date of the first patent application that The OUFCC filed. The OUFCC will apply for this using a Regular Patent Application. With a Regular Patent Application, claims are required and the filing fee is $370. The application will not expire; it will either become abandoned or mature into a patent. The cost for The OUFCC utility patent, including filing, issue and maintenance fees, will be approximately $5,000. When applying for a patent, the writing style is so specialized, and the process so complex, that The OUFCC will hire a patent attorney for approximately $5,000. The patent attorney will perform an initial consultation, a patent search, and all other services that might be involved in obtaining The OUFCC's patent. The total cost for The OUFCC utility patent to approximately $10,000.

e. Personnel

The OUFCC will consist of highly qualified team of employees who are experts in their respective area of the company. A Chief Executive Officer along with seven managers

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[6] \\garfield\group1\Group Websites\Patent and Trademark Attorney - California.htm

will lead the company of approximately 71 employees. Chief Executive Officer and Managers include:

Chief Executive Officer	
Dr. Miguel Bagajewicz	B.S. Chemical Engineering, Universidad Nacional del Litoral, Argentina M.S.Chemical Engineering, California Institute of Technology Ph.D.Chemical Engineering, California Institute of Technology
General Operations Manager	
Caroline Ihejiawu	B. S. Chemical Engineering, University of Oklahoma M. S. Operations Management, University of Texas
Sales Manager	
Jennifer Treece	B. S. Chemical Engineering, University of Oklahoma M. B. A., University of Arkansas
Marketing Manager	
Kristen Martinez	B. S. Chemical Engineering, University of Oklahoma M. B. A., University of Oklahoma
Computer and Information Systems Manager	
Justice Diven	B. S. Chemical Engineering, University of Oklahoma M. S. Management Information Systems, University of Kansas
Financial Manager	
Eric Daugherty	B. S. Chemical Engineering, University of Oklahoma M. S. Finance, University of Arizona
Transportation, Storage and Distribution Manager	
Lola Soyebo	B. S. Chemical Engineering, University of Oklahoma M. B. A., University of Ohio
Engineering Manager	
Thu Nguyen	B. S. Chemical Engineering, University of Oklahoma M. S. Engineering Management, University of Missouri

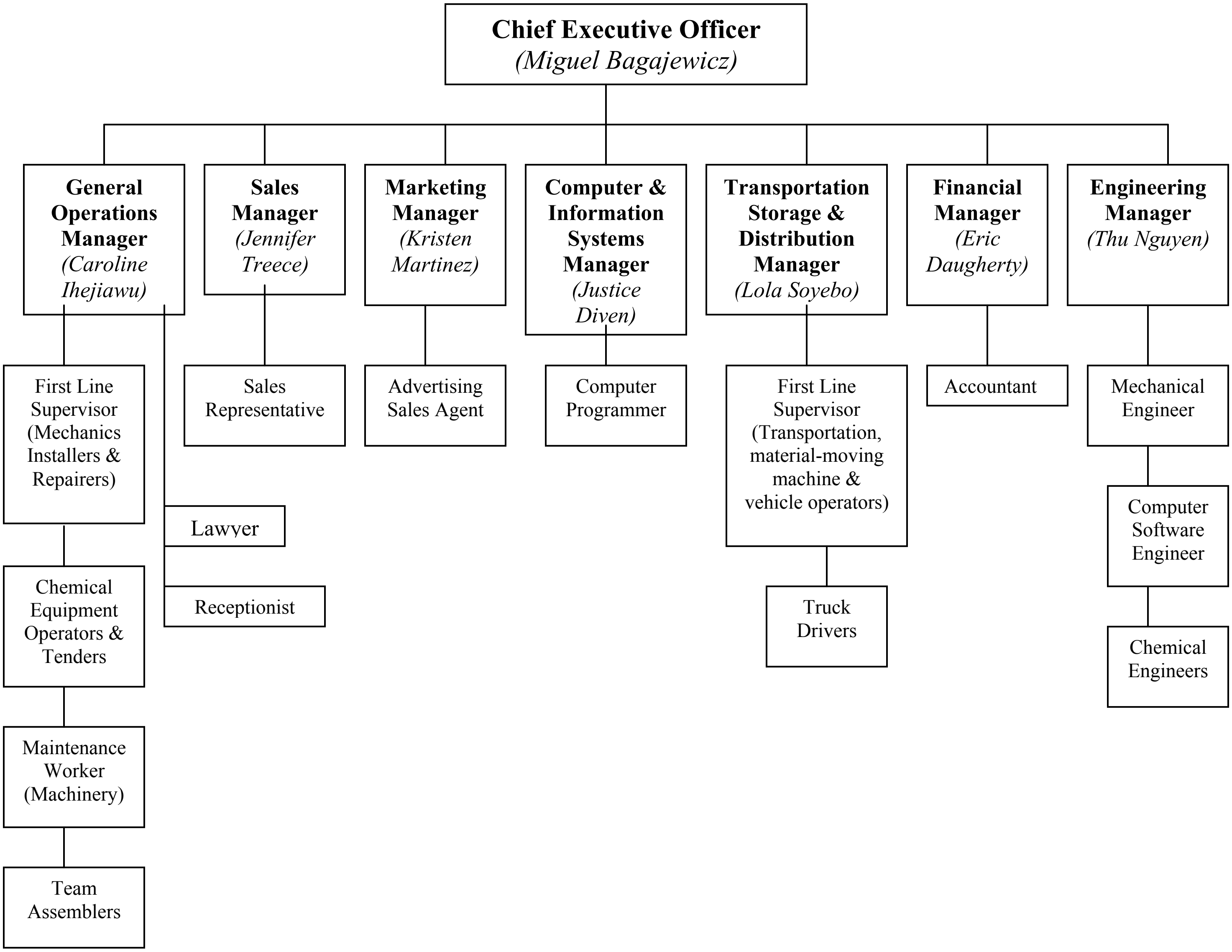

Figure 1: Organizational Chart

f. Business Insurance[7]

The OUFCC will purchase six different kinds of business insurance. These include:

- **Business Insurance** – will preserve the value of the business. Will cover such things as fire, flood, employee and natural disasters.
- **Business Liability Insurance** – will provide coverage in the event that The OUFCC or its employees are subjected to liability claims. It will also protect The OUFCC if a visitor or a visitor's property sustains damage while at the business. (i.e. slipping on a wet floor) It will also cover claims of copyright, trademark, or patent infringement; libel and slander; and invasion of privacy.

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[7] \\garfield\group1\Group Websites\Business Liability Insurance A Financial Safety Net.htm

- **Worker's Compensation** – will cover employees who are ill, injured, or die in the course of providing services to The OUFCC.
- **Group Health Insurance** – will cover all employees with a (minimum premium plan) in which The OUFCC will pay up to a certain specified maximum, and, after which point, the insurer pays. It will offer major medical coverage.
- **Business Property** – will provide coverage when any part of The OUFCC's property is lost, stolen, or damaged.
- **Commercial Truck Insurance** – will cover The OUFCC's fleet of trucks. It will include general liability, property damage, as well as full coverage on the trucks.

The annual combined premium for all of The OUFCC's insurance policies will be approximately $1 million.

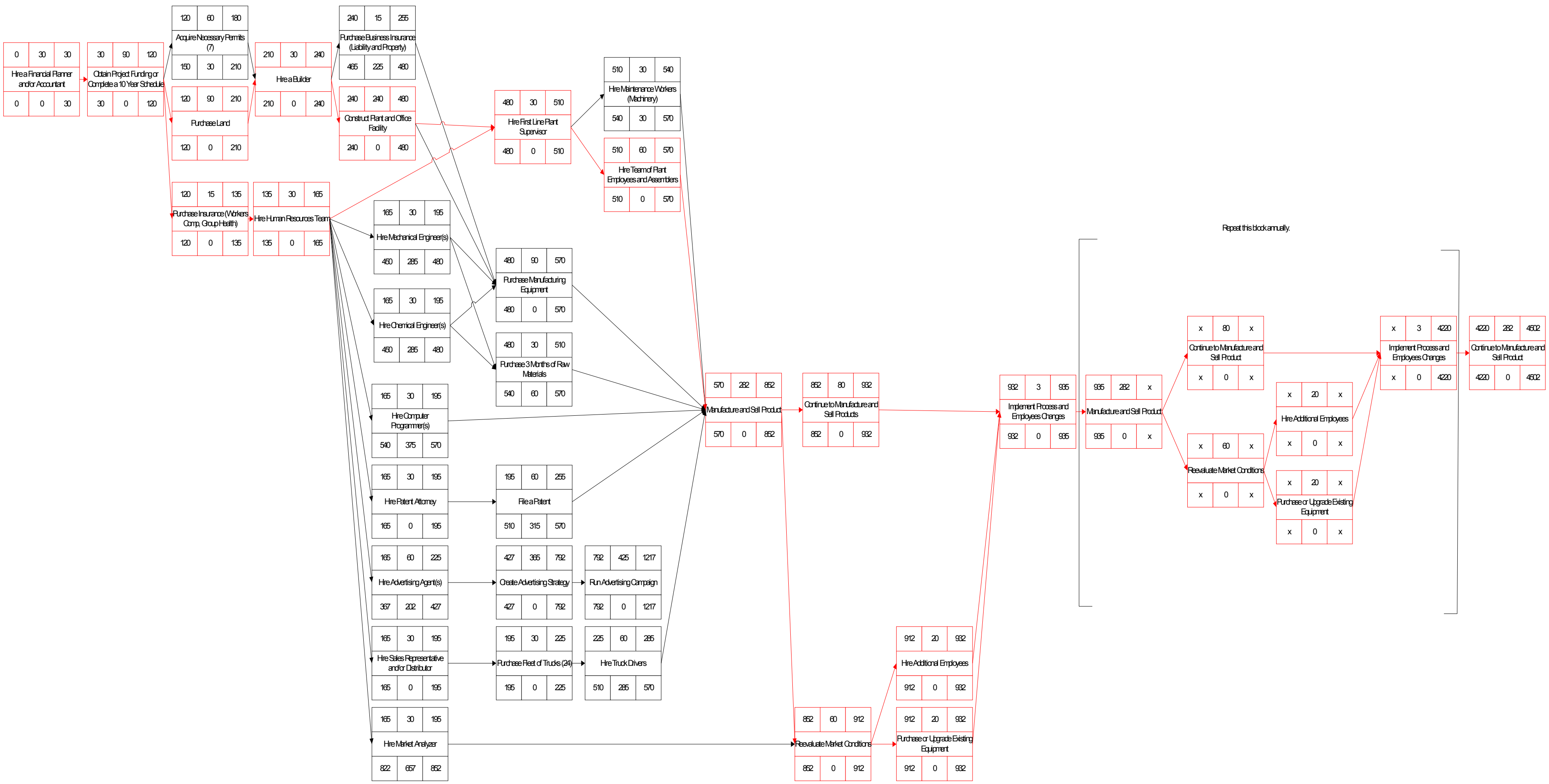
g. Business Timeline

The following chart outlines the approximate amount of time allotted for each task, as well as the order in which the tasks will be completed.

The following is the key for the business timeline:

<table>
<tr><td>Earliest Start</td><td>Duration</td><td>Earliest Finish</td></tr>
<tr><td colspan="3">Activity Description and Identifier</td></tr>
<tr><td>Latest Start</td><td>Float</td><td>Latest Finish</td></tr>
</table>

PERT diagram (Also available separately)



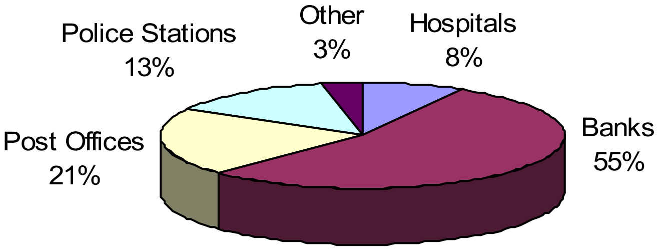
II. MARKET ANALYSIS

a. Description of Target Market

The market consists of small commercial businesses and government-funded institutions that would benefit from a constant supplementary power source or a source of back-up emergency power. Hospitals, for instance, are in great need of a reliable source of power in order to use life-saving equipment and have constant access to important records. Other businesses of similar size are expected to be a large consumer. These types of buildings are banks, post offices, or police stations. Banks rely upon important digital records, and also rely heavily on electrically-powered security systems. Therefore, banks are expected to be one of the largest consumers of fuel cells. Post offices and police stations rely on constant electricity generation, and also are state or federally funded and as a result are more likely eligible for government grants and loans.

The demand for fuel cells by state was tabulated.[8] All public listings for a specific type of business by state were tabulated, and Table B-1 in Appendix B was employed to analyze this demand.

From the data in Table B-1 in appendix B, we take the percentage of each business out of the total business and The OUFCC expects our market to be comprised of the following:



Total Number of Businesses: **150,116**

Figure 2: Market Analysis by Business Application

b. Market Location

The OUFCC identified the locations with the largest market demand. The more favorable locations were chosen based upon analysis of the number of chosen businesses, population, electricity consumption for commercial purposes, and electricity prices.

From the number of businesses located in each state (Appendix B Table B-1), the following figure was constructed to demonstrate the areas with the largest numbers of businesses likely to purchase fuel cells.

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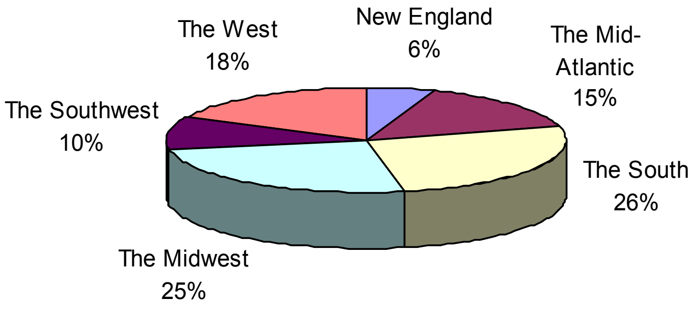
[8] Website Source: www.smartpages.com



Total Number of Businesses: **150,116**

Figure 3: Market Location by Business Application[9]

Population was studied because emission standards are the strictest in the most populous areas of the United States. The government would be more likely to promote fuel cell investments in the regions with the most pollution. If the average population is analyzed for each region, then the regions of the United States rank in the following order (data from Figure B-2 in Appendix B) as shown in Table 1. The region with the greatest average population is likely the one that will use the biggest number of fuel cells.

Region	Total Emissions (lbs/yr)	Average Emissions (lbs/yr)	Rank
New England	424,353,000	70,726,000	6
Mid-Atlantic	1,135,197,000	189,199,000	4
The South	2,396,589,000	199,716,000	3
Midwest	2,479,915,000	206,660,000	2
The Southwest	971,437,000	242,859,000	1
The West	1,838,775,000	167,161,000	5

Table 1: Average Emissions Analyzed by Region[10]

Perhaps the most important factor in evaluating the fuel cell market is the amount of energy consumed for commercial uses by each state, which is tabulated in Table B-2. It can be assumed that the higher the demand for energy in the state, the more likely it is that the current power grids cannot meet the needs of the state, and the risk of power surges and black-outs is probably more apparent. If the average energy consumption for commercial uses is analyzed for each region, then the regions of the United States rank in the following order:

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[9] Website Source: http://www.statehealthfacts.kff.org/

[10] Website Source: http://www.epa.gov/air/data/geosel.html

Rank	Region	Average Electricity Consumed (Billion kWh)
1	Mid-Atlantic	138.9
2	The Southwest	126.5
3	The South	89.6
4	Midwest	86.6
5	The West	64.7
6	New England	35.1

Table 2: Average Electricity Consumption Analyzed by Region[11]

In areas where the electricity price is high, fuel cells are likely to be more sellable. If the average electricity price is analyzed by region, then the regions of the United States rank in the following order:

Rank	Region	Average Electricity Price ($/kWh)
1	New England	10.04
2	Mid-Atlantic	8.96
3	The West	8.43
4	The Southwest	7.44
5	Midwest	6.65
6	The South	6.46

Table 3: Average Electricity Price Analyzed by Region[12]

A mathematical model will also help us choose the best location for our business and will be discussed later in the report.

c. Forecast of Commercialization

There is no doubt that the single major factor limiting the widespread use of fuel cells in power production is their cost. Currently, the cost of fuel cells ranges from about $3,000 to $4,000 per kilowatt. At this cost level, The OUFCC will require some forms of subsidies and market incentives to reduce the cost of fuel cells and yield attractive economies. It was stated by the Department of Energy (DOE) that a key reason for the high cost of fuel cells today is that they are now produced on a single unit basis; if the number of units is increased significantly, the stationary fuel cells can be reduced to $2,000 per kilowatt[13]. However, costs will not go down until the production rate is increased; and production rates will not go up until the cost is decreased. Therefore, it is necessary that the federal government, various state governments, and market incentives subsidize the production, installation, and operation of fuel cells to encourage the development.

We currently sell fuel cells at $3,000/kW. However, the DOE announced a $500 million initiative to reduce the cost of fuel cells dramatically to $1,500/kW by 2005 and $400/kW by 2015. By this fact, The OUFCC may not be able to sell fuel cells at the cost as low as $1,500/kW in 2005 since the company starts in 2004. However, the selling price will be

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[11] Website Source: http://www.eia.doe.gov/emeu/states/sep_use/total/pdf/use_all.pdf

[12] Website Source: http://www.eia.doe.gov/cneaf/electricity/epm/table5_6

[13] See Ref. 11

reduced to \$500-\$800/kW in 2014 due to the incentive of DOE and President George W. Bush announcement of the commitment of the federal government to fuel cell advancement.

The forecast of fuel cell prices in the next ten years is shown in Figure 4:

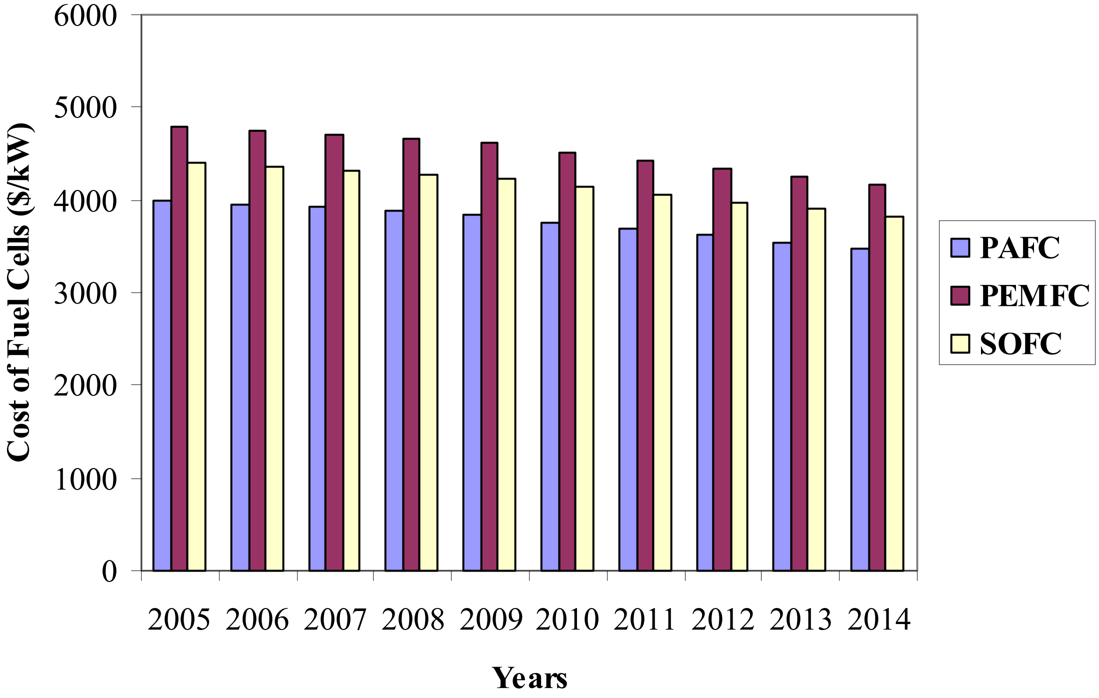

Figure 4: Projected Cost/kW of Installed Capacity[14]

d. Predictions of Market Demand

Based on the analysis performed in the previous section, it is also expected that there will also be a significant fuel cell market in Canada, Hawaii, and Alaska. The current business plan does not include delivery to Canada because of international trade issues; however, this will be soon considered due to North American Free Trade Agreement. Also, the business plan does not include delivery to Hawaii or Alaska because The OUFCC plans to deliver fuel cells only by ground transportation. The markets of Canada, Hawaii, and Alaska (and possibly continents other than North America) will be incorporated into the expansion of the business plan that will take place ten years from the start of production.

Based upon the constraints imposed by the process machinery that will be purchased, the manufacturing plant will be constructed to have a maximum plant capacity of 1000 fuel cells of each type produced per year, and the following is the anticipated schedule of total fuel cells produced per year by type:

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[14] See Ref. 6

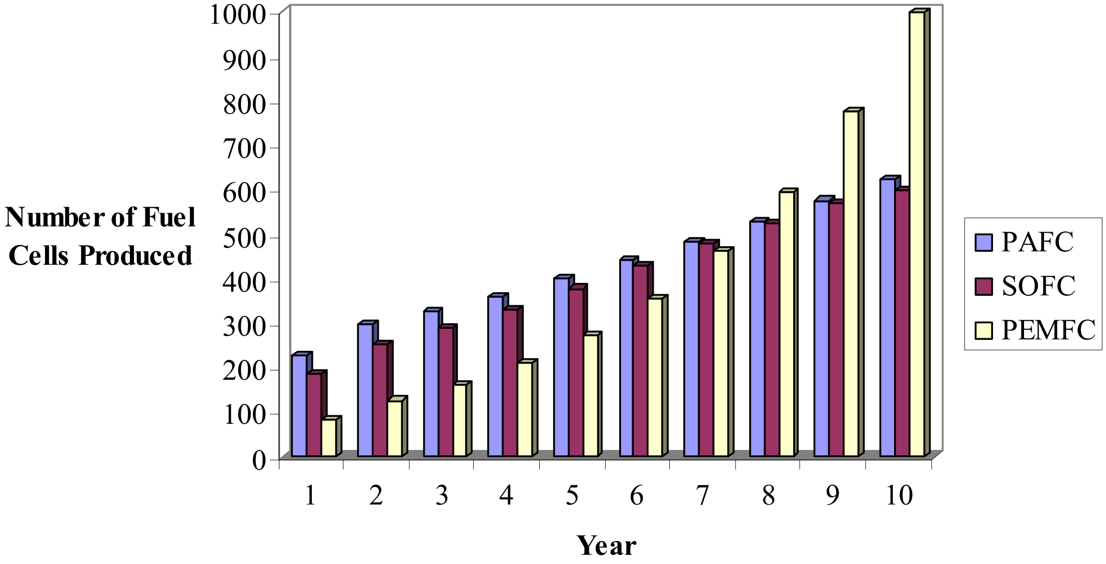

Figure 5: Market Demand by Year

The maximum capacity will be reached in the tenth year of operation. Based on the research on demand of fuel cell in the current year and in the near future, it is expected that fewer fuel cells will be produced in the first years because consumers will be skeptical about buying a new technology. Once the technology is more widely accepted, the number of fuel cells sold is expected to grow exponentially. More PAFCs and SOFCs will be sold in the first few years because they are the most reliable types of fuel cells and the most mature technologies. Slightly more PAFCs will be sold because of their lower price. Ultimately, PEMFCs will replace both technologies because of the benefits of this type of fuel cell. These benefits are discussed later in the report. From research performed, it is expected that in 5 years, PEMFCs will have replaced SOFC and PAFC fuel cell use by 26% and that in 10 years PEMFCs will have replaced them by 45%, and this was incorporated into the figure shown. All these assumptions and speculations will be implemented by the mathematical model.

e. Competing Technology

The OUFCC will compete with other fuel cell companies by providing a quality product at a competitive cost. The OUFCC will also implement an aggressive advertising strategy, as well as offer the most competitive warranty, trial-period, and consultation benefits possible. Also, The OUFCC will manufacture three types of fuel cells so the consumer is given a wide variety of choices from one vendor.

The OUFCC will also compete with other technologies. The following technologies are expected to be the main competitors[15]:

- Microturbines
- Combustion Turbines
- Reciprocating Engines
- Stirling Engines
- Photovoltaic Systems
- Wind Systems

The advantages and disadvantages of each are briefly outlined, and their threat of competition to The OUFCC specifically is analyzed.

Microturbines

Microturbines have the strength of having a small number of moving parts (long intervals between maintenance), but fuel cells also have this advantage. Microturbines, however, are compact in size where fuel cells are very large. Microturbines have an 85% efficiency with cogeneration, and low emissions (less than 9-50ppm), but fuel cells also have these advantages. One disadvantage of microturbines is the loss of power output and efficiency with higher ambient temperatures. Microturbines are currently commercially available and the cost of a microturbine 250kW system is about $250,000. A hybrid system incorporating both a microturbine and fuel cell has been devised, therefore although microturbines offer many advantages that could compete with fuel cells; they do not necessarily pose a threat to The OUFCC because of the hybrid possibility.

Combustion Turbines

Combustions turbines have the advantage of being a mature technology. For this reason, they are relatively inexpensive ($300/kW) when compared to fuel cells ($600/kW). Combustion turbines have a proven reliability and availability and have established marketing and customer servicing channels. Their efficiency is not as high as that of fuel cells.

Reciprocating Engines

Reciprocating engines are another mature technology, and are the most common solution for stationary power generation. A reciprocating engine may cost as little as $30-$900/kW. The start up time for a reciprocating engine can be as low as ten seconds, which is considerably lower than that for a fuel cell (1-4 hours). Their efficiency is not as high as that of fuel cells, but as with combustion turbines, ongoing research could raise this efficiency and lower emissions. Reciprocating engines are a strong competitor of fuel cells.

Stirling Engines

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[15] Website Source: http://www.energy.ca.gov/

Stirling engines are not currently commercially available. Their strengths are low noise, low emissions, and low maintenance. They have low efficiencies (30%) when compared to fuel cells. Since stirling engines are not currently available, they will be very expensive when they do become available sometime around the year 2005. For these reasons, stirling engines should not be a significant source of competition for fuel cells.

Photovoltaic Systems

Photovoltaic (PV) systems are currently available, and are often seen as rooftop panels. PV systems work well for remote locations, are environmentally friendly, and are low maintenance. The disadvantages of PVs are their high cost, and also their inability to provide electricity in certain weather conditions. Since they are not as reliable as fuel cells and also have a high cost, PV systems are not likely sources of competition.

Wind Systems

Wind systems are currently available and becoming more popular. These systems require only a simple installation and have few maintenance requirements. The land underneath the turbines is available for use, such as for farming. The disadvantages of wind systems are their inability to provide power when there is no wind and their low aesthetic appeal. Also, wind systems are a source of competition for fuel cells only in specific high-wind areas (such as California); and wind turbines cause a high bird mortality rate.

III. DESCRIPTION OF THE TECHNOLOGY

a. History of Fuel Cells[16]

In 1839, Sir William Grove discovered that the electrolysis of water might be reversed to produce electricity. He has been referred to as “The Father of the Fuel Cell”. It was not successful initially because electricity was not known much. It was not until 1889 that two researchers, Charles Langer and Ludwig Mond, created the term "fuel cell" as they were trying to build the first practical fuel cell using air and coal gas. While further attempts were made in the early 1900s to develop fuel cells that could convert coal or carbon into electricity, the advent of the internal combustion engine temporarily quashed any hopes of further development of the fledgling technology.

The first success was by Francis Bacon in 1932. His prototype was an alkaline fuel cell system using alkaline electrolyte and porous nickel electrodes. Due to a number of technical hurdles, it was not until 1959 that Bacon and company first demonstrated a practical five-kilowatt fuel cell system. In the same year, Harry Karl Ihrig presented his now-famous 20-horsepower fuel cell-powered tractor.

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[16] Website Source: http://www.sae.org/technology/fuelcells-history.htm

During the same period of the 1950s, fuel cells were used in the Apollo space program. NASA began to build a compact electricity generator for use on space missions. Then fuel cells were also used in Gemini and space shuttles. NASA soon came to fund hundreds of research contracts involving fuel cell technology. Fuel cells now have a proven role in the space program, after supplying electricity to several space missions. The reason for using fuel cells in space is that nuclear power is too dangerous, solar panels are too bulky, and batteries are too heavy.

In more recent decades, fuel cell technology has been supported by many manufacturers and federal agencies. A number of projects on the development of fuel cell technology have been investigated. “Fuel cell energy is now expected to replace traditional power sources in coming years - from micro fuel cells to be used in cell phones to high-powered fuel cells for stock car racing”.

b. Technology Overview

Fuel cells are electrochemical devices that convert a fuel’s chemical energy directly to electricity with the help of catalyst and with heat as a by product. With no internal moving parts, fuel cells are similar to batteries in operation and constituents. It should be noted here that oxygen and hydrogen are not the internal part of the fuel cell that is mentioned above. Oxygen and hydrogen are the fuels that are fed to the fuel cells through a reformer that will be discussed later in this report; and they need to move to cause the reactions in order to produce electricity. The key difference between batteries and fuel cells is that while batteries store energy, fuel cells produce electricity continuously if fuels are supplied[17].

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[17] Website source: http://auto.howstuffworks.com/fue-cell.htm/printable

A typical single cell fuel cell structure can be viewed in Figure 6 below:

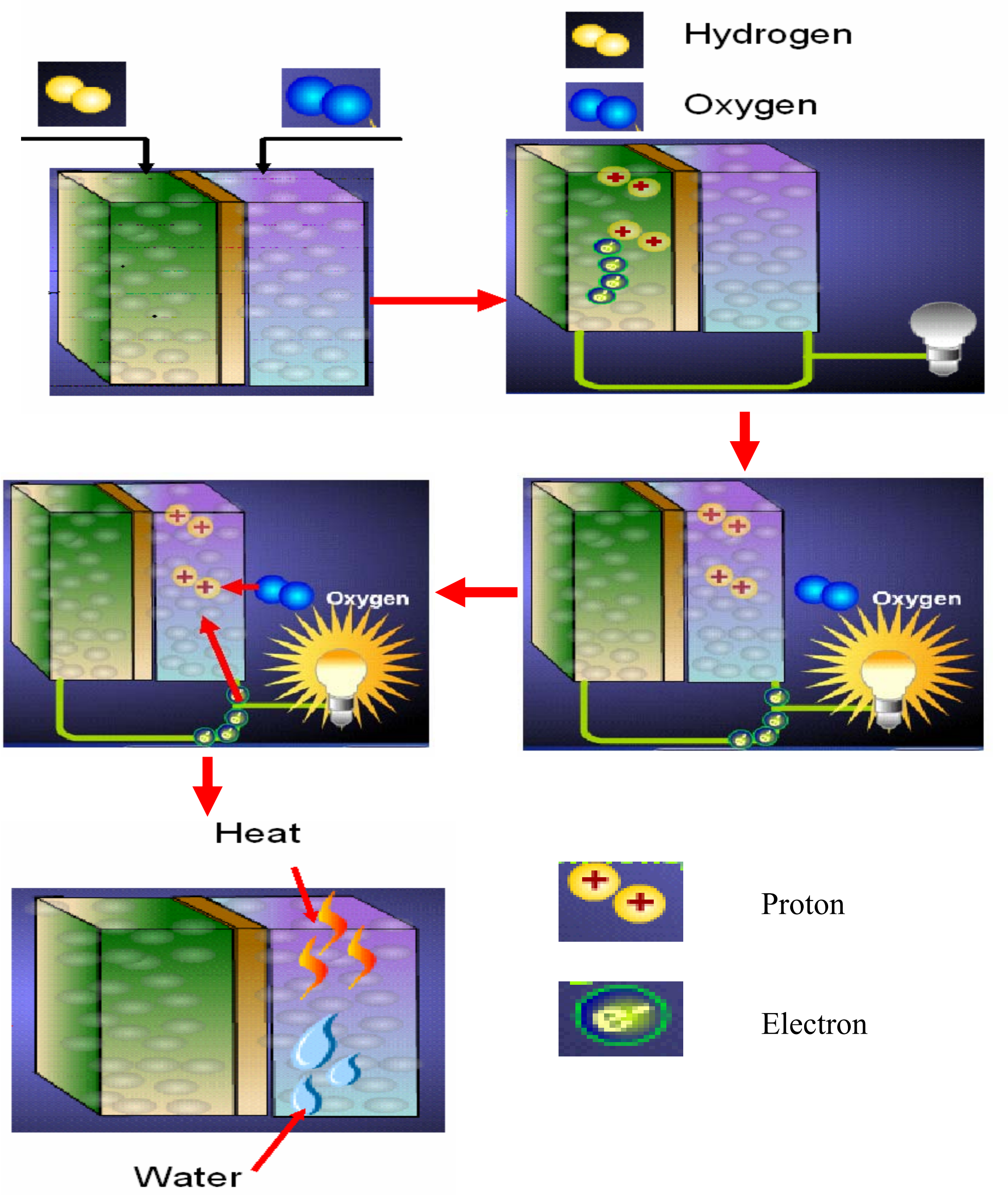

Figure 6: Structure of a Fuel Cell[18]

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[18] Website source: http://www.nfcrc.uci.edu/fcresources/FCexplained/FC_howItWorks.htm

A typical single fuel cell is comprised of three main parts: two oppositely charged electrodes on two sides an electrolyte in the center. The anode is negatively charged and repels electrons. The cathode is positively charged and attracts electrons. The electrolyte can be a membrane, a liquid solution, or a solid depending on the type of the fuel cell. For instant, solid oxide fuel cells (SOFCs) use a non-porous metal oxide as the electrolyte while phosphoric acid fuel cells (PAFCs) utilize a concentrated 100% phosphoric acid liquid as the electrolyte. As a result, the conduction mechanisms are different. SOFCs have ionic conductions accomplished by oxygen ions while PAFCs have the permeation of hydrogen ions through the electrolyte layer[19]. The catalyst is coated at the interface of each electrode with the electrolyte. The catalyst is used to promote the electrochemical reaction. Therefore, the type of catalyst used depends upon the operating temperature of each type of fuel cell. Generally, high operating temperature fuel cells can use common metals as catalyst, but the low operating temperature fuel cells require noble metals as catalyst, typically platinum because at low temperature noble metals like platinum has a better ability to break the hydrogen bonding than common metals due to the effect of outer layer of the electron configuration.

The fuels used in fuel cells are typically hydrogen and oxygen. Hydrogen fuel flows into the anode side of the fuel cell while oxygen in air is introduced to the cathode side. At the anode, catalyst particles help to break down the hydrogen molecules into proton (hydrogen ions) and electrons. Since the electrolyte layer allows only the proton to pass through it to the cathode side, the electrons have to follow an external circuit to the cathode and produce electric current that can power an electric load such as a light bulb as shown in Figure 6.

At the cathode, the catalyst breaks down the oxygen molecules and facilitates the electrochemical reaction that combines oxygen, protons, and electrons to produce water and heat. Figure 2 shows the whole process taking place in a single fuel cell.

The electrochemical reactions that occur are[20]:

Anode: $H_2 \xrightarrow{catalyst} 2H^+ + 2e^-$
Cathode: $1/2O_2 + 2H^+ + 2e^- \xrightarrow{catalyst} H_2O$
Overall: $H_2 + 1/2O_2 \rightarrow H_2O$

Many individual single cells can be combined into a fuel cell stack and connected electrically in series or parallel to produce the voltage and current level desired. They are stacked one on top of the other. Most individual fuel cells are small in size and produce between 0.5 and 0.9 direct current electricity. The number of fuel cells connected in series determines the stack voltage because in series, the total voltage equals to the sum of individual voltages. For a stack of fuel cells, since each individual cell has the same voltage, we just need to multiply that voltage with the number of single cells to calculate the total voltage of the stack. The number of the cells connected in parallel determines the total currents produced because in parallel, the total current equals to the sum of

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[19] Website source: http://www.nfcrc.uci.edu/fcresources/FCexplained/FC_Types.htm
[20] Website source: http://science.howstuffworks.com/fuel-cell2.htm

individual currents. Then the power can be found as the product of the current and the voltage[21].

The block diagram in Figure 7 represents a fuel cell power plant. Generally, most of fuel cell systems consist of four basic components:

- A fuel processor
- An energy conversion device or power section (the fuel cell or fuel cell stack)
- A current converter (power conditioner)
- Heat recovery system

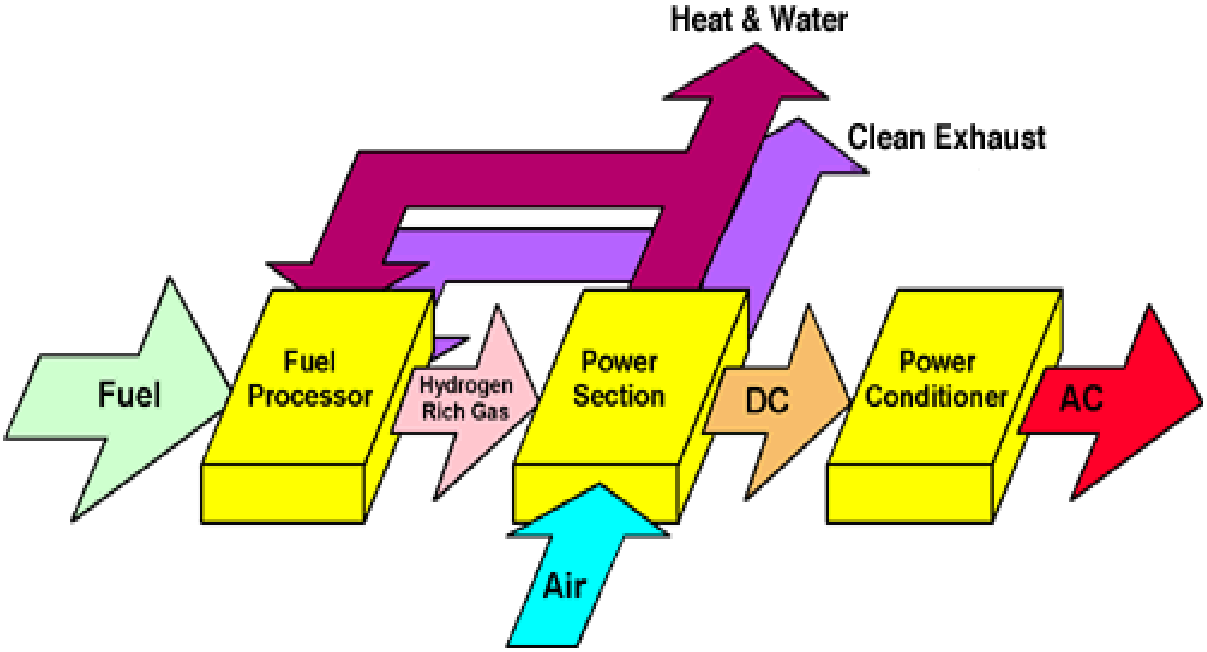

Figure 7: Fuel Cell Power Plant[36]

The first component of a fuel cell system is the fuel processor or the reformer. Fuel is introduced into a fuel processor or reformer, which produces hydrogen-rich gas from natural gas or other fuels, emitting carbon dioxide and trace amount of carbon monoxide compounds called “reformate”. In other words, the fuel processor converts fuel into a form usable by the fuel cell. If hydrogen is fed to the system, a processor may not be required or it may only be needed to filter impurities out or the hydrogen gas. In many cases, the reformate is then sent to another reactor to remove impurities, such as carbon oxides or sulfur before it is sent to the fuel cell stack. This prevents impurities in the gas from binding with the fuel cell catalysts. This binding process is also called “poisoning” since it reduces the efficiency and life expectancy of the fuel cell. Depending on the types of fuel cells and their operating temperature, the reformer can be internal or external. For example, high operating temperature fuel cells such as molten carbonate and solid oxide

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[21] Website source: http://www.dodfuelcell.com/paper2.html
[22] See Reference 32

fuel cells do not require external reformers; they can be reformed internally[23]. More details on reforming process will be discussed later in this report.

After reforming process, the hydrogen-rich gas and oxygen from air flow into a power section where direct current is generated from electrochemical reactions that take place in the fuel cell. Water and heat are also produced[24].

The power conditioner consisting of an inverter converts the direct current electricity to alternative current electricity for suitable use in most of electrical devices. The power conditioners can be used to control current flow, voltage, frequency, and other characteristics of the electrical current to meet the needs of the application. The power conversion and conditioning reduce the system efficiency very slightly, only about 2 to 6 percent[25].

Heat recovery system is typically used in high-temperature fuel cell systems such as molten carbonate and solid oxide fuel cells used for stationary applications. Fuel cells systems, by producing electricity, generate significant amounts of heat that can be used to produce steam or hot water or can be converted to electricity via a gas turbine or other technology. This cogeneration can increase the overall thermal efficiency of the systems[26].

c. Fuel Cell Applications

The OUFCC considered manufacturing fuel cells of a range of sizes for use in various applications. The applications taken into consideration where the following:

- Industrial – An example is power for waste water treatment.
- Business – Examples are power for government and non-government funded buildings such as hospitals and banks.
- Residential –An example is power for private homes.
- Cars – For example, it can be used as an automotive fuel source.
- Small devices – An example is battery replacements for laptops and cell-phones.

The following decisions were made by The OUFCC in order to narrow the scope of the business.

The OUFCC decided to eliminate small devices from production since cost is a primary consideration in their design and construction, and producing fuel cells below this cost would be a challenge in the current economy. While fuel cells may last longer than batteries for this application, they have limitations on where and how they can be used (for example, fuel cells are not approved for use on an airplane). It also seems that other

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[23] Website source: http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/how.html

[24] See Reference 32

[25] See Reference 32

[26] See Reference 33

companies have explored fuel cells applications in small devices (Toshiba for example) and are already providing and marketing products.
Fuel cells made for application in cars was eliminated from production based upon the strength of the competition. Hybrid cars, although more expensive than conventional internal combustion models, do not require any change in the current transportation infrastructure and thus have an advantage over fuel cells, even if fuel cells could provide lower emission at a comparable cost. There are also safety and reliability concerns associated with fuel cells. Additionally, there already exists a large number of companies investing and researching this field.

Fuel cells made for application in homes was eliminated from production since most electricity is currently available cheaply from grids. Potential exists for fuel cells to power homes which are not located near power grids; however, asking individual consumer to bear the heavy capital cost would be unreasonable. Further market research may relieve these concerns, and this application may be considered in expansion planning.

All of these applications require fuel cells that can operate at low temperatures. A fuel cell built for these applications would require expensive catalysts (platinum for example) which in turn increases the capital cost of the fuel cells.

The OUFCC has decided to focus production on fuel cells for use in small businesses. Since power demand will be large and constant, and the need for cogeneration is usually apparent, the high temperature of operation will not be as large of a concern as for other applications.

d. Fuel Cell Types

Extensive research has been performed on each fuel cell type that can be used in small buildings as a supplementary or back-up source of electricity. Four fuel cell types were considered for this application: phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), and proton exchange membrane fuel cell (PEMFC). The results of this investigation will convey which fuel cell type or types are best to manufacture and enter into the market for purchase. Several criteria were considered, and characteristics of each fuel cell were examined carefully; the following table displays these criteria and the results. Table 4 provides an analysis of important characteristics of each fuel cell type.

CRITERIA	Phosphoric Acid	Molten Carbonate	Solid Oxide	Proton Exchange Membrane
Efficiency[27]	**37% - 42%** ***80 - 85% with cogeneration**	**50% - 55%** ***85% with cogeneration**	**50% - 60%** ***85% with cogeneration**	**50%** ***80% with cogeneration**
Operating Temp.[1]	**375 - 410°F**	**1200°F**	**1800°F**	**175°F**
Durability/Corrosion Issues[2]	**catalyst poisoned @ low temp.**	**electrode corrodes @ high temp.**	**Not poisoned by CO**	**catalyst poisoned @ low temp.**
Start-up Time[2]	**1 - 4 hr**	**6 - 10 hr**	**5 – 10 hr**	**6 min**
Peak Power Density[28]	**~ 200 mW/cm^2**	**~ 160 mW/cm^2**	**~ 150 - 200 mW/cm^2**	**~ 700 mW/cm^2**
Availability of Raw Materials[2] [29]	**Massachusetts**	**limited**	**Ohio**	**Massachusetts**
Cost of Raw Materials[2]	**$550/kW**	**N/A**	**$657/kW**	**$750/kW**

Table 4: Fuel Cell Type Analysis

Each category was analyzed in an effort to determine which fuel cell type would be economically feasible for implementation in a manufacturing process. The categories titles “Operating temperature” and “Durability/Corrosion Issues” were analyzed simultaneously since the operating temperature directly affects the durability of the fuel cell. It can be seen from the table, that the solid oxide has the highest operating temperature. However, the components of the SOFC are not affected at high operating temperatures, unlike the MCFC. Therefore, the MCFC possesses the least desirable characteristic in these two categories. It is important that an adequate amount of raw materials is available in order to meet the demand of consumers. It is difficult to find raw material suppliers for MCFCs. Based on research, MCFCs are considered obsolete; there are currently only 3 facilities in the United States that manufacture MCFCs due to a low demand of this product. The cells highlighted in yellow represent areas in which a particular fuel cell possesses the least desirable characteristic. It can be seen from Table 4 that the characteristics of the MCFC are not impressive. Therefore, The OUFCC has decided not manufacture this fuel cell type in its facility.

e. Description of Fuel Cell Types

i. Phosphoric Acid Fuel Cell

The Phosphoric Acid Fuel Cell (PAFC) is the most mature fuel cell technology in terms of system development and commercialization. It has been under development for more than 20 years and has received a total research investment of $500 million. Like most fuel cells PAFCs use purified hydrogen as a fuel source in order to induce adequate operation. The PAFC uses liquid phosphoric acid as the electrolyte. The phosphoric acid is contained in a Teflon® bonded silicone carbide matrix. The porous structure of the

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[27] Website source: http://www.appice.es/eng/2/2_3.htm
[28] Website source http://www.cambridgeconsultants.com/PDFs/fuelCells00.pdf
[29] Website source http://starfire.ne.uiuc.edu/~ne201/1997/cjohnsn3/mol.html

matrix preferentially keeps the acid in place through capillary action. A platinum catalyst is used on both sides of the porous anode and cathode in order to increase the rate of reactions. Figure 8 is a depiction of a PAFC and it includes the chemical reactions that occur at the anode and cathode.

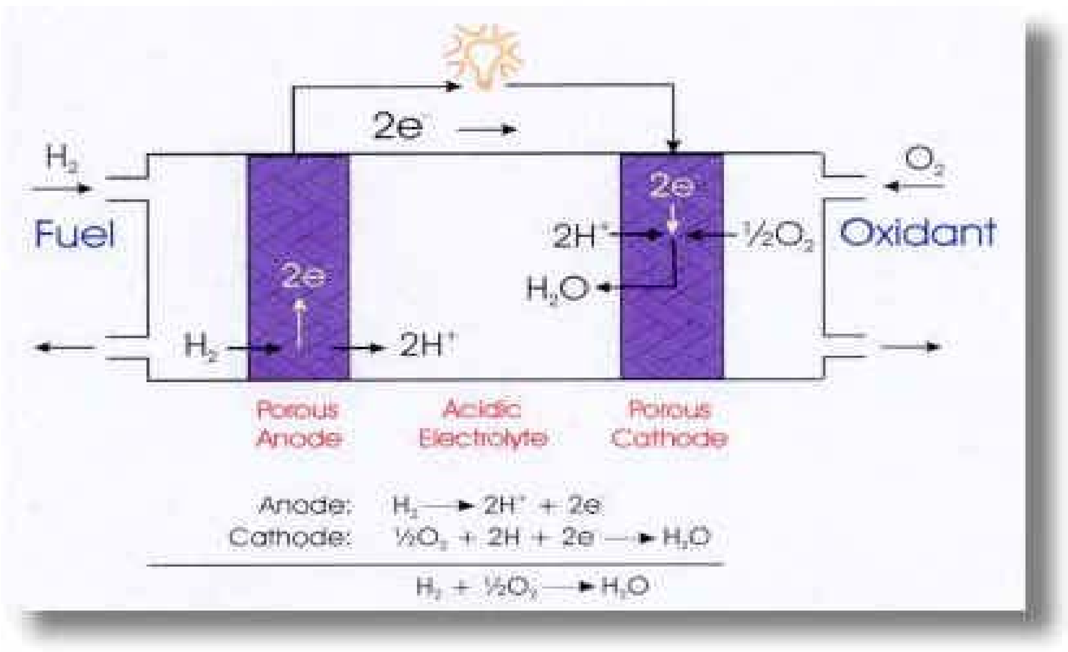

Figure 8: Phosphoric Acid Fuel Cell Including Chemical Reactions of Electrodes[30]

The oxygen needed for the cathode of the fuel cell is simply taken from the air. The hydrogen required for the anode must be extracted from liquid natural gas or methanol. This process is called reformation, it requires several steps, and a detail description of this process can be found in Section III-h of this report. The purified hydrogen is fed into the anode of the fuel cell. This fuel is fed through parallel grooves formed of carbon composite plates. These plates are electrically conductive and conduct electrons from the anode to the cathode of the adjacent cell. The design requires the plates to be "bi-polar" which means that one side supplies fuel to the anode, while the other side supplies air or oxygen to the cathode. All of the hydrogen in the anode exhaust is not consumed in the fuel cell. The remaining anode exhaust is fed back into the reformer burner, which burns the remaining hydrogen and maintains the high temperature required for the reforming process. Also, water (steam) is recovered from the cathode exhaust to maintain the necessary water supply to the reformer. The water recovery procedure requires that the system be operated at temperatures around 375°F[31]. If the water is not removed, it will dissolve in the phosphoric acid electrolyte and decompose the acid. Figure 9 shows an example of a complete PAFC system including the fuel cell and the reformer.

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[30] Website Source: http://webpages.ull.es/users/jcruiz/otras_fc.htm

[31] Website Source: http://www.appice.es/eng

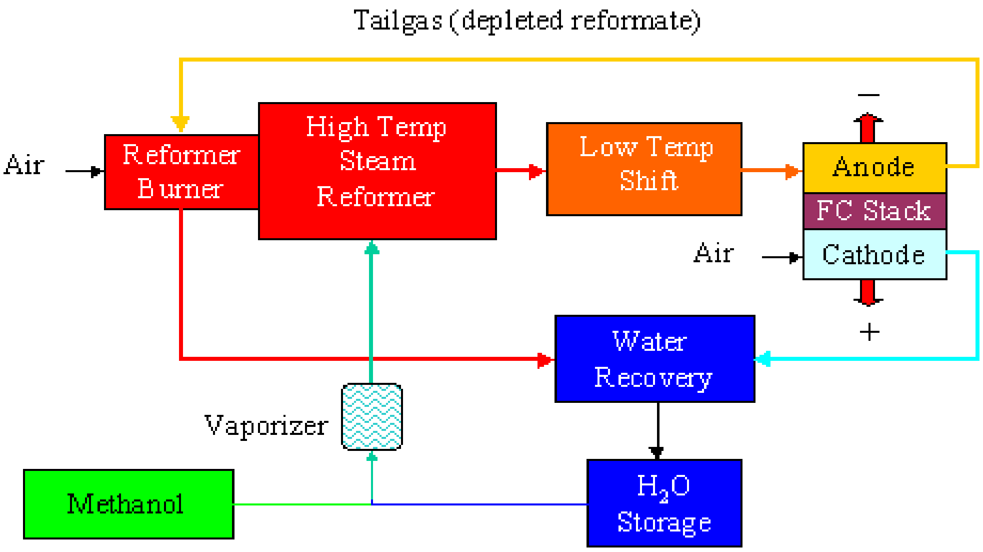

Figure 9: Operation of a Phosphoric Acid Fuel Cell System[32]

Currently, the average selling cost of a fuel cell system is $1,000,000. A detailed explanation of costs for raw materials, fabrication, and necessary equipment, is essential in determining the capital investment required to run a fuel cell manufacturing facility. The complete "life-cycle" of a fuel cell system involves purchase or manufacture of raw materials, assembly of stack, system assembly, purchase by consumer, installation and regular maintenance. Figure 10 shows the flow of tasks necessary to construct a fuel cell system.

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[32] Website Source http://fuelcell.georgetown.edu/ifctech.cfm

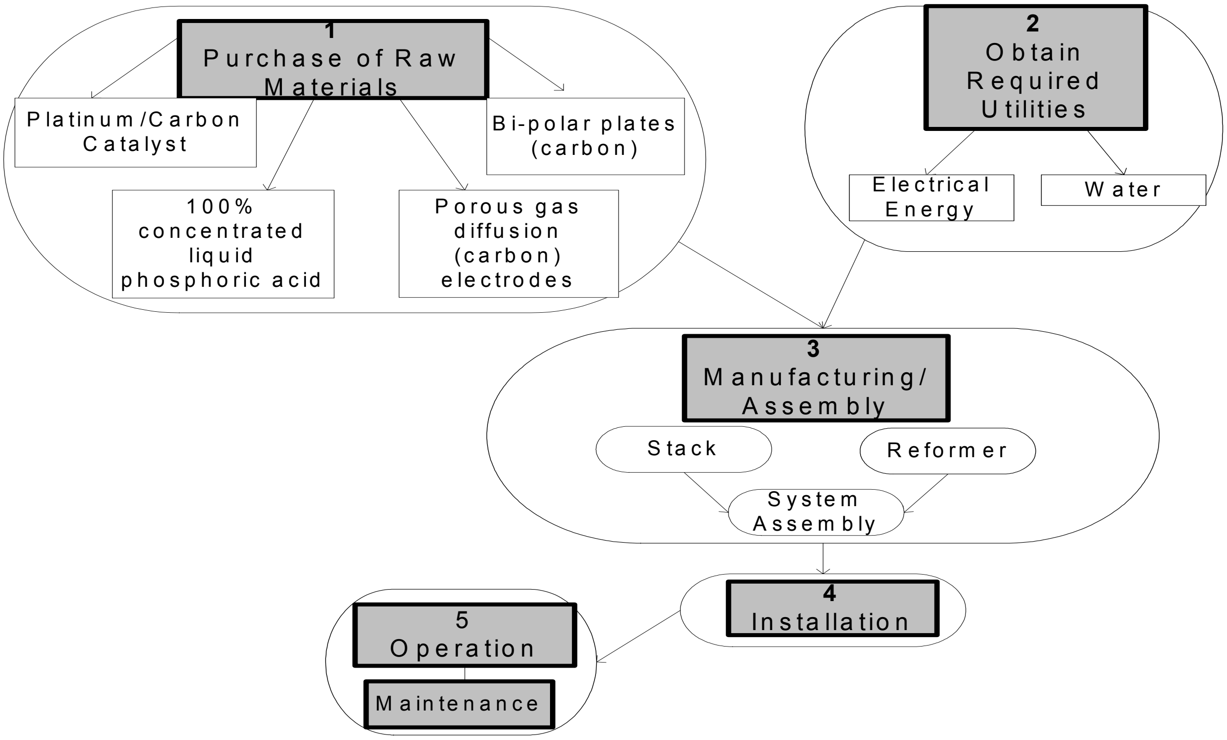

Figure 10: "Life Cycle" of Fuel Cell System

1. **Purchase of Raw Materials**: The major components of a PAFC include the electrodes, phosphoric acid, bio-polar plates and platinum/carbon catalyst. The catalyst layer is made of platinum and carbon powder and is roll-coated on with a poly-tetra-fluro-ethylene which binds and maximizes gas diffusion. Both the electrodes have the same layers bonded to them. In between the electrodes is phosphoric acid, which moves hydrogen ions from the anode to cathode. Table 5 shows the costs associated with raw materials for a 1 unit cell. An average fuel cell stack has 50 unit cell composed in the system. Therefore, the total cost calculated in the table below must be multiplied by 50 in order to determine the total cost of raw materials for a 250 kW PAFC system.

Component	Cost
Anode	$125.00
Cathode	$125.00
Bi-Polar Plates/Ancillary Parts	$2,500.00
Catalyst	$54.00
Phosphoric Acid	$312.00 (per ton)
	Total Cost: $3,116

Table 5: PAFC Raw Material Costs

Figures 11 and 12 show an estimate of the amount of each material that is required to construct a phosphoric acid unit cell, bi-polar plates, and ancillary components.

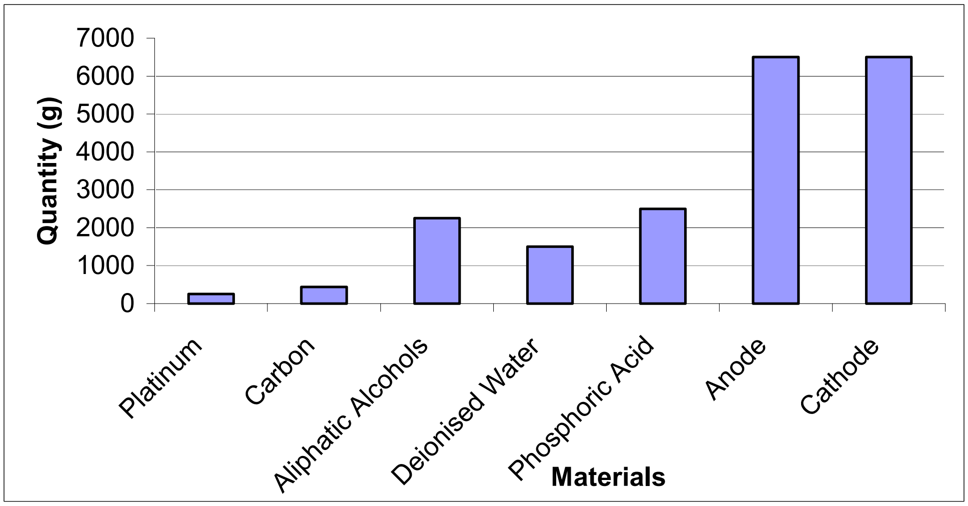

Figure 11: Material Inputs for Manufacturing of PAFC

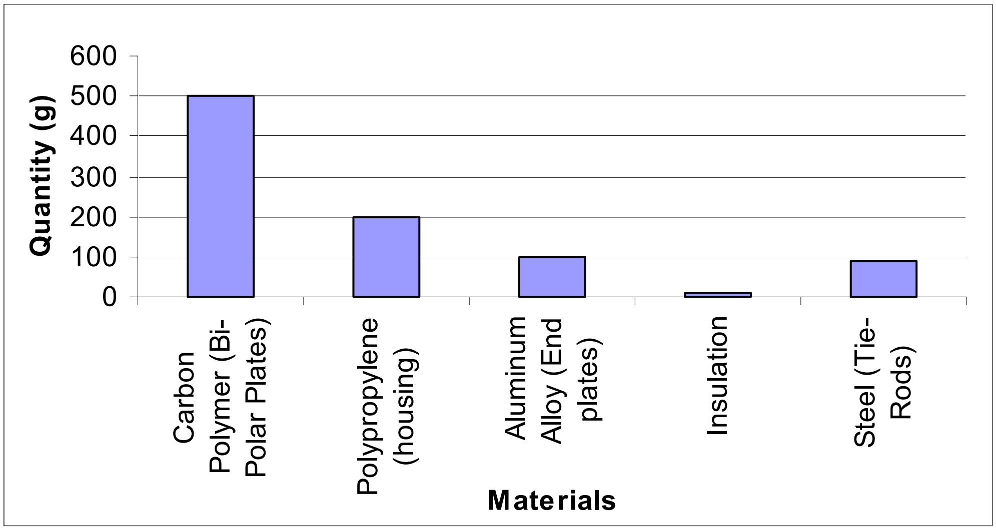

Figure 12: Material Inputs for Manufacturing of PAFC Bi-Polar Plates and Ancillary Components

2. **Obtain Required Utilities**

   The utilities necessary for the production and assembly of a phosphoric acid fuel include deionized water, cooling water, and electricity. The next section details each process, a description of the process, and the associated energy.

3. **Manufacturing/Assembly**: The typical stack design consists of a flat planar carbon anode, a phosphoric acid electrolyte, and a carbon cathode assembled in series. Bi-polar plates are attached on each side of the anode and cathode in order to produce a sufficient voltage to provide useful power. The bi-polar plate is a sheet with grooves which provide both fuel/oxidant supply channels and electrical connection between the fuel cells. Table 6 describes each manufacturing process

involved in preparing the catalyst, anode, cathode, phosphoric acid electrolyte, and bi-polar plates.

Process	Description	Energy Inputs for Manufacturing Process (kW)
Shear mixing	Platinum and carbon powder are mixed with deionized water and aliphatic alcohol as solvents	0.0834
Constant volume displacement distillation and viscosity reduction	Catalyst slurry is heated to boiling point of aliphatic alcohol, which starts to boil off. As volume is reduced, deionized water is added to keep volume constant. Once all organic solvent is evaporated, the solution is heated further to reduce viscosity	20.8
Electrode coating	The catalyst mixture and is roll-coated onto both sides of the anode and cathode with poly-tetra-fluro-ethylene which binds and maximizes gas diffusion.	0.007
Drying	The remaining water in the catalyst mixture is dried off in a tunnel dryer	0.568
Electrolyte preparation	The phosphoric acid is poured in a Teflon bonded silicone carbide matrix. The porous structure of the matrix preferentially keeps the acid in place through capillary action	0.007
"Injection" molding of bi-polar plates	Polypropylene, carbon fibres, and carbon power are mixed together to form a carbon polymer. The polymer is molded into the shape of the bi-polar plates by injecting the carbon-based material and creating grooves.	1.25 **Total: 22.7 kW**

Table 6: Catalyst, Anode, Cathode, Phosphoric Acid Electrolyte, and Bi-polar Plates Manufacturing

Ancillary components are comprised in the integrated stack package (ISP), and are tools essential in providing support and protection to the fuel cell. Table 7 below shows these components and its associated manufacturing process.

Component	Manufacturing Process	Energy Inputs for Manufacturing Process (kW)
ISP	Structural Foam	0.58
Endplates	Aluminum Casting	2.26
Insulators	Die-Cutting	0.000287
Current collectors	Aluminum Stamping	0.942
Tie-rods	Machining	0.57
		Total: 4.4 KW

Table 7: Ancillary Components of the Integrated Stack Package

The total required energy required to produce one PAFC is **27.1 kW**. The energy that will be supplied will be given in terms of power. The average cost of energy is $0.08/kwh. The 27.1 KW mentioned above translates into **650.4kWh**; this is only an estimate of the energy required for daily production on the phosphoric acid line. Figure 12, is a flow diagram of a PAFC production/assembly line.

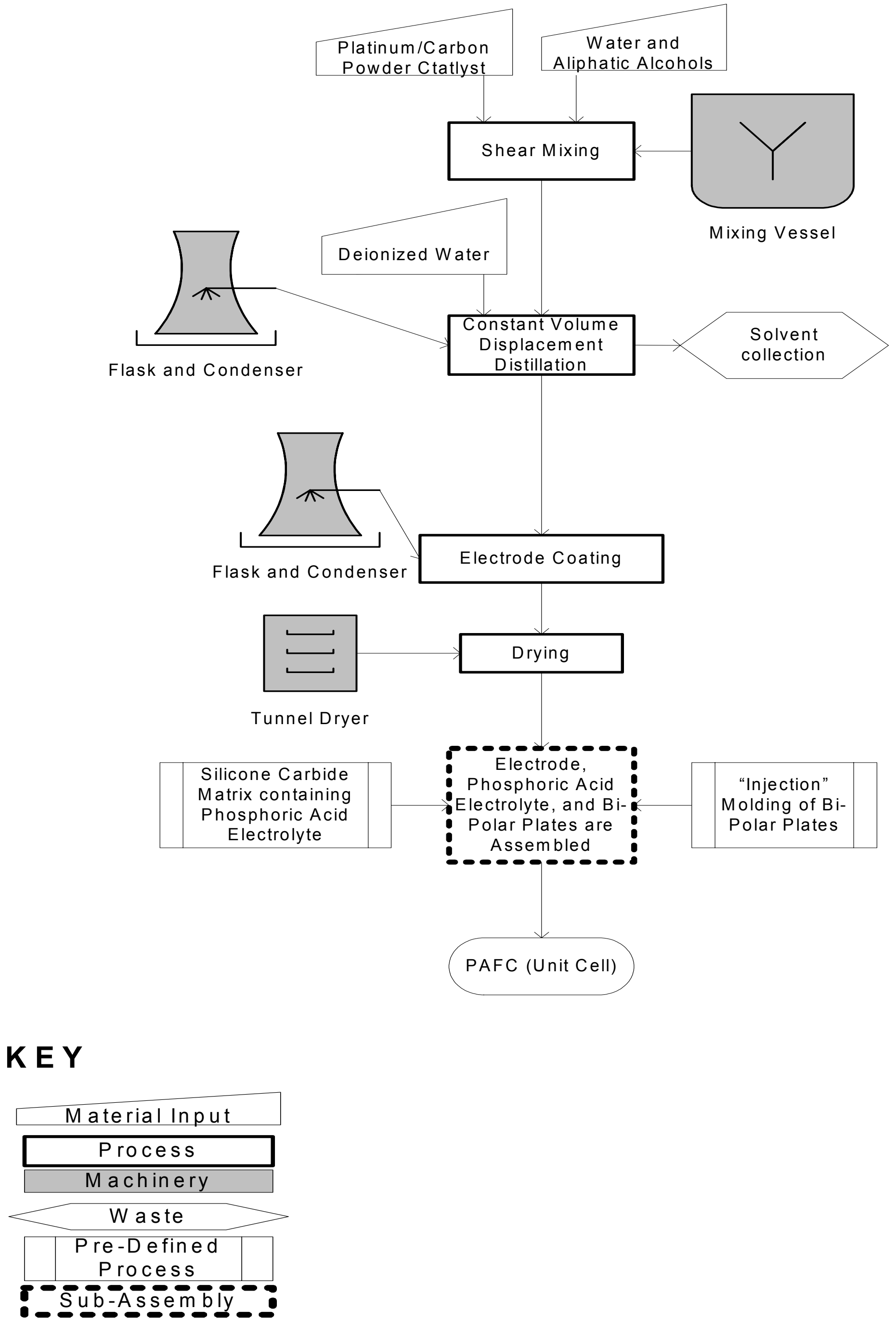

Figure 13: Flow Diagram of a PAFC Production/Assembly Line

As mentioned previously, the fuel cell stack requires a comparatively pure hydrogen stream to operate. A reformer is needed to convert natural gas to hydrogen and CO (further clean-up processes are required). The reformer will be purchased from Ztek corporation or ChevronTexaco for approximately $125,000.00. The fuel cell stack and reformer are then housed together in a humidity-controlled package.

4. **Installation:** The University of Oklahoma Fuel Cell Corporation will provide consultation during the installation process. OUFCC will only provide the fuel

cell stack and the reformer upon delivery. The fuel cell and reformer will be housed together. The dimensions of this system are the following: 5.5 m wide, 3 m high, and 3 m in depth.

5. **Maintenance**: It is required that regular maintenance is performed all machinery in the production line. The OUFCC will shut down the operation of the production line twice a month in order to ensure reliable functioning machines. Maintenance of a fuel cell is expected to be comparable to a microturbine, ranging from \$0.005 to \$0.010[33].

ii. Proton Exchange Membrane Fuel Cell (PEMFC)

According to the Department of Energy, the proton exchange membrane fuel cell (PEMFC) is one of the most promising types of fuel cells for use in small buildings as a supplementary or back-up source of electricity.[34] The proton exchange membrane (or electrolyte) is a permeable thin plastic sheet that allows hydrogen ions to pass through, but keeps electrons and whole atoms from passing through. This membrane is called a membrane electrolyte assembly, MEA. The electrolyte is coated on both sides with platinum that acts as a catalyst; the solid state of the electrolyte is advantageous because it reduces corrosion. PEMFCs are sensitive to fuel impurities; therefore, the hydrogen fuel supplied must be 99% pure. Figure 14 shows a diagram of a PEMFC:

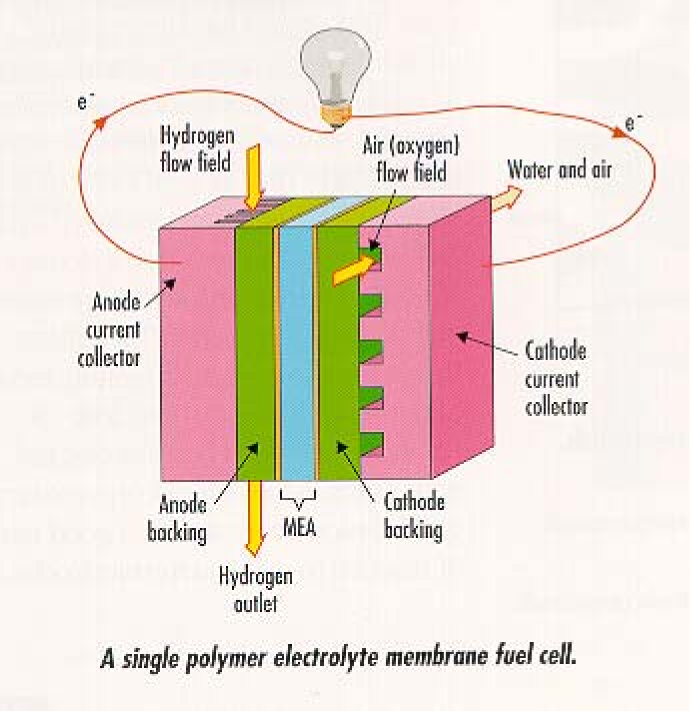

Figure 14: Diagram of a PEMFC[35]

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[33] Website source: http://www.energy.ca.gov/distgen/equipment/fuel_cells/cost.
[34] Website Source: http://www.eere.energy.gov/RE/hydrogen_fuel_cells.html
[35] Website Source: www.netl.doe.gov/

PEMFCs operate at relatively low temperatures (about 175 °F), have high power density, can vary their output quickly to meet shifts in power demand, and have very quick start-up time (1 – 3 min). They also have an excellent efficiency of 50%, and with cogeneration, an efficiency of 80% is possible. Cogeneration is the utilization of the waste heat expelled from the fuel cell for other uses. The following companies currently manufacture PEMFCs: Ballard, Plug Power, Energy Partners, H-Power, Honeywell, American Fuel Corporation, Northwest Power Systems, Avista Labs, DuPont, Johnson Matthey, 3M and GORE.[36]

The following is the manufacturing process for a unit cell, 50 of these are included in the ISP (Integrated Stack Package) which along with the ancillary components make up the 250 kW PEMFC. Each process, M1-M8, is described in Table 8.

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[36] Website Source: http://www.nfcrc.uci.edu/fcresources/links/FuelCellType_B

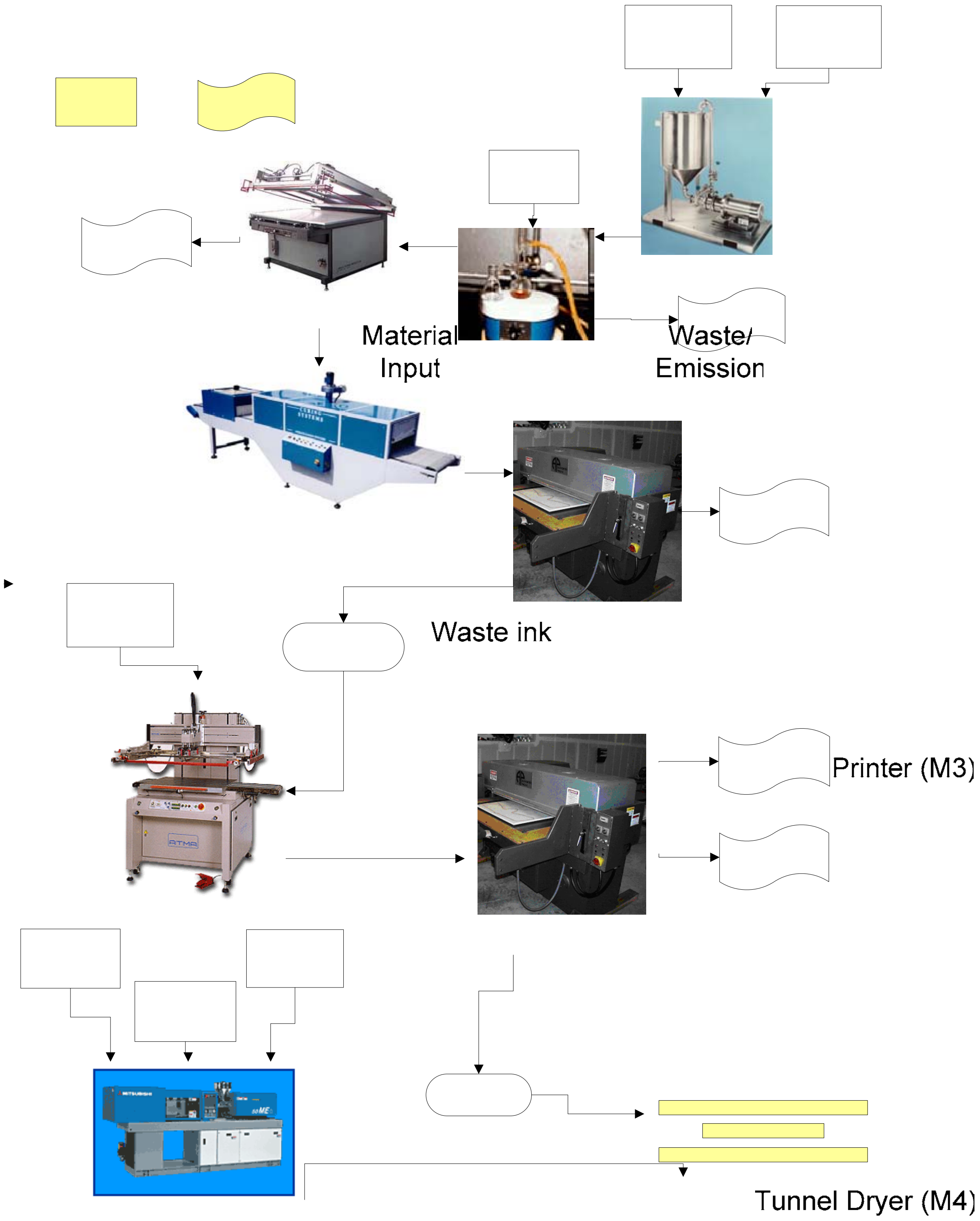

Figure 15: Flow Sheet Drawing for Manufacturing of a Unit Cell[37]

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[37] http://www.dti.gov.uk/energy/renewables/publications/pdfs/f100164.pdf, Pictures: http://www.mag-knight.com/diecutting/Die_Cutting_Service.htm, http://www.mhi.co.jp/sanki/injection/injec_e/, H:\Fuel Cells\Open Directory - Business Publishing and Printing Printing Processes Screen Printing Equipment and Supplies.htm

Process	Description	Power Requirement (kW/Fuel Cell)
(M1) *Shear Mixing*	Pt and Ru catalysts, supported on C are shear mixed with Nafion solution containing de-ionised water & lower aliphatic alcohol as solvents.	.0834
(M2) *Constant Volume Displacement Distillation & Viscosity Reduction*	Catalyst slurry is heated to boiling point of the organic solvent which starts to evaporate off. As volume is reduced, de-ionised water is added to keep volume constant. Once all organic solvent is evaporated, the solution is heated further to reduce viscosity.	20.8
(M3) *Screen Printing*	Aqueous catalyst ink is screen printed onto sheets of carbon paper.	.014
(M4) *Drying*	The remaining water in the screen printed catalyst ink is dried off in a tunnel dryer.	.568
(M5) *Die Cutting Catalyst Coated Carbon Paper*	The catalyst coated carbon paper electrode is die cut using steel rule dies to the desired shape and size.	.00824
(M6) *Medium Size Low Temperature Pressing*	A sheet of extruded Nafion polymer is sandwiched under pressure between two previously die cut electrodes at a temperature around the glass transition temperature of Nafion.	1.06
(M7) *Final Die Cutting of MEA*	The pressed MEA is die cut to the desired shape and size using steel rule dies.	.0082
(M8) *Injection Molding Bipolar Plates*	Polypropylene, Carbon fibers and Carbon powder are mixed together to form a Carbon polymer. The polymer is injection molded to the shape of the bipolar plates.	1.25

Table 8 – MEA and Bipolar Plates Manufacturing and Power Requirements for a Unit Cell[38]

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[38] http://www.dti.gov.uk/energy/renewables/publications/pdfs/f100164.pdf

Once the unit cells are manufactured, they are assembled together in order to make the ISP. The ISP is housed in structural foam and cast in aluminum once ancillary components have been added.

Process	Description	Power Requirement (kW/Fuel Cell)
Structural Foam	Creating structural foam for the housing of the ISP	.58
Aluminium Casting	Casting the endplates for the ISP	2.26
Die Cutting	Creating the insulators for the ISP	.000287
Aluminium Stamping	For the current collectors in the ISP	.942
Machining	Creating the tie-rods for the ISP	.57

Table 9: Ancillary Components of the ISP and Manufacturing and Power Requirements[52]

The total power requirement for the process is 28.14 kW/ Fuel Cell. Please see Appendix E for the power requirement calculations for the 250 kW PEMFC.

The following tables show the quantity of materials needed to make the various components of the 250 kW fuel cell. 50 MEAs and 100 bipolar plates make up the ISP, which is then combined with the ancillary components to make the entire 250 kW fuel cell.

Materials	Quantity g/kW	Quantity g/FC
Platinum	1	250
Ruthenium	.5	125
Carbon	1.75	437.5
Carbon Paper	62.36	15590
Nafion Sheet	79.82	19955
Nafion dry polymer	1	250
Lower aliphatic alcohols	9.5	2375
De-ionised water	6.5	1625

Table 10: Material Inputs of the ISP and Manufacturing of the MEA[52]

Materials	Quantity g/kW	Quantity g/FC
Carbon Polymer (for the bipolar plates)	768.60	192150
Polypropylene (for ISP housing)	100	25000
Aluminium Alloy (for end plates)	40	10000
Polytetrafluoroethylene (PTFE) (for insulation)	5	1250

Soft Aluminium Alloy (for the current collectors for ISP)	20	5000
Steel (for tie rods)	25	6250

Table 11: Material Inputs for the Manufacturing of the Bipolar Plates & Ancillary Components[52]

Component	Cost ($)
Hardware	187,500
Electrode	17,400
Catalyst	2,700

Table 12: Raw Materials Cost for 250 kW PEMFC[39]

The total cost for the raw materials for a 250 kW PEMFC is $207,600. The suppliers of the raw materials for the PEMFC can be found in Massachusetts and Canada.

iii. Solid Oxide Fuel Cell (SOFC)

SOFCs are composed of all solid-state materials made of ceramic substances. The solid-phase nature of the solid oxide fuel cell reduces corrosion because the electrolyte is not a corrosive acid like in some types of fuel cells. Secondly, they operate at temperatures as high as 1830°F (1000°C), making it possible for internal reforming of hydrocarbon fuels. The temperature also produces high-quality waste gases that can be used for cogeneration applications. SOFCs also exhibit less restriction on the cell configuration, thus making it possible to shape the cell in two different design concepts. These two distinct designs (tubular and planar) will be discussed later in this section. Also, SOFCs are known to have fuel flexibility. Biogases and hydrocarbons such as methanol can be used as fuels without the need of an external reformer. This is feasible because the water gas shift reaction involving CO and the steam reforming of CH_4 in the high temperature environment of SOFCs produces H_2 that is easily oxidized at the anode. [40] Listed below are some of the advantages and disadvantages of SOFCs. [41,42]

Advantages

- They are not poisoned by carbon monoxide (CO); they are also sulfur-resistant.
- The high operating temperatures support effective fuel processing (internal reforming), therefore producing high quality byproduct heat for cogeneration uses and efficiencies up to 85%.
- They do not require expensive catalysts.
- There is less restriction on the cell's configuration because of its solid state character.
- Due to an all solid-state ceramic construction, it offers stability and reliability.

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[39] Directed Technologies, Inc., Contact: Brian D. James

[40] Website Source: http://www.fossil.energy.gov/programs/powersystems/fuelcells

[41] Website Source: http://www.netl.doe.gov.

[42] Website Source: http://www.seca.doe.gov.

Disadvantages

- There are strict restrictions on the raw materials due to the high operating temperature. The reason for this is to ensure chemical stability in the reduction-oxidation reactions, conductivities and thermochemical compatibility.
- There is a slow start-up time of about 1-4 hours to prevent component failure as a result of thermal shock.

Components

The materials for the components used in this case have been chosen based on the following criteria[43]:

- High electronic conductivity, about 100%
- Adequate chemical and structural stability at high temperatures during cell fabrication and operation
- Minimal reactivity among the cell components
- Matching thermal expansion among different cell components

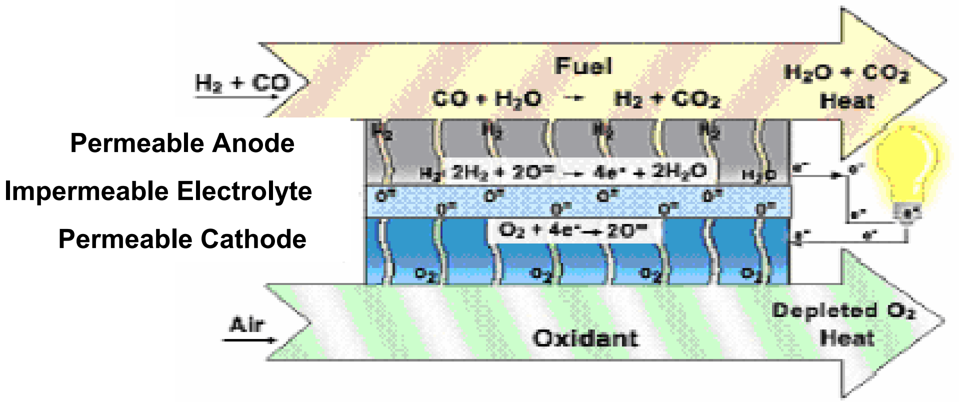

Figure 16: How a SOFC Works[44]

Figure 16 shows a diagram of the SOFC. There are four basic components for the SOFC – the anode, cathode, electrolyte, and interconnect. The anode is permeable to CO, CO_2, H_2, and H_2O while the cathode is permeable to O_2. The electrolyte allows O^{2-} ions to pass through it by ion diffusion yet it is impermeable to gas molecules.

Cathode

The cathode is the air electrode. It operates in an oxidizing environment of air or oxygen at about 1830°F and takes part in the oxygen reduction reaction:

$$O_2\,(g) + 4e^- \rightarrow 2O^{2-}\,(s)$$

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[43] Zhu, W. Z, Deevi S.C., *Development of Interconnect materials For Solid Oxide Fuel Cells*, MSEA A348, p228 -230

[44] Website Source: http://www.bu.edu/mfg/pdf/singhal.pdf

The oxygen in the air is reduced to its ions, thereby consuming four electrons in the process. The cathode must also have the following characteristics:

- porosity that permits the rapid transport of reactant and product gases, that is, the gas phase to the cathode/electrolyte interface.
- compatibility and minimal reactivity with the electrolyte and the side of the interconnection that the cathode comes in contact with.

Anode

The anode is the fuel electrode. The fuel gas containing hydrogen is passed over the anode and the oxygen ions migrate through the porous anode to oxidize the fuel. The electrons that are generated at the anode move out through the circuit, creating electricity. Note that one of the properties of the electrode is that it must have sufficient porosity to allow the transport of electrons. The reaction that takes place is as follows:

$$H_2\,(g) + O^{2-}(s) \rightarrow H_2O\,(g) + 2e^-$$
$$CO\,(g) + O^{2-}\,(s) \rightarrow CO_2\,(g) + 2e^-$$
$$CH_4\,(g) + 4O^{2-}(s) \rightarrow 2H_2O\,(g) + CO_2\,(g) + 8e^-$$

Electrolyte

The electrolyte is an oxygen ion-conducting component through which oxide ions (O^{2-}) migrate from the cathode to the anode where the ions will react with the fuel to generate an electrical voltage. The electrolyte must not have any porosity that permits gas to permeate from one side of the electrolyte layer to the other. It also has to be thin to minimize ohmic loss.[45]

Interconnect

The interconnect serves as the electric contact from the anode to the cathode. It protects the cathode from the reducing potential of the fuel on the anode side and prevents anode material from making contact with the oxidizing atmosphere of the cathode side.[46] The interconnection must have the following characteristics:

- low permeability for oxygen and hydrogen; this reduces the direct combination of oxidant and fuel.
- non-reactive to the anode.
- thermal expansion that is close to the cathode and electrolyte.

<u>Types of Configurations</u>

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[45] Fuel Cell Handbook, US Department of Energy, Morgantown, WV, 2002, Sections 5.1 -5.10

[46] Zhu, W. Z, Deevi S.C., Development of Interconnect materials For Solid Oxide Fuel Cells, MSEA A348, p228 -230

There are two major configurations for the solid oxide fuel cell: tubular and planar. Although the tubular configuration is more developed than the planar configuration, there has been increasing research being done on the latter.[47]

Tubular

The tubular SOFC design constructs the cell stack as a bundle of tubular electrode-electrolyte assemblies connected in series. The air is introduced to the interiors of the individual tubes while the fuel passes through the exteriors of the tubes to produce electricity. The major advantage to this design is that is alleviates the problem of using high temperature seals. Research has also shown that the stacks of tubular design have been operated over 100,000 hours and have shown little or no cell degradation. However, the long current path from the cell to the interconnect limits the performance of the cell. Examples of companies that make this design are Siemens Westinghouse Power Corporation and a few Japanese companies such as Mitsubishi Heavy Industries. Below is an illustration of a tubular SOFC design.

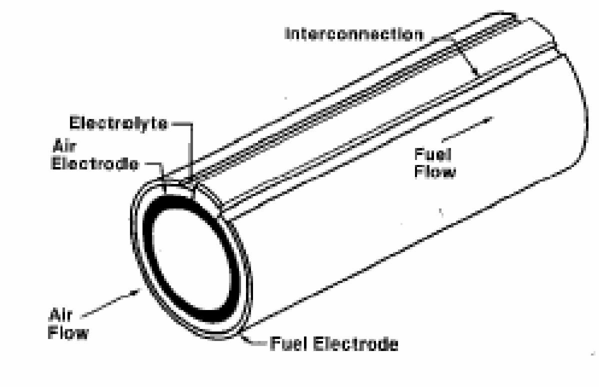

Figure 17a[48]
Figure 17a:Cross-section of the Tubular Design.

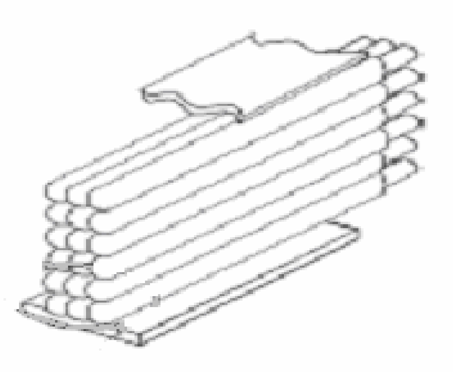

Figure 17b[49]
Figure 17b:Complete Stack Tubular Design.

Planar

The planar (also known as flat-plate) design is common for other fuel cell stacks such as PAFCs. The flat plates are bonded together in series to form electrode-electrolyte layers unlike the tubular design. The overall stack performance is improved since there is a lower ohmic resistance and higher power densities. The planar design is easier to manufacture and is about 25% cheaper to make.[50] The only disadvantage to this design is that high temperature seals are necessary. Examples of companies that use this concept are Ceramatec, Inc., General Electric, SOFCo, and AlliedSignal. Figure 18 is an illustration of the planar SOFC design.

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[47] J. Brouwer, Solid Oxide Fuel Cell Materials; Fuel Cell Catalyst Vol. 2, No.3, Spring 2002
[48] Fuel Cell Handbook, US Department of Energy, Morgantown, WV, 2002, Section 5.9
[49] Fuel Cell Handbook, US Department of Energy, Morgantown, WV, 2002, Section 5.10
[50] Website source: http://www.eyeforfuelcells.com

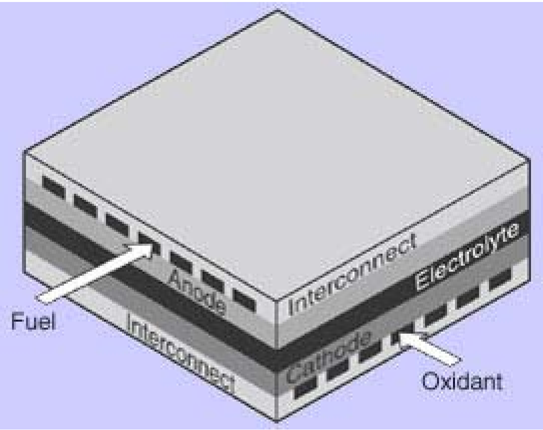

Figure 18: Planar Cell Design[51]

The OUFCC chose to produce planar SOFCs because they are an emerging technology which shows promise and they are cheaper to manufacture.

Raw Materials[52]

This section discusses in detail the various types of raw materials available for each component of the solid oxide fuel cell and these materials meet the requirements that were mentioned earlier. For this project, the powder forms of the materials will be purchased, however, the other forms have been listed for comparison purposes. The reason for purchasing the powder form of the materials is because they use improved and cheaper manufacturing processes such as tape-casting, which will be discussed later.

Electrolytes

Electrolyte materials can either be zirconia-based or ceria-based. The various types are listed next.

Zirconia Based Electrolytes

They are popular because of their high crystalline phase and chemical purity (99.9%) and their enhanced densification at lower sintering temperatures. They are operated ideally at a temperature range from 1470°F to 1830°F which is currently the standard temperature range for planar SOFCs. The two common types are listed below and the costs for each form of the electrolyte can be found in Appendix E.

- *Yttrium Stabilized Zirconia [(YSZ) or* $ZrO_2(Y_2O_3)$*]*

  YSZ is the most popular electrolyte material for solid oxide fuel cells because it conducts only oxygen ions over a wide range of oxygen partial pressures. YSZ is offered in three forms: tape cast powders, dispersed aqueous suspension, and spray coating formulation which is ideal for directly depositing thin YSZ films on substrates via ultrasonic spray coating.

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[51] Website source: http://www.cmc.llnl.gov/s-t/solid-oxide.html
[52] Website source: http://www.nextechmaterials.com

- *Scandium Stabilized Zirconia (ScZ)*

  ScZ is a ceramic electrolyte material with about three times the ionic conductivity of yttrium-stabilized zirconia. Thus, it can be used as an electrolyte for solid oxide fuel cells operating at lower temperatures (typically about 1470°F).

Ceria Based Electrolytes

These electrolytes have some advantages over zirconia-based electrolytes. They have notably higher conductivities at lower operating temperatures and are compatible with high performance cathode materials. However, these electrolytes work best at temperatures that are currently too low for most industrial sized SOFCs.[53] The use of ceria in SOFC anodes enhances the electro-catalytic activity and provides a pathway for internal reforming and/or direct utilization of fuel cells. The two common types are listed below. Appendix E shows the cost of materials for these two types of electrolytes.

- *Gadolinium-Doped Ceria (GDC-10)*

  Gadolinium-doped ceria ceramic electrolytes exhibit higher ionic conductivities than YSZ and can be used in solid oxide fuel cells. GDC-10 is an excellent SOFC electrolyte at temperatures below 1290°F. GDC-10 has been shown to enhance catalytic performance of SOFC cathodes and anodes. A particular advantage of this ceria product is that it can be sintered due to high density at temperatures between 2190-2370°F. GDC-10 is offered in three forms: nanopowders, ceramic grade powder and aqueous suspension.

- *Samarium Doped Ceria (SDC)*

  This electrolyte has similar properties as the GDC-10 electrolyte. SDC is offered in two forms: nanopowder and ceramic grade powder.

The OUFCC chose to use Yttrium Stabilized Zirconia for its electrolytes. This is because it is currently the most common material used for electrolytes, it is the cheapest, and it is readily available. It is also well known that YSZ can withstand the high temperatures required in SOFCs.

Cathodes

There are three types of materials that can be used for the cathode. Standard formulations include**:**

- Lanthanum strontium manganite [(LSM) or strontium doped $LaMnO_3$]
- Lanthanum strontium ferrite (LSF)
- Lanthanum strontium cobalt ferrite (LSCF)

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[53] Website source: http://www.osti.gov/bridge/product.biblio.jsp?osti_id=224951

The most commonly used is lanthanum strontium manganite (LSM). All of these electrode materials are available as screen printing inks that can be diluted for other methods of electrode deposition (e.g., spraying or dip coating or as powders). Materials such as LSCF and LSF can be used for SOFC systems operating at temperatures between 1290 -1470°F. Appendix E shows operating temperatures and costs for these cathode materials.

The OUFCC chose to use LSM for its cathodes. This is because it is the most common material used for cathodes, it is the cheapest, and it has also been found to be readily available.

Anodes

Anode materials are based on composite powder mixtures of nickel oxide (NiO) and an electrolyte, either GDC or YSZ. Appendix E shows the cost for these two materials in both powder and ink form.

The OUFCC chose to use a blend of nickel oxide and YSZ [Ni-$ZrO_2(Y_2O_3)$] for its anodes. This is because it is the cheapest and it is known to be sufficient for the use in SOFC anodes.

Interconnect

The most common material used for the interconnect is lanthanum chromite ($LaCrO_3$). This is an all-ceramic material that is ideal at temperatures of 1830°F. Metallic alloys are another option for the interconnect material. These could be chromium-based alloys or iron-based alloys. Appendix E compares the cost of all-ceramic and metallic alloy interconnects.

The OUFCC chose to use a chromium alloy as its interconnect material. This is because chromium alloys have been found to be able to withstand the high temperatures associated with SOFCs. They are also cheaper when compared to all-ceramic interconnect materials.

Raw Materials Breakdown

Table 13 shows a breakdown of the material inputs and the process material losses involved in manufacturing planar SOFCs. This information has been put in a spreadsheet[54] that calculates yearly raw material needs for different plant capacities.

Materials	Quantity (g/kW)
ZrO2(Y2O3)	4000
Doped LaMnO3	135
Ni-ZrO2(Y2O3)	154
Cr alloy	13413

Table 13: Material Inputs for the Manufacture of Planar SOFCs[55]

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[54] <u>File:</u> \\garfield\group1\Portfolios\Eric Daugherty\SOFC Materials

Manufacturing Process for SOFCs

Figure 19 is a generalized flowchart for our manufacturing process. There are four major components to solid oxide fuel cells: the anode, the electrolyte, the cathode and the interconnect. In this figure, the cathode-electrolyte-anode assembly is referred to as the PEN (positive-electrolyte-negative). The terms in this figure are described in more detail later in this section.

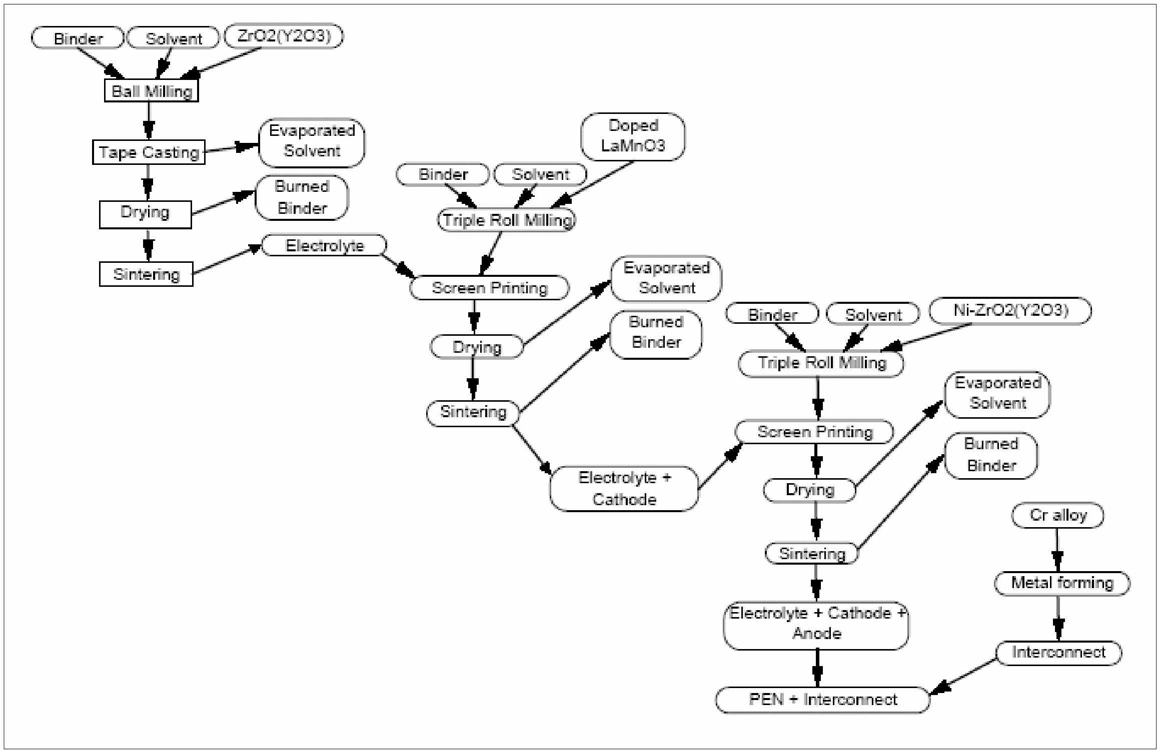

Figure 19: Process Flowchart for SOFCs[56]

Figure 19 shows that although there are many steps in the manufacturing process, several of the steps are the same for producing the electrolyte, anode, and cathode. The process can be broken down into four steps: preparing the electrolyte, preparing and attaching the cathode, preparing and attaching the anode, and preparing and attaching the interconnect.

The anode, electrolyte and cathode materials are prepared from their powder forms by milling methods known as ball milling and triple roll milling. These milling methods mix the ceramic powders with binders and solvents to produce a powder solution (or ink). Ball milling is a process that involves grinding and mixing material in a rotating cylinder mill partially filled with a tough grinding media such as metal balls. Ball mills can grind materials to colloidal fineness (approximately 1 micron and below). For the manufacture of SOFCs ball milling is specifically used to prepare the electrolyte ink. Figure 20 shows how a ball mill works.

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[55] Website Source: http://www.dti.gov.uk/energy/renewables/publications/pdfs/f100164.pdf
[56] Website Source: http://www.dti.gov.uk/energy/renewables/publications/pdfs/f100164.pdf

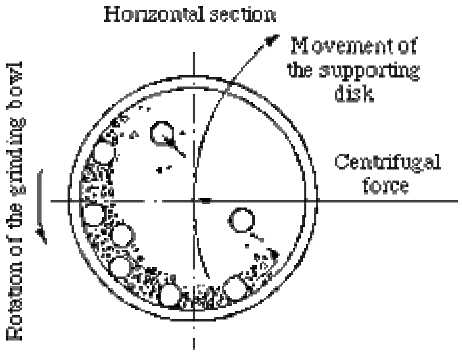

Figure 20: How a Ball Mill Works[57]

Triple roll milling is used to produce the cathode and anode inks. The powders are mixed with solvents and binders which are then passed through rolls that produce the inks by adjusting the distance between the rolls. With the inks prepared, they are then ready to be made into thin films.

After the electrolyte powder solution has been prepared, it undergoes a process known as tape casting. This is a shape forming technique for powder solutions which produces thin flat ceramic sheets. The powder solution is fed to a slip where a casting blade and a carrier film work together to produce a thin film. Varying the speed or the carrier film determines the thickness of the film. Figure 21 shows how tape casting works.

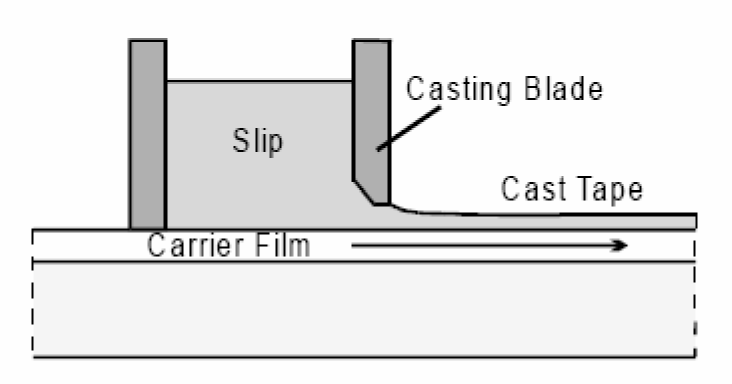

Figure 21: How Tape Casting Works[58]

The cathode and anode are made into thin films by screen printing. In screen printing, the inks are forced through a thin wire mesh and onto a substrate which in this case is the hardened electrolyte. Figure 22 shows how screen printing works.

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[57] Website Source: http://www.ilpi.com/inorganic/glassware/ballmill.html

[58] Website Source: http://www.keram.se/eng/pdf/tape_casting.pdf

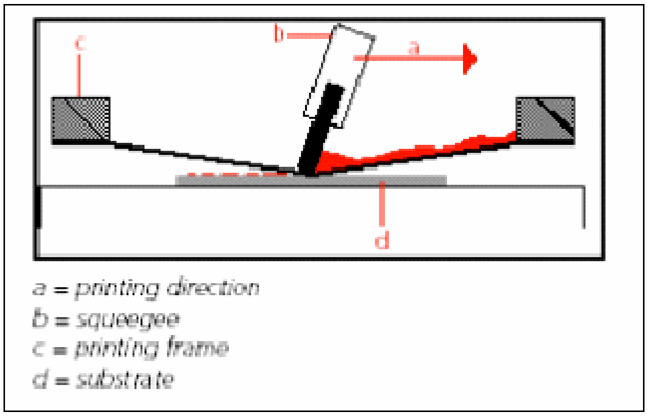

Figure 22: How Screen Printing Works[59]

From the tape-casting and screen printing processes, the anode, the cathode, and the electrolyte films are fused together in a series of processes known as drying and sintering. Drying occurs in a low temperature continuous furnace. In this process, most of the solvent in the ink is evaporated. After which, the sheets are heat-treated by a process known as sintering, which induces optimal strength. Sintering occurs in a controlled-atmospheric pressure furnace where films straight from drying are heated to a temperature close to, but not at, their melting point. For SOFCs, the furnace is kept at a temperature of approximately 1450^{o}C. A quality control check is done at this point to check the electrical layers that are being formed in the sinter. The checks also look for any leaks or dimension flaws. Through three steps of drying and sintering, a PEN is formed consisting of an electrolyte between an anode and a cathode.

Meanwhile, the interconnect components are being made by metal forming techniques such as roll forming or metal forming. Roll forming is a continuous metal forming process taking sheet, strip, or coiled stock and bending or forming it into shapes of essentially identical cross section by feeding the metal between successive pairs of rolls that increasingly shape it until the desired cross section is completed adding both strength and rigidity to lightweight materials. During the roll forming process, only bending occurs. The thickness of the metal is not changed except for a slight thinning of the material at the bend radius.

Finally, with the PEN and interconnect complete a brazing paint is applied to the pieces and then the pieces are brazed**.** Brazing is the joining of metals through the use of heat and a filler metal whose melting temperature is above 840°F (450°C) but below the melting point of the metals being joined.

Energy Inputs for the Manufacturing of SOFCs

Table 14 shows the energy inputs required to manufacture the PEN and interconnect for a SOFC. The "per fuel cell" total is based on producing 250 kW fuel cell units. This

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[59] Website Source: http://www.wpi.edu/Pubs/ETD/Available/etd-0428103-235205/unrestricted/hwoodward.pdf

information has been put in a spreadsheet[60] that calculates yearly energy needs for different plant capacities.

Process Step	**Equipment**	**Electricity Inputs per kW of FC electricity (MJ/kW)**	**Electricity Input per Fuel Cell (kW-hr/FC)**
Ball Milling	Ball Mill	0.3812	26.47
Tape Casting	Tape Casting Machine	0.0267	1.85
Drying	Low Temp Continuous Furnace	0.6823	47.38
Sintering	High Temp Furnace	4.2135	292.61
Preparation of Cathode Ink	Triple Roll Mill	0.0561	3.90
Screen Printing	Screen Printing Machine	0.0251	1.74
Drying	Low Temp Continuous Furnace	0.6823	47.38
Sintering	High Temp Furnace	3.4396	238.86
Preparation of Anode Ink	Triple Roll Mill	0.0593	4.12
Screen Printing	Screen Printing Machine	0.0251	1.74
Drying	Low Temp Continuous Furnace	0.6823	47.38
Sintering	High Temp Continuous Furnace	3.4396	238.86
Metal Interconnect	Metal Forming	0.1728	12.00
Total		13.8859	964

Table 14: Energy Inputs for the Manufacturing of the PEN and Interconnect[61]

Costs

The cost of raw materials was calculated to be approximately $1500/kW. This was found by combining the raw material requirements and the cost of raw materials. The energy cost depends on the capacity of the plant. Figure 22 shows the approximate percentages of process costs for manufacturing SOFCs. This includes labor, power, and raw materials. It can be seen that layer assembly is the most expensive aspect of the manufacturing process. This is because the high energy cost from sintering and the sintering furnace cost.

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[60] File: \\garfield\group1\Portfolios\Eric Daugherty\SOFC Energy

[61] Website Source: http://www.dti.gov.uk/energy/renewables/publications/pdfs/f100164.pdf

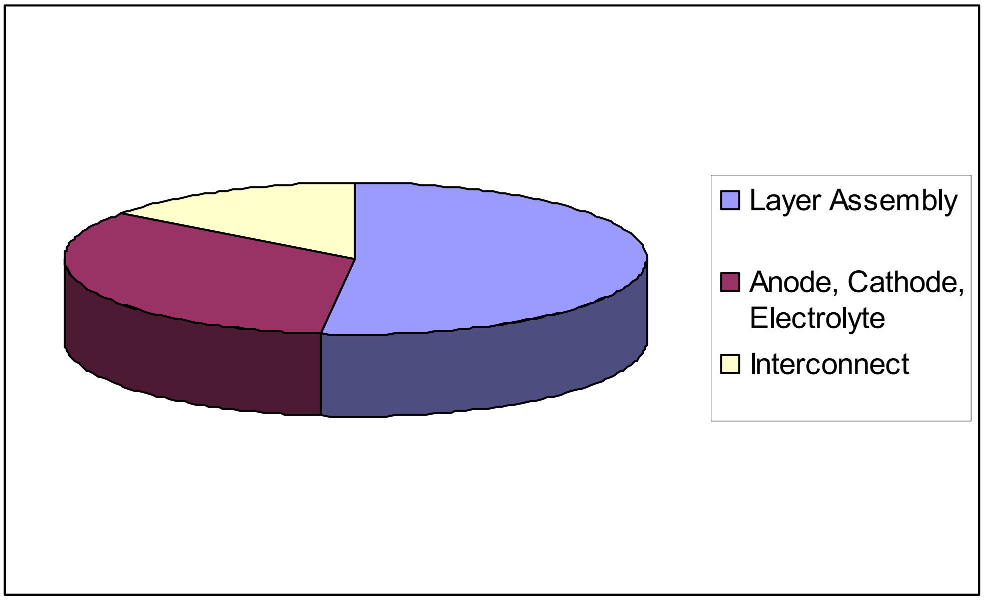

Figure 23: SOFC Process Cost Breakdown

The equipment costs involved in manufacturing SOFCs are described in a later section.

f. Other Components of the Fuel Cell Units[62]

Balance of Stack (BOS)

The balance of stack refers to components such as the reformer equipment, seals, manifolds, pressure vessels and the support structure. The estimates used for the total system cost were obtained from the National Energy Technology Laboratory (NETL), U.S. Department of Energy website. The BOS cost incorporated into each type of fuel cell was based on the types of BOS equipment necessary in each case (i.e. differences in reformer equipment).

Balance of Plant (BOP)

The balance of plant refers to supporting and/or auxiliary components based on the power source or site-specific requirements and integrated into a comprehensive power system package. These include:

- Turbine/Generator
- Grid Interface –Seals/Gaskets
- Controls
- Piping and Valves
- Power Conditioning

It was found that the BOP equipment costs approximately $600/kW. This cost was incorporated into the total system cost for each type of fuel cell.

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[62] Website Source: http://www.netl.doe.gov.

g. Reformers and Fuels

Most fuel cell operations use hydrogen to power the cells. In this section, different fuels and hydrogen sources are briefly discussed. This is followed by a presentation of issues surrounding the preparation of fuel for use with each of the three fuel cell types being considered by The OUFCC. While hydrogen is the most common fuel, there are direct methanol fuel cells which use a PEMFC with a modified anode catalyst to help increase the activity, but these cells have worse performance than traditional hydrogen powered PEMFCs due to fuel crossover from the anode to the cathode which reduces cell potential and the more complicated (and slower) methanol oxidation reaction[63]. Only hydrogen based fuel cells are considered for production by The OUFCC. There are numerous sources of hydrogen for fuel cell which are listed below:

- Hydrogen stored in tanks.
- Alcohols (Methanol, Ethanol)
- Gasoline and Diesel
- Natural Gas

Hydrogen stored in tanks[64]

Hydrogen can be produced in large quantities as an industrial by-product (solid waste pyrolysis), coal gasification, electrolysis of water powered by nuclear or renewable resources or through any of the possibilities suggested below. The hydrogen fuel considered here is not created at the fuel cell site. Instead, it is stored on site using tanks either highly compressed, in a chemical absorber or in a cryogenic liquid form. The Advantage of this form is the high purity of hydrogen removes the need for gas reforming before use in any of the fuel cells. In this case, the gas reforming is not the responsibility of the fuel cell user. Disadvantages of this method are safety hazards associated with storing such an explosive and corrosive gas, energy costs associated with either compression or cooling, and costs associated with purchasing hydrogen from a supplier rather producing the hydrogen in situ.

Alcohols (Methanol, Ethanol)[65]

Methanol and ethanol are much easier than hydrogen to store as liquids and have a higher energy density (energy that can be released per unit volume). Methanol can be produced from syngas (a product gas containing largely hydrogen and carbon monoxide) which can be produced from biomass (such as municipal waste or corn). Ethanol can be produced via fermentation of various agricultural products. Methanol and ethanol can be reformed to produce hydrogen in a manner similar to that of natural gas. As biological sources of energy become better developed with regards to infrastructure and production, methanol and ethanol will become more important sources of power.

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[63] Larminie J., & Dicks A., *Fuel Cell Systems Explained, 2nd Edition*,p.141-143
[64] Ibid p.279-286
[65] Ibid p.236-237

Petroleum (Gasoline)[66]

With its installed infrastructure and current use as a fuel, gasoline seems like an obvious choice for use in fuel cells. Availability, storage and popularity are in favor of gasoline as a fuel source. However, the additives and compositional complexity of current gasoline grades complicates their reformation into usable hydrogen leading to a higher expense than other production methods. If gasoline will be used in the future, its production methods will have to be changed to eliminate the additional process steps and simplify the composition.

Natural Gas

Natural gas is a combustible, gaseous mixture of simple hydrocarbon compounds, usually found in deep underground reservoirs formed by porous rock. It generally consists almost entirely of methane, but smaller amounts of other hydrocarbons such as ethane and propane are also present.[67] Natural gas also contains various quantities of nitrogen, carbon dioxide, sulfur (mostly in the form of hydrogen sulfide), heavier hydrocarbons (mainly chains with 6 or fewer carbons) and traces of other gases.[68] It has a very mature infrastructure (pipelines) and is both clean and widely available. While The OUFCC will tailor fuel cells to fit the needs of the customer and the fuels which are most accessible to them, it is anticipated that the majority of the fuel cell purchasers will use natural gas to supply their fuel cells.

h. Reforming Natural Gas

There are different mechanisms which may be employed to reform natural gas depending on the fuel cell for which it is intended. SOFCs are relatively flexible with respect to the qualities of the fuels they can use. Methane is reformed internally in the SOFC because of its high operating temperatures. The main reaction (in the absence of steam) is of the type[69]:

$$CH_4 + CO_2 \rightarrow 2CO + 2H_2$$

The CO_2 can come from a recycle stream of SOFC anode exhaust gas.

For PEMFCs and PAFCs, steam reforming reactors (similar to those used in ammonia synthesis) can react methane of the natural gas with water to produce hydrogen and carbon monoxide. This requires the addition of steam to the gas stream. An alternative to steam reforming is partial oxidation where methane is reacted with oxygen (usually from air) to form carbon monoxide and hydrogen. While partial oxidation has a smaller

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[66] Larminie J., & Dicks A., *Fuel Cell Systems Explained, 2nd Edition*, p 232-233

[67] Website source: http://www.energy.ca.gov/reports/500-02-040F/APPENDIX_VI_FUEL_VARIABILE.PDF p.8

[68] Website source: http://www.iangv.org/jaytech/files/IANGVGasCompositionStudyDecember2002 p. 11

[69] Larminie J., & Dicks A., *Fuel Cell Systems Explained, 2nd Edition,* p 243

capital cost than steam reformation (the addition of steam to the process stream increases required reactor sizes), it is less efficient since steam reforming can take advantage of heat produced by cogeneration[70]. The heat exchange network required to do this also adds to the capital cost of the fuel cell. In the steam reforming process, the following reactions take place over a nickel catalyst[71]: The reforming reaction (CH_4 to CO) is strongly endothermic and is run at temperatures around 800 °C.

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
$$CO + H_2O \rightarrow CO_2 + H_2$$

The second reaction is water gas shift which occurs to a slight degree in the steam reformer. At this point the content of the natural gas comes into play. The nickel catalyst and the PEMFC and PAFC anodes are highly susceptible to sulfur poisoning. Sulfur compounds must be removed from the gas feed before the steam reforming process can take place. A hydrodesulphurization (HDS) reactor is used to do this. In an HDS reactor, any organic sulfur-containing compounds are converted into hydrogen sulfide using a supported nickel-molybdenum oxide or cobalt-molybdenum oxide catalyst. These hydrogenolysis reactions are in the form:

$$(C_2H_5)_2S + 2H_2 \rightarrow 2C_2H_6 + H_2S$$

In the above reaction, the diethyl sulfide represents one of the many possible sources of sulfur in natural gas. The hydrogen sulfide that is formed from these reactions is then absorbed onto a bed of zinc oxide, forming zinc sulfide:

$$H_2S + ZnO \rightarrow ZnS + H_2O$$

This reaction occurs at a temperature of about 300 °C.

The PEMFC and PAFC catalysts are both sensitive to CO poisoning, which is formed as part of the steam reforming process. In order to reduce the CO to about 0.5%, stages of high temperature and low temperature water-gas shift reactions of the form must occur:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

These shift reactions usually employ an iron-chromium catalyst for high temperatures and a copper catalyst at low temperatures. The reasons for running the reaction in two steps are primarily economic. In order to drive the equilibrium towards the products side, more steam would have to be added which would increase the reactor size. Additionally, while the first reaction occurs quickly, it is equilibrium limited (thus limiting the CO removal) which is a problem traditionally overcome by following the reactor with the lower temperature reactor using the lower cost catalyst.

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[70] Mechanical Engineering Design 2003-Reform Thinking

[71] Larminie J., Dicks A., *Fuel Cell Systems Explained 2nd* p.241

Figure 24 shows a typical fuel processing system for a PAFC. For a PEMFC, a methanation unit would have to be added to further remove carbon monoxide because PEMFC cells are more sensitive to poisoning.

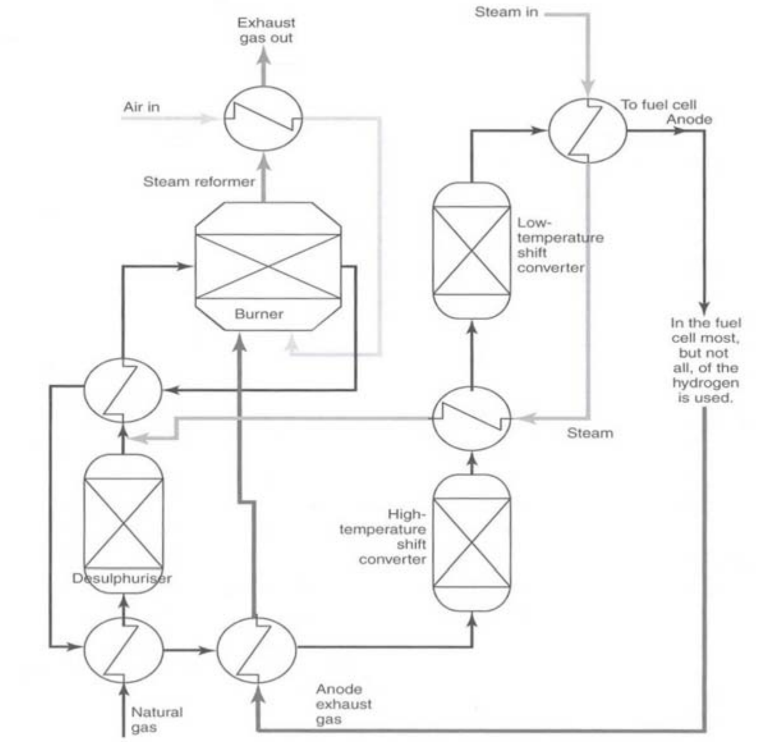

Figure 24: Fuel-processing System for a PAFC[72]

Fuel requirements for a 250 kW PEMFC

Mass Balance

This design may also be applied to the PAFC, although the PAFC will not require the methanation reactor since its catalyst is not as sensitive to carbon monoxide poisoning as PEMFCs. The SOFC is capable of direct internal reforming[73] and thus does not require additional reforming equipment other than a hydrodesulfurization unit.

Determination of Hydrogen Fuel Requirement of Fuel Cell

Using an efficiency (Lower Heating Value, LHV) of 40% for the PEMFC and the heat of combustion of hydrogen equal to –241.8 kJ/mol[74] calculate first the number of moles of hydrogen burned per hour to produce 250 kW of electrical power.

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[72] Larnimie J., & Dicks A., *Fuel Cell Systems Explained, 2nd Edition*, p 255

[73] Ibid p 247

[74] Ibid, p. 253

Starting with 1 Nm^3/hr (1 m^3/hr at Normal Temperature and Pressure, 20°C and 1 atm) of hydrogen, find the number of kg-moles per hour using ideal gas law:

$$n = \frac{\left(1\frac{m^3}{hr}\right)\cdot(101325\,Pa)}{(293K)\cdot\left(8{,}314\frac{J}{kmol\cdot K}\right)} = 0.0416\frac{kmol}{hr}\,\mathrm{H_2}$$

Next calculate the energy released per hour:

$$Q = 0.0416\frac{kmol}{hr} * 214.8\frac{kJ}{hr} * 1{,}000\frac{mol}{kmol} = 8{,}936\frac{kJ}{hr}$$

Or, in kilowatts:

$$Q = 8{,}936\frac{kJ}{hr} * \frac{hr}{s} = 2.48kW$$

Dividing the desired fuel cell power by this power gives:

$$\frac{250kW}{2.48kW} = 100.8$$

Which means the minimum input hydrogen flow rate needs to be 100.8 * 0.0416 *kmol/hr* or **4.19 kmol/hr**.

Determining Natural Gas Flow Rate Into Reformer

Assuming a gas composition of 95 mol% methane, 2 mol % heavier hydrocarbons, 1 mol % nitrogen, 1 mol % carbon dioxide, some oxygen and water and about 2 ppm sulfur compounds[75], flow rates of methane may be determined.

Methane

From the stochiometry of the steam reforming reactions (methane to carbon dioxide), there is a net gain of 4 hydrogen molecules from every methane molecule. Assuming 85 % conversion of methane, the methane flow rate may be calculated as:

$$\frac{4{,}190\,\mathrm{mol\,H_2}}{\mathrm{hr}} \times \frac{1\,\mathrm{CH_4}}{4\,\mathrm{H_2}} = \frac{1{,}048.4\,\mathrm{mol\,CH_4\ converted}}{\mathrm{hr}}$$

$$\frac{1{,}048.4\,\mathrm{mol\,CH_4\ converted}}{\mathrm{hr}} \times \frac{\mathrm{mol\,CH_4\ inlet}}{0.85\,\mathrm{mol\,CH_4\ converted}} = \frac{1{,}233.4\,\mathrm{mol\,CH_4\ inlet}}{\mathrm{hr}}$$

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[75] Website Source: www.copper.org/applications/fuelgas/ SoCal%20Gas%20Final%20Report.pdf

$$\frac{1{,}233.4\ \text{mol}\ \text{CH}_4\ \text{inlet}}{\text{hr}} \times \frac{\text{mol feed gas}}{0.95\ \text{mol}\ \text{CH}_4} = \frac{1{,}298.3\ \text{mol feed gas}}{\text{hr}}$$

In practice, additional feed gas is required to heat the burner. This can be crudely estimated by assuming that the natural gas is pure methane. The energy released from the combustion of methane is 843.56 Btu per mole. From the steam reformer design, the energy required to heat the reactor is 316800 Btu/hr which means about 375 moles an hour of natural gas (combined with fuel cell exhaust and outside air) needs to be combusted.

i. Hazard and Operability (HAZOP) Study

The purpose of a HAZOP study is to identify challenges associated with potential hazards and deviations of plant operation from design specifications. The first step in performing a HAZOP study is to define the scope and purpose of the study. The scope and purpose of this study is to examine the design and operation of a fuel cell manufacturing plant. The results of the study are presented in the following tables for the SOFC manufacturing process:

Guide Word	**Property**	**Possible Cause**	**Possible Consequence**	**Action Required**
More	Required particle size	1. Vendor provides wrong size materials	1. If particle size exceeds 1 micron, tape casting slip will not be formed correctly or machine and balls may be damaged.	1. Require a plant employee to inspect size of each new batch of materials to be added to the ball-mill.
No	Fastened bowl	2. Operator did not fasten bowl down.	2. When ball-mill is turned on, bowl will be tossed possibly damaging the machine.	2. Install safety feature on ball-mill where bowls must be fastened to turn machine on.
No	Cover lowered	3. Operator did not lower the ball-mill cover.	3. Everything in the machine may be thrown from the machine, possibly damaging the machine, bowls, and balls, and maybe harming nearby employees and equipment.	3. Install safety feature on ball-mill where cover must be lowered to turn machine on.

Part of	Components	4. One component is not added to the ball-mill mixture.	4. Product of the ball-milling process must be discarded, losing money for The OUFCC	4. Train plant employees in charge of ball-milling of correct component addition or require a plant employee to inspect each product batch from the ball-mill.
As well as	Components	5. Impure components	5. See Ball-Milling Process Consequence #4.	5. See Ball-Milling Process Action #4.

Table 15.1: Ball-Milling Process

Guide Word	**Property**	**Possible Cause**	**Possible Consequence**	**Action Required**
More	Required particle size	1. Particle size of components entering ball-mill was too large	1. Blade used in tape casting may be damaged, and the blade or entire unit may have to be replaced.	1. See Ball-Milling Process Action #1.
More	Tape thickness	2. Setting for thickness (blade position) on tape casting machine is too high.	2. If tape thickness exceeds 25 micrometers then drying may not occur in the next process step and drying will take a longer amount of time than scheduled, costing The OUFCC money and putting them behind production schedule.	2. Install an alarm on the tape casting machine so that thickness may not be set too high.
Less	Tape thickness	3. Setting for thickness (blade position) on tape casting machine is too low.	3. If tape thickness is less than 5 micrometers, this may cause more cracks in the subsequent drying process.	3. Install an alarm on the tape casting machine so that thickness may not be set too low.

Table 15.2: Tape Casting of the Electrolyte

Guide Word	**Property**	**Possible Cause**	**Possible Consequence**	**Action Required**
More	Tape thickness	1. Setting for thickness (blade position) on tape casting machine is too high.	1. See Tape Casting of the Electrolyte Process Consequence #2.	1. See Tape Casting of the Electrolyte Process Action #2.

Less	Tape thickness	2. Setting for thickness (blade position) on tape casting machine is too low.	2. See Tape Casting of the Electrolyte Process Consequence #3.	2. See Tape Casting of the Electrolyte Process Action #3.
More	Temperature	3. Temperature is manually or automatically set too high.	3. If the drying temperature exceeds the melting or boiling points of the solvent(s), the formation of bubbles may occur in the tape.	3. Install an alarm on the drying machine so that the temperature may not be set too high.
Less	Temperature	4. Temperature is manually or automatically set too low.	4. If the temperature is set too low, the tape may not completely dry or will take a longer amount of time to dry than scheduled, costing The OUFCC money and putting them behind production schedule.	4. Install an alarm on the drying machine so that the temperature may not be set too low.

Table 15.3: Drying of the Electrolyte

Guide Word	**Property**	**Possible Cause**	**Possible Consequence**	**Action Required**
More	Tape thickness	1. Setting for thickness (blade position) on tape casting machine is too high.	1. See Tape Casting of the Electrolyte Process Consequence #2 and a solid electrolyte is not formed in the sintering process therefore making the final product unusable.	1. See Tape Casting of the Electrolyte Process Action #2.
Less	Tape thickness	2. Setting for thickness (blade position) on tape casting machine is too low.	2. See Tape Casting of the Electrolyte Process Consequence #3 and a solid electrolyte is not formed in the sintering process therefore making the final product unusable.	2. See Tape Casting of the Electrolyte Process Action #3.
More	Temperature	3. Temperature is manually or automatically set too high.	3. Binder and plastisiser will be completely burned off, and the electrolyte may crack or be burned.	3. Install an alarm on the sintering machine so that the temperature may not be set too high.

Less	Temperature	4. Temperature is manually or automatically set too low.	4. Binder and plastisiser will not be completely burned off, thus sintering will take longer than scheduled, putting the entire process behind schedule.	4. Install an alarm on the sintering machine so that the temperature may not be set too low.

Table 15.4: Sintering of the Electrolyte

Guide Word	**Property**	**Possible Cause**	**Possible Consequence**	**Action Required**
More	Required cathode particle size	1. Particle size of cathode components is too large	1. Rollers used in roll-milling may be damaged, and the rollers or entire unit may have to be replaced.	1. Require a plant employee to inspect size of each new batch of cathode to be added to the roll-mill.
More	Ink thickness	2. Setting for thickness (roller position) on roll-mill is too high.	2. Ink may be too thick to use for screen printing.	2. Install an alarm on the roll-mill so that thickness may not be set too high.
Less	Ink thickness	3. Setting for thickness (roller position) on roll-mill is too low.	3. Ink may be too thin to use for screen printing.	3. Install an alarm on the roll-mill so that thickness may not be set too low.

Table 15.5: Preparation of Cathode Ink (Triple Roll Milling)

Guide Word	**Property**	**Possible Cause**	**Possible Consequence**	**Action**
More	Ink loaded onto machine	1. Operator error	1. Cathode ink on electrolyte will be too thick, causing delays in the drying step.	1. Train plant employees in charge of Screen Printing the Cathode to load the correct amount of ink.
Less	Ink loaded onto machine	2. Operator error	2. Cathode ink on electrolyte will be too thin, causing problems in the drying step.	2. Train plant employees in charge of Screen Printing the Cathode to load the correct amount of ink.
No	Cathode ink loaded	3. Operator error	3. Delays in the overall process or an electrolyte will be sent to the next step with no cathode layer.	3. Install an alarm on the printer that alerts the user that cathode ink is not loaded.
No	Electrolyte loaded	4. Operator error	4. Delays in the overall process or cathode ink will be wasted, costing The OUFCC money.	4. Install an alarm on the printer that alerts the user that the electrolyte is not

				loaded.

Table 15.6: Screen Printing the Cathode

Guide Word	Property	Possible Cause	Possible Consequence	Action Required
More	Temperature	1. Temperature is manually or automatically set too high.	1. If the drying temperature exceeds the boiling point of the cathode ink or exceeds the melting or boiling points of the solvent(s), the formation of bubbles may occur in the film.	1. Install an alarm on the drying machine so that the temperature may not be set too high.
Less	Temperature	2. Temperature is manually or automatically set too low.	2. If the temperature is set too low, the film may not completely dry or will take a longer amount of time to dry than scheduled, costing The OUFCC money and putting them behind production schedule.	2. Install an alarm on the drying machine so that the temperature may not be set too low.
More	Cathode ink thickness	3. Operator error in Screen Printing the Cathode Process	3. Drying will take a longer amount of time than scheduled, costing The OUFCC money and putting them behind production schedule.	3. See Screen Printing the Cathode Process Action #1.
Less	Cathode ink thickness	4. Operator error in Screen Printing the Cathode Process	4. May cause cracks in the cathode during the drying process.	4. See Screen Printing the Cathode Process Action #2.

Table 15.7: Drying of the Cathode onto the Electrolyte

Guide Word	Property	Possible Cause	Possible Consequence	Action Required
More	Temperature	1. Temperature is manually or automatically set too high.	1. Binder and plastisiser will be completely burned off, and the cathode or electrolyte may crack or be burned.	1. Install an alarm on the sintering machine so that the temperature may not be set too high.
Less	Temperature	2. Temperature is manually or automatically set too low.	2. Binder and plastisiser will not be completely burned off, thus sintering will take longer than scheduled,	2. Install an alarm on the sintering machine so that the temperature may

			putting the entire process behind schedule.	not be set too low.
More	Cathode ink thickness	3. Operator error in Screen Printing the Cathode Process	3. See Consequence #2.	3. See Screen Printing the Cathode Process Action #1.
Less	Cathode ink thickness	4. Operator error in Screen Printing the Cathode Process	4. See Consequence #1.	4. See Screen Printing the Cathode Process Action #2.

Table 15.8: Sintering of the Cathode onto the Electrolyte

Guide Word	Property	Possible Cause	Possible Consequence	Action Required
More	Required anode particle size	1. Particle size of anode components is too large	1. Rollers used in roll-milling may be damaged, and the rollers or entire unit may have to be replaced.	1. Require a plant employee to inspect size of each new batch of anode to be added to the roll-mill.
More	Ink thickness	2. Setting for thickness (roller position) on roll-mill is too high.	2. Ink may be too thick to use for screen printing.	2. Install an alarm on the roll-mill so that thickness may not be set too high.
Less	Ink thickness	3. Setting for thickness (roller position) on roll-mill is too low.	3. Ink may be too thin to use for screen printing.	3. Install an alarm on the roll-mill so that thickness may not be set too low.

Table 15.9: Preparation of the Anode Ink (Triple Roll Milling)

Guide Word	Property	Possible Cause	Possible Consequence	Action
More	Ink loaded onto machine	1. Operator error	1. Anode ink on electrolyte will be too thick, causing delays in the drying step.	1. Train plant employees in charge of Screen Printing the Anode to load the correct amount of ink.
Less	Ink loaded onto machine	2. Operator error	2. Anode ink on electrolyte will be too thin, causing problems in the drying step.	2. Train plant employees in charge of Screen Printing the Anode to load the correct amount of ink.

No	Anode ink loaded	3. Operator error	3. Delays in the overall process or an electrolyte will be sent to the next step with no anode layer.	3. Install an alarm on the printer that alerts the user that anode ink is not loaded.
No	Electrolyte loaded	4. Operator error	4. Delays in the overall process or anode ink will be wasted, costing The OUFCC money.	4. Install an alarm on the printer that alerts the user that the electrolyte is not loaded.

Table 15.10: Screen Printing the Anode

Guide Word	**Property**	**Possible Cause**	**Possible Consequence**	**Action Required**
More	Temperature	1. Temperature is manually or automatically set too high.	1. If the drying temperature exceeds the boiling point of the anode ink or exceeds the melting or boiling points of the solvent(s), the formation of bubbles may occur in the film.	1. Install an alarm on the drying machine so that the temperature may not be set too high.
Less	Temperature	2. Temperature is manually or automatically set too low.	2. If the temperature is set too low, the film may not completely dry or will take a longer amount of time to dry than scheduled, costing The OUFCC money and putting them behind production schedule.	2. Install an alarm on the drying machine so that the temperature may not be set too low.
More	Anode ink thickness	3. Operator error in Screen Printing the Anode Process	3. Drying will take a longer amount of time than scheduled, costing The OUFCC money and putting them behind production schedule.	3. See Screen Printing the Anode Process Action #1.
Less	Anode ink thickness	4. Operator error in Screen Printing the Anode Process	4. May cause cracks in the anode during the drying process.	4. See Screen Printing the Anode Process Action #2.

Table 15.11: Drying of the Anode onto the Electrolyte

Guide Word	**Property**	**Possible Cause**	**Possible Consequence**	**Action Required**
More	Temperature	1. Temperature is manually or automatically set too high.	1. Binder and plastisiser will be completely burned off, and the cathode, anode or	1. Install an alarm on the sintering machine so that the

			electrolyte may crack or be burned.	temperature may not be set too high.
Less	Temperature	2. Temperature is manually or automatically set too low.	2. Binder and plastisiser will not be completely burned off, thus sintering will take longer than scheduled, putting the entire process behind schedule.	2. Install an alarm on the sintering machine so that the temperature may not be set too low.
More	Anode ink thickness	3. Operator error in Screen Printing the Anode Process	3. See Consequence #2.	3. See Screen Printing the Anode Process Action #1.
Less	Anode ink thickness	4. Operator error in Screen Printing the Anode Process	4. See Consequence #1.	4. See Screen Printing the Anode Process Action #2.

Table 15.12: Sintering of the Anode onto the Electrolyte

Guide Word	**Property**	**Possible Cause**	**Possible Consequence**	**Action Required**
More	Anode ink or cathode ink thickness	1. Operator error in Screen Printing the Anode Process or operator error in Screen Printing the Cathode Process	1. Cathode or anode did not completely dry, thus will not shape correctly.	1. See Screen Printing the Anode Process Action #1 or see Screen Printing the Cathode Process Action #1.
Less	Anode ink or cathode ink thickness	2. Operator error in Screen Printing the Anode Process or operator error in Screen Printing the Cathode Process	2. Cathode or anode is cracked or brittle, and may break when shaped.	2. See Screen Printing the Anode Process Action #2 or see Screen Printing the Cathode Process Action #2.

Table 15.13: Metal Forming Interconnect

For the PAFC manufacturing process, all of the steps closely resemble those of the SOFC, although with different components and in a different order. The following table shows the manufacturing steps for a PAFC and the corresponding SOFC process that shows the causes and consequences for the step:

PAFC Process	**Corresponding SOFC Process**
Shear Mixing	Ball-Milling Process (without balls)
Constant Volume Displacement Distillation and	Sintering

Viscosity Reduction	
Electrode Coating	Triple Roll Milling
Drying	Drying
Electrolyte Preparation	Screen Printing
“Injection” Molding of Bi-Polar Plates	Metal Forming Interconnect

Table 15.14: PAFC Processes

For the PEMFC manufacturing process, again, all of the steps closely resemble those of the SOFC, as illustrated in the following table:

PEMFC Process	Corresponding SOFC Process
Shear Mixing	Ball-Milling Process (without balls)
Constant Volume Displacement Distillation	Sintering
Screen Printing	Screen Printing
Drying	Drying
Die Cutting	Metal Forming Interconnect
Pressing	Triple Roll Milling
Die Cutting	Metal Forming Interconnect

Table 15.15: PEMFC Processes

Therefore, for each PAFC and PEMFC process, the possible safety actions that should be taken correspond to those detailed for the SOFC process.

The OUFCC is committed to operating its manufacturing facility operates under safe conditions at all times. The parameters investigated above were chosen because these would cause the most detrimental effects in our finished product and result in the most dangerous situation for our employees. Material Safety Data Sheets (MSDS) will be available near the operating area. Furthermore, all employees will be required to attend biweekly safety meetings where the dangers of the working environment and preventative methods will be reiterated. A thorough HAZOP meeting including all engineers and plant employees will be conducted every two years to ensure the safety of all employees and the community surrounding the plant**.**

IV. FINANCIAL ANALYSIS

a. Equipment Costs

The equipment costs were generated from the National Energy Technology Laboratory database.[76]The machinery listed below is for the manufacturing process for the three types of fuel cells. We assumed that will be making about 1000 “250 kW” fuel cells a year. Table 25 below shows a list of the machinery and their costs for each fuel cell type.

Process Description	Component	Equipment Description	Equipment Cost	Tool Cost
Automated Tape Casting	Anode, Cathode, Electrolyte	Tape Caster	$300,000	n/a
Vacuum Leak Test	Fabrication	Inspection Machine	$300,000	n/a

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[76] <u>Website source:</u> www.netl.doe.gov

Finishing Edges		Blanchard Grinder	$300,000	$2,000
IC Forming Step	Interconnect	Metal Forming	$130,000	$12,100
IC Shear	Interconnect	Shear + flying Die	$55,000	$15,000
IC joining -Paint	Interconnect	Paint Gun	$10,000	n/a
IC joining -Heat Treatment	Interconnect	Brazing Furnace	$400,000	n/a
Stack Calendar		Press + Heating Dies	$20,000	$15,000
Roll Calendar	Interconnect	Roll Calendar	$60,000	n/a
Blanking/Slicing	Fabrication	Press + Heating Dies	$150,000	$30,000
Continuous Sinter	Fabrication	Sintering Furnace	$500,000	n/a
Weigh Powders	Anode, Cathode, Electrolyte	Weigh Scales	$5,000	n/a
Ball Milling	Anode, Cathode, Electrolyte	Ball Mills	$22,000	n/a
Air Classification	Fabrication	Air Classifier	$100,000	n/a
SUBTOTAL			$2,352,000	$74,100
TOTAL			**$2,426,100**	

Table 16: Cost Break-down for Machinery in SOFC Manufacturing Process

Process Description	**Equipment Description**	**Number Needed**	**Equipment Cost**	**Tool Cost**
Drying	Tunnel Dryers	1	$45,000	n/a
Distillation & Collection	Condensers	2	$7,000	n/a
Distillation & Collection	Flasks	2	$7,000	n/a
Vacuum Leak Test	Inspection Machine	1	$300,000	n/a
Weigh Powder	Weigh Scales	1	$5,000	n/a
Air Classification	Air Classifier	1	$100,000	n/a
Blanking/Slicing	Press + Heating Dies	1	$150,000	$30,000
SUBTOTAL			$614,000	$30,000
TOTAL			**$644,000**	

Table 17: Cost Break-down for Machinery in PEMFC Manufacturing Process

Process Description	**Equipment Description**	**Number Needed**	**Equipment Cost**
Drying	Tunnel Dryers	1	$45,000
Distillation & Collection	Condensers	2	$7,000
Distillation & Collection	Flasks	2	$7,000
Vacuum Leak Test	Inspection Machine	1	$300,000
Air Classification	Air Classifier	1	$100,000
SUBTOTAL			$459,000
TOTAL			**$918,000**

Table 18: Cost Break-down for Machinery in PAFC Manufacturing Process

b. Reformer Costs

The OUFCC has decided to purchase gas reformers from separate suppliers, rather than produce them in-house. While producing the gas reformer units at the fuel production facility would potentially reduce costs since The OUFCC would not have to pay for the supplier's fixed costs or for their profit margins. However, this would also require additional facilities to collect and process the reformer catalyst and additional production lines, which in turn, require additional capital investment. Individual reactor costs are estimated in appendix F. The OUFCC identified two potential gas reformer suppliers on both the east and west coasts of the United States.

Ztek Corporation (www.ztekcorp.com) is located on the east coast and are currently developing a commercial reformer which can run on gasoline or natural gas which produces 4000 standard cubic feet (SCF) per hour of hydrogen, which is sufficient to power a 250 kW fuel cell. On the west coast, The OUFCC will partner with ChevronTexaco[77] to apply their Helias gas reformer technology to our fuel cells. Based upon a quick scale up of the Osaka Gas Company's gas reformer cost[78] and another gas reformer setup[79], the estimated gas reformer cost is about $125,000. The cost for the components estimated in appendix F came to about $200,000, with the furnace taking up the majority of the cost, although heat integration costs were not included and could add about another $10,000. Costs for facilities to produce in house gas reformers were not calculated.

c. Labor Costs

Thirteen states were chosen for further analysis based on the origin of our raw materials, our possible market locations, low tax rates and low labor costs. These states were analyzed further using a mathematical model to determine the location of the OUFCC plant.

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[77] Website Source: http://www.chevrontexaco.com/technologyventures/commercialize_tech/fuel_processing.asp

[78] Website Source: http://www.osakagas.co.jp/rd/sheet/136e.pdf

[79] Website Source: http://www.memagazine.org/medes03/refmthnk/refmthnk.html

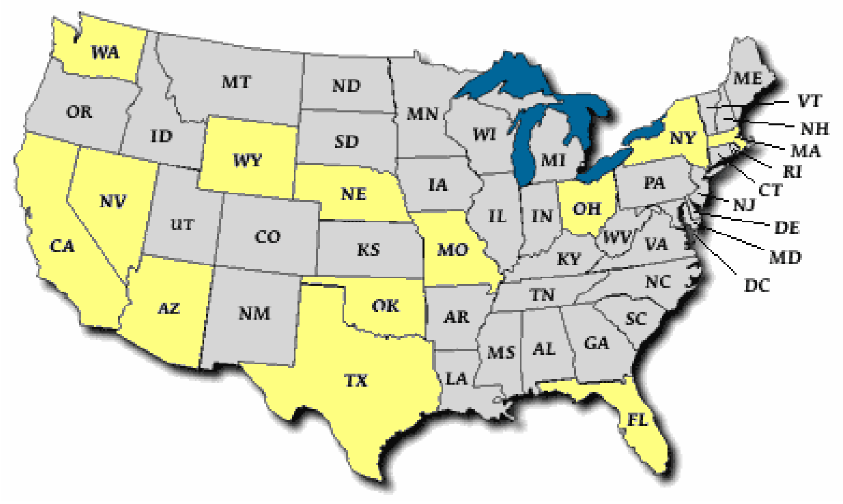

Figure 25: Potential Plant Locations Highlighted in Yellow

In order to have a location with a low cost of labor, median hourly wages per state were used as the labor data input into the mathematical model.

State	Median Hourly Wage ($)
CA	14.68
NY	15.32
FL	11.80
AZ	12.58
OK	11.24
TX	12.32
WA	15.31
NE	11.90
NV	12.66
WY	12.07
OH	13.36
MO	12.50
MA	15.94

Table 19: Median Hourly Wages for Potential Plant Locations[80]

The plant will be located in Wyoming. Labor costs for this location are as follows:

OUFCC Employee Position	# of Employees	Wage / yr ($)	Total wage / yr ($)
Chief Executive	1	125,240	125,240
General Operations Manager	1	76,110	76,110
Sales Manager	1	82,050	82,050
Marketing Manager	1	81,140	81,140
Computer & Information Systems Manager	1	87,280	87,280
Engineering Manager	1	95,650	95,650

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[80] Website Source: http://bls.gov/oes/2002/oessrcst.htm

Transportation, Storage & Distribution Manager	1	63,710	63,710
Financial Manager	1	79,960	79,960
First Line Supervisor (Mechanics, Installers & Repairers)	3	47,070	141,210
Sales Representative	1	60,330	60,330
Advertising Sales Agent	1	48,060	48,060
Computer Programmer	1	69,510	69,510
First Line Supervisor (Transportation, machine & vehicle operators))	3	44,880	134,640
Accountant	1	51,850	51,850
Mechanical Engineer	1	71,250	71,250
Chemical Engineer	2	78,500	157,000
Computer Software Engineer	1	71,250	71,250
Lawyer	1	115,680	115,680
Receptionist & Information Clerk	1	21,260	21,620
Chemical Equipment Operators & Tenders	2	45,220	90,440
Team Assemblers	30	20,780	207,800
Maintenance Worker (Machinery)	15	29,750	446,250
		Total	***$ 2,378,030***

Table 20: OUFCC Employees and Annual Wages[81]

d. Taxes

In order to have a location with low tax rates, corporate tax rates as well as state sales tax were used as the tax data input into the mathematical model.

State	Corporate Tax Rate as % of Income	% Sales Tax
CA	8.84	7.25
NY	7.5	4
FL	5.5	6
AZ	6.97	5.6
OK	6.0	4.5
TX	none	6.25
WA	none	6.5
NE	7.81	5.5
NV	none	6.5
WY	none	4
OH	8.5	6

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[81] Website source: http://bls.gov/oes/2002/oessrcst.htm

MO	6.25	4.225
MA	9.5	5

Table 21: Tax Rates for Potential Plant Locations

There will be no yearly corporate tax costs due to the fact that the plant location will be in Wyoming. The property taxes that will incur on The OUFCC will be 11.5% of the market value of our land and building, multiplied by the average mill levy number of .069539.[82] The federal income tax paid each year will be 35% of The OUFCC's income for that year.[83]

e. Delivery of Product

The fuel cells will be supplied to all markets in the continental United States by ground transportation. Two options were taken into account when calculating transportation costs: contracting the American Freight Company or The OUFCC purchasing its own fleet. For either option, the federal regulations for cargo dimensions and weight must be met. There are no length limitations for interstates or highways. The width limitation is 2.6m (8.5ft), but may be extended to 16ft with a permit. The height limitation is 4.1m (13.5ft), but may be extended to 18ft with a permit (truck and load). Permits are approximately (for a fleet) $1,500 annually, plus $25 per vehicle to be permitted, but for the size of the product that The OUFCC manufactures, these permits will not be needed.[84]

If a company is contracted, then the company responsible for all ground transportation is the American Freight Company[85] who has agreed to ship based upon the following charges and conditions:

- The OUFCC is responsible for packing, crating, and addressing the shipments.
- The freight company will charge $1.45 per mile traveled (miles obtained from Table B-4).
- There will be a large city surcharge of $100 for each shipment.
- A flat fee of $668 will be charged for each delivery, and will cover insurance, pick-up and delivery.

The possibility of The OUFCC purchasing its own fleet of trucks was also analyzed. A new chassis of the size needed to haul a fuel cell costs approximately $49,950, and a flatbed trailer costs approximately $5000[86]. It is assumed that during the time of highest production (year 10) approximately 6 fuel cells will be produced each day. Only one fuel cell may be shipped on each truck, and an average delivery time (from plant location to the market location then back to the plant location) is approximately 4 days. Therefore, a fleet of about 24 trucks and 48 drivers will be needed. Assuming an average salary for a trained truck driver is $40,000,[87] the fleet, including personnel, would cost $20,518,800 for a ten year period. The price of diesel is approximately $1.15 per gallon, and the

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[82] \\garfield\group1\PROJECT FINAL REPORT\References\Taxes.htm
[83] \\garfield\group1\PROJECT FINAL REPORT\References\2003 Federal Income Tax Rates.htm
[84] Website Source: http://www.access.gpo.gov/cgi-bin/cfrassemble.cgi?title=200323
[85] Website source: www.freightcenter.com
[86] Website source: www.dieseltrucksales.net
[87] Website source: www.freightcompanyresource.com

average Mack truck gets 9 miles per gallon of diesel. Assuming an average distance of 1,300 miles (from plant to market and back to plant) and a total of 12,355 fuel cells being shipped over 10 years, the approximate cost for diesel gasoline over the ten year period is $2,052,300.

The following factors must also be taken into account when costs for a fleet are calculated[88]:

- License- $650 annually per truck
- Tires- $141.67 annually per truck
- Insurance- $375 annually per truck
- Maintenance- $1,800 annually per truck

Taking all of these costs into consideration, the cost over ten years of The OUFCC employing its own fleet is approximately $23,283,100.

If the quote from American Freight Company is analyzed over a ten year period, the total cost to The OUFCC (estimating an average distance of 1,300 miles per delivery and a total of 12,355 fuel cells delivered over a 10 year period) is $32,777,800.

Therefore, it is a better business decision for The OUFCC to employ its own fleet of 24 trucks. If this charge is distributed over each fuel cell, the resulting transportation cost is $1880 per fuel cell.

f. Federal Regulations[89]

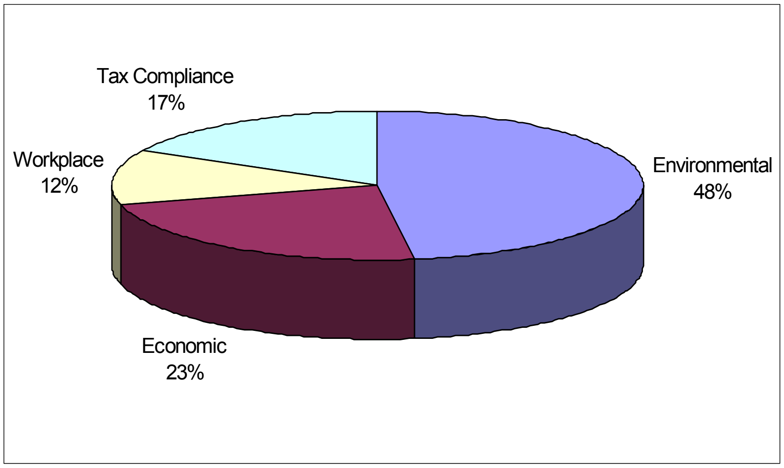

Figure 26: Breakdown of Cost of Federal Regulations

Since The OUFCC employs 71 people, the cost of workplace, environmental and economic federal regulations will be approximately $7,000 per employee, or a total of $497,000.

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[88] Website source: www.omeda.org

[89] Website source: www.sba.gov/advo/research/rs207.pdf

g. Means and Cost of Advertising

The OUFCC's fuel cells will be advertised by means of advertisements placed in scientific journals, government endorsements, participation (including demonstrations) in various conferences, by hiring a team of 2 salesmen, and finally by television advertisements. All methods of advertisement will be ongoing, except that of television. Television ads will be placed during the three months prior to the fuel cells being publicly available for purchase and the three months after. After this six month television campaign, word-of-mouth and The OUFCC's reputation will be relied upon for advertising. Approximately $2,000,000 will be allocated for this advertising strategy.

h. Economic Analysis (TCI, NPW, ROI)

The following results were attained with the use of a mathematical model called General Algebraic Mathematical Software (GAMS). The specifics of this model will be discussed in further detail in the next section.

The model decided that the plant location for The OUFCC should be **Cheyenne, Wyoming.** The plant will also be built in 2005 and production of fuel cells will begin in 2006. The total capital investment for the first year of production is about **$41.2 million**, which is very reasonable. The net present worth over 10 years for The OUFCC was determined to be **$83.2 million**

ITEM	Amount
Fixed Capital Investment	$35.8 million
Total Capital Investment	$41.2 million
Net Present Worth	$83.2 million

Table 22: Economic Results

The number of PAFCs and PEMFCs that are sold each year remains constant, however, the SOFC sales gradually increase. In order to make this process a worthwhile venture, the model decided to build only SOFCs since it requires the most expensive machinery and has the lowest raw materials costs. Figure 27 below illustrates the number of fuel cells sold over the project lifetime.

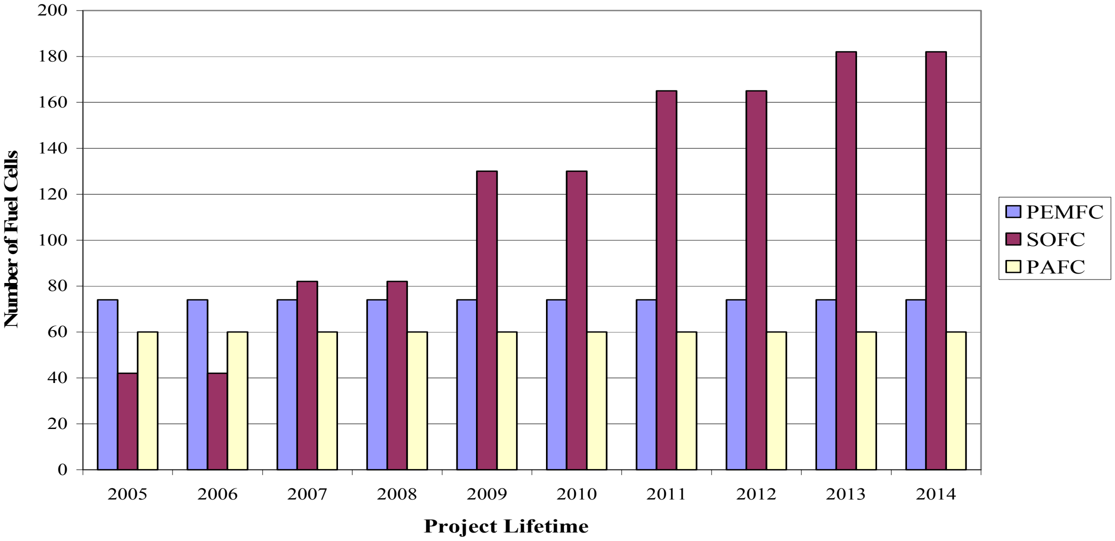

Figure 27: Project Sales for Fuel Cells

The selling prices for the three types of fuel cells were also varied over the ten year period. This is to take into account the competition we expect to have from other fuel cell companies and also, better technology that will drive the expensive cost of fuel cells down. Figure 28 shows the varying selling prices for PEMFC, PAFC and SOFC.

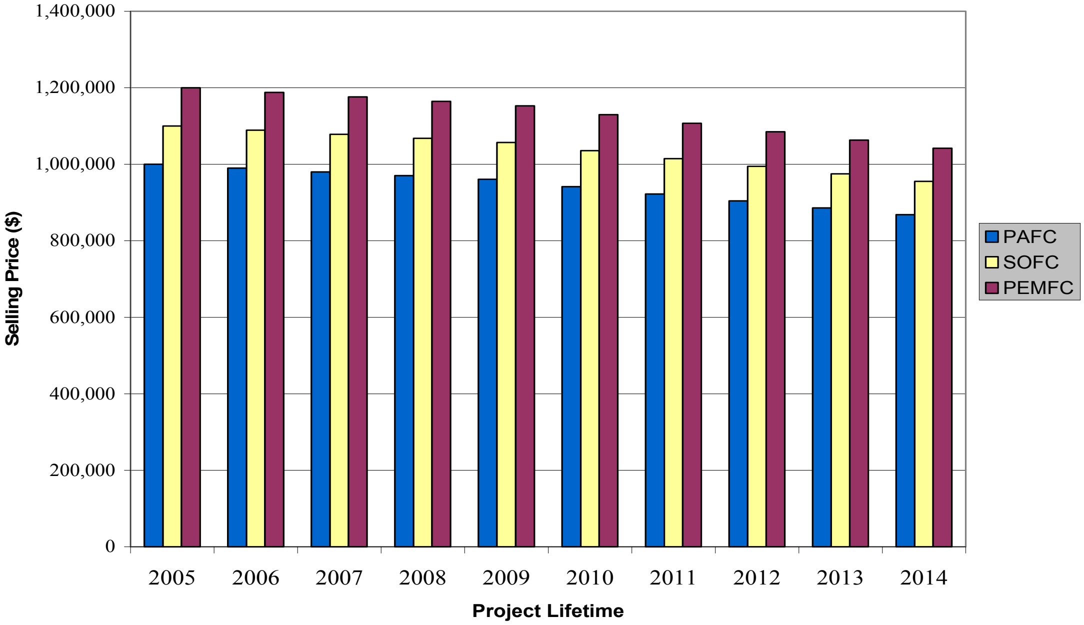

Figure 28: Selling Prices of Fuel Cells

The revenue for the project varies over the years and this might be as a result of the varying number of fuel cells that are being produced each year. It peaks in year 2010, and this is when we reach our market demand. Figure 29 below illustrates this trend.

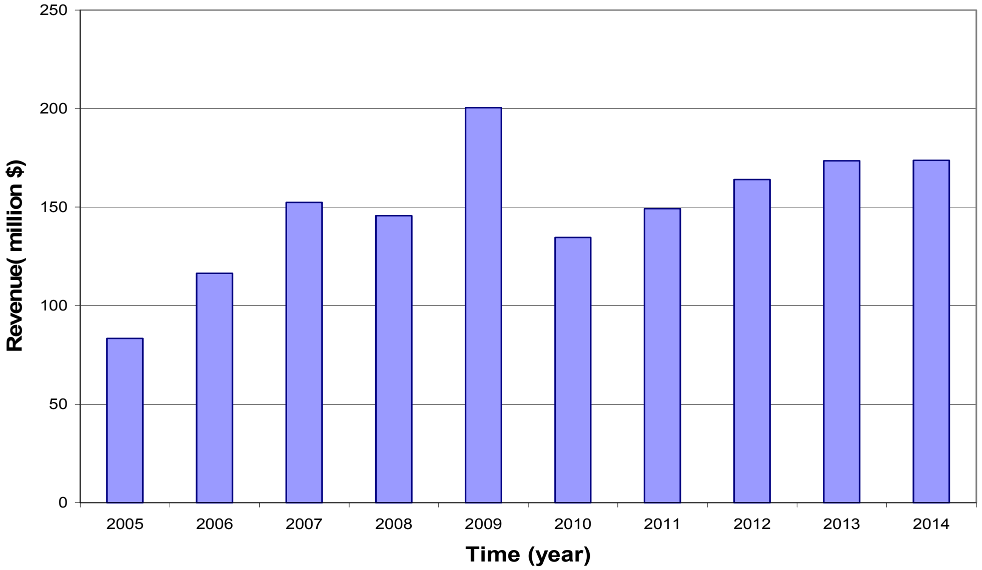

Figure 29: Revenue over 10 years

The cashflow for The OUFCC is fluctuating over the project lifetime and this might be as due to the varying revenue. The cash flow also peaks in year 2009 which is directly to the increase in revenue for that particular year. Figure 30 illustrates the cash flow trend.

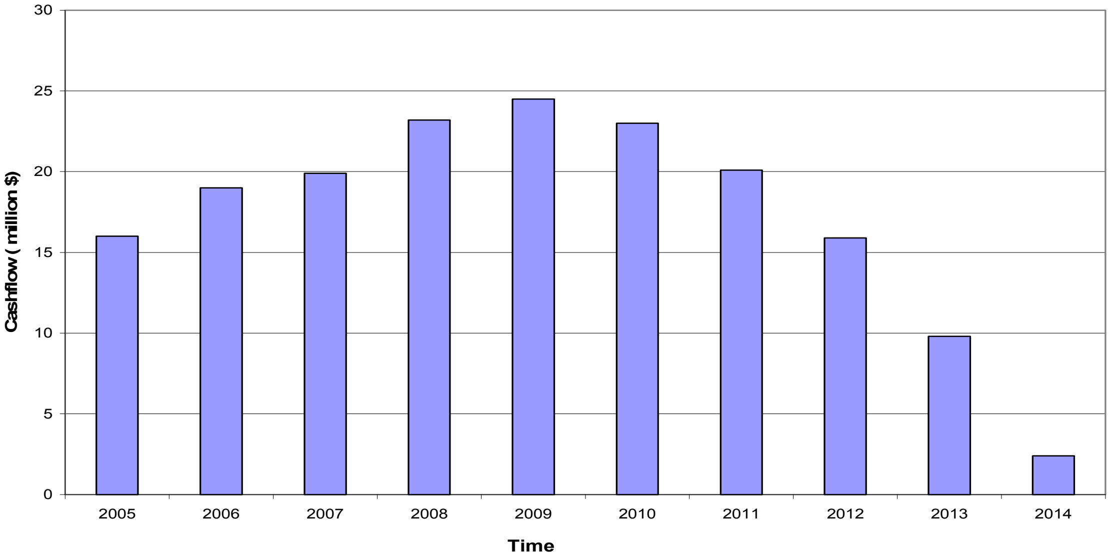

Figure 30: Cashflow over 10 years

By year 2007, we expect to repay any loans that were used in our total capital investment. The reason why it will take about 2 years is due to the selling prices of our fuel cells. Figure 31 shows the break-even point of our process.

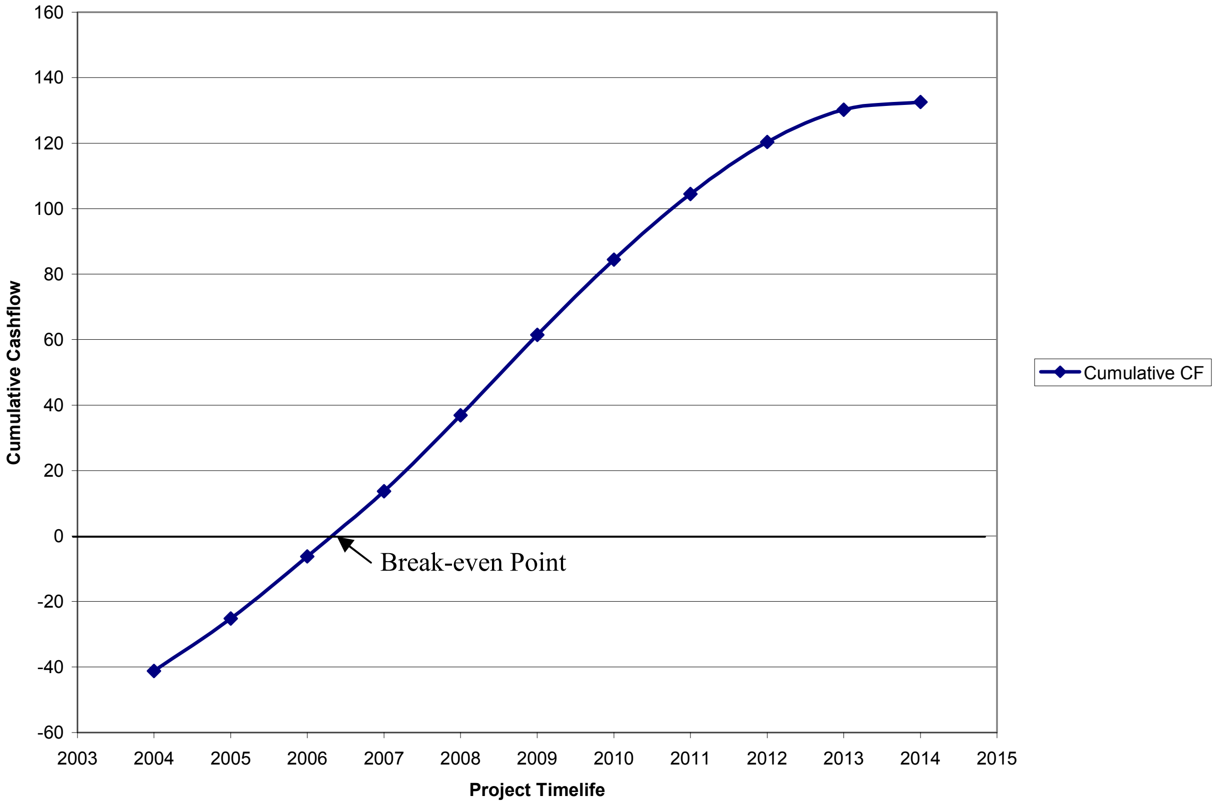

Figure 31: Breakeven Chart

i. Risk and Uncertainty

Any business venture, especially one that includes a new technology, has an associated risk and uncertainty. Stochastic Optimization Modeling can be used to maximize the expected value of the net present worth over all possible realizations of uncertain parameters. The uncertain parameters included in this risk analysis are: the selling price of each fuel cell, raw material costs, equipment costs, electricity, and capacity, which is a function of the market demand. Three different scenarios were created and the risks associated with each situation were examined. The following table gives a clear depiction of the three scenarios that were analyzed.

Scenario	Description
“Best Case”	High selling price and low raw material costs
Standard	Standard selling price and raw material costs
“Worst Case”	Low selling price and high raw material costs

Table 23: Scenario Description used for Risk Analysis

For each scenario, the selling price was fixed, while the raw material costs, electricity costs and capacity, were varied 20% around the mean value. *Excel* was used to obtain random numbers for each scenario. The random numbers were inputted into the Stochastic Model created in *GAMS*. Two different methods were used to examine the associated risks: *Crystal Ball* and *Stochastic Modeling*. Figure 32, below, are the risk curves generated using *Crystal Ball.*

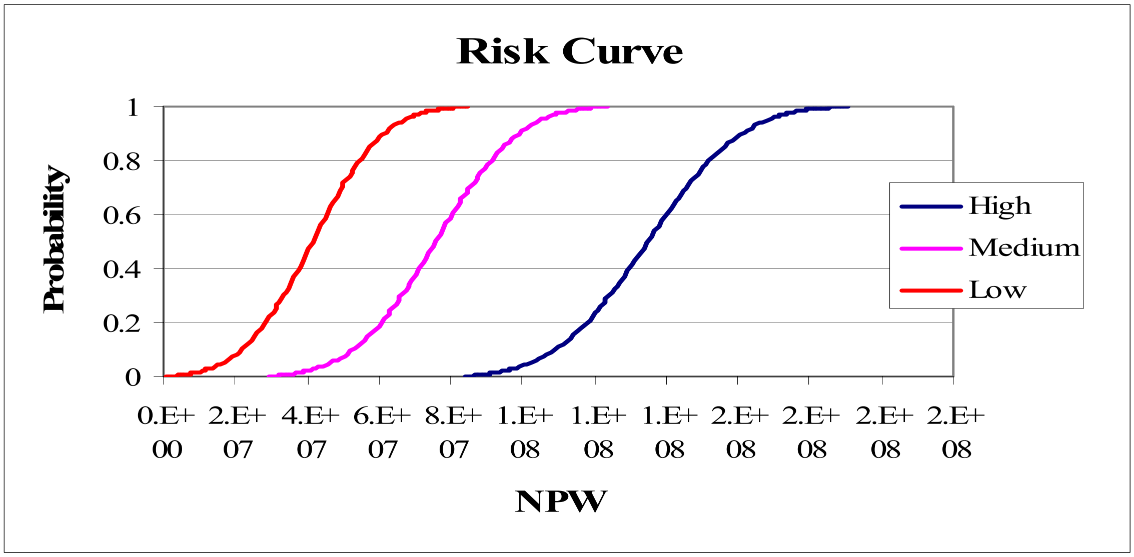

Figure 32: Risk Curve using Crystal Ball

From Figure 32, the following conclusions can be drawn. These conclusions can be seen in Table 24.

Scenario	Associated Risk	Possible Money Lost/Gained
"Best Case"	0	$85,000,000 gained
Standard	0	$30,000,000 gained
"Worst Case"	0	No money lost or gained

Table 24: Results from Risk Curve

Figure 33, below, is the risk curve generated in GAMS using Stochastic modeling. This Figure shows only the best of the 10 scenarios that were examined. This curve is very similar to the "medium", or standard, curve seen in Figure 32 above. Like the curve above, it can be seen that there is no risk associated with the curve generated using Stochastic modeling.

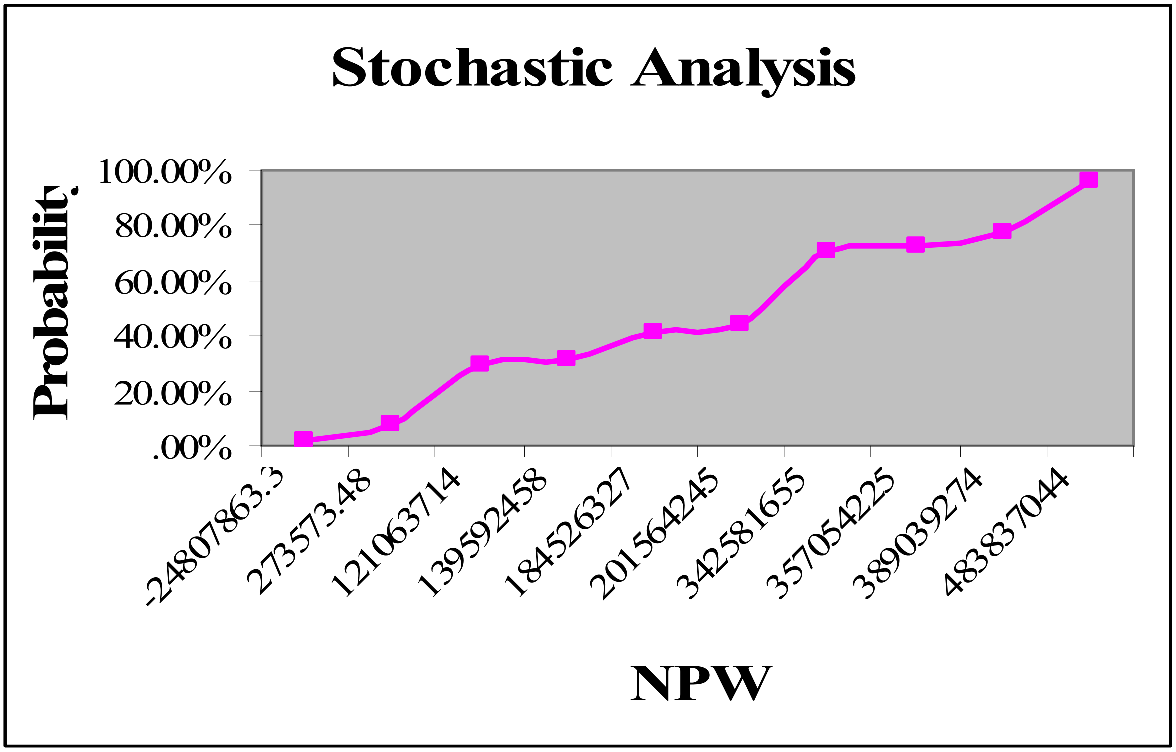

Figure 33: Stochastic Analysis

V. MATHEMATICAL MODEL

A mathematical model was developed to help The OUFCC consider multiple design options simultaneously and make specific decisions. The model used for this project is the General Algebraic Mathematical Software (GAMS)[90]. The model was used to maximize the net present worth (NPW) of the entire project. Another objective of the mathematical model was to obtain the most economic solution by minimizing all estimated costs for a project lifetime of 10 years. There were two types of models used:

- Deterministic model (based on one scenario with constant parameters)
- Stochastic model (based on many scenarios with varying parameters)

Deterministic Model

The deterministic model was also used to determine the following:

a) Where to build the first plant
b) Number and type of fuel cell to produce each year
c) When to increase production line
d) Annual operating cost
e) Annual cash flow and revenue
f) Additional capital needed to increase production line
g) Total Capital Investment (TCI)
h) Net Present Worth (NPW)

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[90] GAMS can be attained from www.gams.com

Sets

The mathematical model included three data sets and one time set. These sets are:

- **(i),** Possible plant locations
- **(j)**, Possible market locations
- **(k)**, types of fuel cells considered
- **(t)**, Time

For the plant locations, these were narrowed down to 13 possible locations based on various factors discussed earlier.[91] The plant locations that used in the model are Arizona, California, Florida, Massachusetts, Montana, Nebraska, Nevada, New York, Ohio, Texas, Washington and Wyoming. The model currently incorporates the 50 states excluding Alaska and Hawaii as possible market locations. The type of fuel cells been considered are PEMFC, PAFC and SOFC. The time period is from 2005 to 2014. The plant will start producing fuel cells in the year 2005.

Parameters

A project life of ten years was used in the model, with varying fuel cell demand for each market. The fuel cell demand used was projected into the future based on complied data from previous fuel cell analysis.[92] The maximum production capacity was determined to be 1000 fuel cells. This was determined by the number of fuel cells that can be produced from our purchased equipment. The taxes and labor wages for each state were also inputted into the model.[93] The electricity and water rates were also determined and inputted into the model. The costs of raw materials and the power requirements for each type of fuel cell were predetermined and included in the model.[94]

Model Equations and Constraints

This section includes all the important equations that were implemented into the mathematical model used to determine if fuel cell production would be a viable business venture. Constraints were also added to the model to make it converge on a reasonable solution. The model was designed to maximize the net present worth.

The following constraints were used in the mathematical model:

1. **Location: ($z_{i,t}$)**

This is a decision variable that decides if and where we will build the first plant and thus, limits the model to choose a plant location based on the possible 13 locations. The decision variable is also a binary variable, therefore, if z = 0, no plant is to be built and if z= 1, a plant will be built.

$$location \Rightarrow \sum_{i} z_{i,t} \leq 13$$

2. **Decision Variable 1: (decision1$_{i,t}$)**

This is a decision variable that rejects values of *x*, number of fuel cells at plant locations, *i,* we know do not have a plant built there.

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[91] See *Section II-b* for a detailed analysis on possible plant locations.

[92] See *Section II-b* for a detailed explanation on market demand for fuel cells.

[93] See *section IV- d &e* for a detailed explanation on taxes and labor wages.

[94] See *Section III-e* for raw materials needed for each type of fuel cells

$$decision1_{i,t} \Rightarrow \sum_j \sum_k x(i,j,k,t) - gamma * sum(t, z_{i,t}) = l = 0$$

where: x(i ,j, k, t) = number of fuel cells,
gamma = random number that is larger than x,
z_i = decision variable that decides the location.

3. **Capacity($capacity_{k,t}$)**

This is a constraint that limits the model so it does not produce more fuel cells than the maximum capacity. It states that for every number of fuel cell type, *k*, that is sent to every market, *j*, the number should be less than or equal to maxcap (k,t)

$$capacity_{k,t} \Rightarrow \sum_i \sum_j x(i,j,k,t) \le \text{maxcap}_{k,t}$$

where: x(i ,j, k, t) = number of fuel cells,
$\text{maxcap}_{k,t}$ = capacity of type of fuel cells produced per year.

4. **Market demand ($marketdemand_{j,k,t}$)**

This constraint ensures that the plant does not ship more than the market's projected demand, *j*, to the specified market. The demand numbers can be found in appendix B.

$$marketdemand_{j,k,t} \Rightarrow \sum_i x(i,j,k,t) \le demand_{j,k}$$

where: x(i ,j, k, t) = number of fuel cells,
$\text{demand}_{j,k}$ = demand for each type of fuel cell for each market.

The equations below were used in the mathematical model:

1. **Amount of fuel cells produced ($produce_{i,t}$)**

This equation tells us the number of fuel cells to produce each year for each type of fuel cell and market.

$$produce_{i,t} \Rightarrow \sum_j \sum_k x(i,j,k,t)$$

2. **Equipment Cost Equation**

This statement means that for every type of fuel cell, *k,* produced in plant location, *i*, the total equipment cost will be the sum of the equipment cost for fuel cell, k, over that particular plant location.

$$TotalEqCost_i = \sum_k EqCost_k * z_{i,t}$$

where: Eqcost_k = the equipment cost for each fuel cell, *k*,
$z_{i,t}$ = decision variable that decides the location.

3. **Raw Materials Cost Equation**

This statement below means that for every type of fuel cell, *k*, summed over the plant location, *i*, and selling to market, *j*, at a time, *t*, the total sum of the raw materials cost is as follows:

$$TotalRawCost_{i,t} = \sum_j \sum_k RawCost_k * (1 + \text{infl}) * (Time_t) * x(i,j,k,t)$$

where: RawCost_k = the total amount of raw materials needed for fuel cell, *k*, in $,

infl = inflation of 5%[95],
Time$_t$ = time period in years,
x(i ,j, k, t) = number of fuel cells.

4. **Electricity Cost Equation**

This statement below means that for every type of fuel cell, *k*, produced at plant location, *i*, and selling to market, *j*, the total cost of electricity would be the sums of the power requirement of each type of fuel cell, *k*, multiplied by the cost of electricity at each plant location, *i*, multiplied by the number of fuel cells produced, *x*.

$$TotalElecCost_{i,t} = \sum_{j}\sum_{k} \mathrm{PowReq}_k * ElecCost_i + (1+\mathrm{infl}) * (Time_t - 1) * ElecCost_i * x(i,j,k,t) + (elecbldg)$$

where: ElecCost$_i$ = the cost of electricity at location, *i*, in $,
PowReq$_k$ = power requirement needed to make a fuel cell, *k*, in kwh,
infl = inflation of 5%[96],
Time$_t$ = time period in years,
x (i ,j, k, t) = number of fuel cells,
elecbldg = amount of electricity needed for the building in $,
z$_{i,t}$ = decision variable that decides the location.

5. **Water Cost Equation**

This statement below means that for every type of fuel cell, *k*, produced at plant location, *i*, and selling to market, *j*, the total cost of water would be the sums of the cooling water needed for each fuel cell, *k*, multiplied by the cost of cooling water and the amount of deionized water needed for PAFC and PEMFC respectively multiplied by the cost of DI water multiplied by the number of fuel cells produced, *x*.

$$TotalWaterCost_{i,t} = \sum_{j}\sum_{k} \begin{array}{l} x(i,j,k,t) * (CoolWat/1000) * (CWCost + (1+\mathrm{infl}) * Time_t * CWCost) \\ + (x(i,j,"PAFC",k) * (DIWater/1000) * (DIWCost + (1+\mathrm{infl}) * Time_t * DIWCost)) \\ + (x(i,j,"PEMFC",k) * (DIWater/1000) * (DIWCost + (1+\mathrm{infl}) * Time_t * DIWCost)) \end{array}$$

where: CoolWat = amount of cooling water needed per fuel cell in gallons,
CWCost = cost of cooling water in $/gal,
DIWater = amount of deionised water needed per specified fuel cell in gallons,
DIWCost = cost of deionised water in $/gal,
Time(t) = time period in years,
infl = inflation of 5%[97],
x (i ,j, k, t) = number of fuel cells.

6. **Fixed Costs (FxCost$_{i,t}$)**

This is the amount it would cost to install various plant needs such as piping, contingency, wiring, building, yard improvement, service facilities, construction, cost of the land and the cost of trucks. These have been factored into the model as scalars.

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[95] Peters, M.S., Timmerhaus K.D., "Plant Design and Economics for Chemical Engineers" 1991, p207

[96] Peters, M.S., Timmerhaus K.D., "Plant Design and Economics for Chemical Engineers" 1991, p207

[97] Peters, M.S., Timmerhaus K.D., "Plant Design and Economics for Chemical Engineers" 1991, p207

$$FxCost_{i,t} = z_{i,t} * \beta * (contingency + wiring + buildings + \text{yardimprov} + servfact + construct)$$
$$+ \text{landcost} + \text{truckcost}$$

where: β = the total equipment cost for the entire process ($3,988,100)

$z_{i,t}$ = decision variable that decides the location.

7. **Fixed Capital Investment ($FCI_{i,t}$)**

This was determined using the fixed costs of the equipment with a cost for expanding our capacity.

$$FCI_{i,t} = FxCost_{i,t} + \sum_k \alpha * \text{AddProd}_{i,k,t}$$

where: $FxCost_{i,t}$ = the total fixed costs for the process

α = 2400

AddProd = the amount of fuel cell produced in each expansion year.

8. **Total Capital Investment ($TCI_{i,t}$)**

This was determined using the fixed capital investment and the working capital.

$$TCI_{i,t} = FCI_{i,t} * (1 + WC)$$

where: FCI = fixed capital investment,

WC = working capital as a percentage of FCI (17.6%)[98].

9. **Total Operating Costs ($TOC_{i,t}$)**

This includes the manufacturing and operating costs for running the plant(s) and miscellaneous expenses that will be incurred.

$$TOC_{i,t} = TotalRawCost_{i,t} + TotalElec_{i,t} + TotalWater_{i,t} + advert * z_{i,t}$$

where: advert = fixed cost of advertising

$z_{i,t}$ = decision variable that decides the location.

10. **Revenue ($Rev_{i,t}$)**

Revenue is the earnings of the plant before any costs or expenses are deducted. It includes all net sales of the plant plus any other costs associated with the main operations of the business. It does not include dividends, interest income or non-operating income.

$$\text{Rev}_{i,t} = \sum_j \sum_k (Sell(k) * x(i,j,k,t) - TOC_{i,t}$$

where: Sell(k) = selling price of one fuel cell,

x (i ,j, k, t) = number of fuel cells.

11. **Cashflow ($CF_{i,t}$)**

The cashflow is the amount of cash derived over an annual period of time from the plant. This was determined using the equation below:

$$CF_{i,t} = \text{Rev}_{i,t} - (\text{Rev}_{i,t} - Dep * FCI_i) * Tax_i - TPC_{i,t}$$

where: Dep = depreciation (straight line method),

Tax_i = taxation rate in the specified state, *i*.

12. **Bank accounts ($amtbank_t$)**

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[98] Peters, M.S., Timmerhaus K.D., “Plant Design and Economics for Chemical Engineers” 1991, p207

The equations were set up to determine how much money there is after all bills and sales have been finalized. The first equation is the amount in the bank account for the first year only. The equation is as follows:

$$amtbank_{2005} = Initial\,investment - \sum_i TCI_{i,2005}$$

The second equation is summing all the money made after cash flows from previous years and the revenues, operating costs and fixed capital investment for the specified year. The equation stated below applies to all other years but the first one.

$$amtbank_t = \sum_i CF_{i,t-1} + \sum_i \mathrm{Re}\,v_{i,t} - \sum_i TOC_{i,t} - \sum_i FCI_{i,t}$$

where: initial investment = the initial amount invested

13. **Net Present Worth (NPW*i,t*)**

The net present worth is the expected future cash flows minus the total capital investment.

$$NPW = \sum_i \sum_t (CF_{i,t} - TCI_i)/(1+\mathrm{int}^{Time_t})$$

where: int = interest rate at 15%[99],

Time(t) = time period in years.

The code for the deterministic model can be found in appendix D.

Stochastic Model

The stochastic model was also used to determine the net present worth for each scenario. In this model, everything from the deterministic model was remained. However, in order to do the uncertainty analysis, a "for" loop was added to the model. The objective of this for loop was that every time the model run, it would choose a location and a capacity and keep those for the next run. The code for the model can be viewed in Appendix D.

VI. PLAN FOR BUSINESS EXPANSION

The University of Oklahoma Fuel Cell Corporation currently plans on adding a new production line every other year. However, each line will still have the capacity to produce 1000 fuel cells per year for each of three types, and thus 3000 fuel cells total per year. In the future, due to the predicted higher consumption demand, the number of fuel cells produced each year will grow exponentially. More research on fuel cell technology development will be completed to find a way to reduce the fuel cell costs. As discussed earlier, the number of SOFCs increases annually. Currently, the fuel cells that The OUFCC is producing are for stationary applications, such as power source for banks, hospitals, police stations, and post offices as discussed earlier in the report. In the future, when the technology reaches the higher development and the cost for fuel cells can be reduced, The OUFCC will also expand the production by applications; for example, there will be an increase in number of PEMFCs that can be used to power portable devices such as laptops and cell phones, and mobile devices such as cars.

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[99] Peters, M.S., Timmerhaus K.D., "Plant Design and Economics for Chemical Engineers" 1991, p207

The business will expand in regards to changes in market demand and location. The current market is the continental United States. In the future, more markets will be located outside of the United States, extending to Canada and Mexico. For market expansion, more expense will be put in building new facility and employment.

In order to implement all the expansion as discussed above, The OUFCC will need to have enough capital investment. The mathematical model, namely GAMS, will help to examine the money available for expansion. Therefore, The OUFCC plans to run the GAMS program every year to check if there will be enough capital investment for production and market expansions.

VII. CONCLUSIONS

The University of Oklahoma Fuel Cell Corporation (OUFCC) proposes to build a fuel cell manufacturing plant in Texas to produce three types of 200 – 250 kW fuel cell units. The three types of fuels that the OUFCC will produce are: solid oxide fuel cell (SOFC), phosphoric acid fuel cell (PAFC), and proton exchange membrane fuel cell (PEMFC). The target markets are small commercial and government buildings such as hospitals, banks, police stations, and post offices. The fuel cells will serve as a constant supplementary power system or as an occasional emergency supply of electricity.

It is projected that by the tenth year of fuel cell production The OUFCC will reach its maximum capacity of 3,000 fuel cell systems per year (i.e. 1000 of each type). The amount of each fuel cell type produced will depend on the demand of the consumer. Since SOFC and PAFCs are currently older and cheaper technologies, it is expected that more of these types of fuel cells will be sold in the initial years of fuel cell production. In later years, once technical problems are overcome, it is expected that more PEMFC units will be in demand.

The OUFCC will transport its units using a fleet of 24 trucks.

Economic investments associated with our manufacturing process are shown below:

- FCI: $35,789,500
- WC: $5,368,430
- TCI: $41,157,930

Based on these numbers the net present worth of the project is approximately $83.2 million and the return on investment is 23%.

Appendix A

GLOSSARY OF ABBREVIATIONS

DOE	Department of Energy
DSIRE	Database of State Incentives for Renewable Energy
FCI	Fixed Capital Investment
GAMS	General Algebraic Modeling System
GDC-10	Gadolinium Doped Ceria
GDE	Gas Diffused Electrolyte
GDM	Gas Diffused Medium
HAZOP	Hazard and Operability study
HDS	Hydrodesulphurization
IC	Interconnect
LSCF	Lanthanum Strontium Cobalt Ferrite
LSF	Lanthanum Strontium Ferrite
LSM	Lanthanum Strontium Manganite
MACRS	Modified Accelerated Cost Recovery System
MCFC	Molten Carbonate Fuel Cell
MEA	Membrane Electrolyte Assembly
NETL	National Energy Technology Laboratory
NPW	Net Present Worth
OUFCC	University of Oklahoma Fuel Cell Corporation
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
ScZ	Scandium Stabilized Zirconia
SDC	Samarium Doped Ceria
SECA	Solid State Energy Conversion Alliance
SOFC	Solid Oxide Fuel Cell
TCI	Total Capital Investment
WC	Working Capital
YSZ	Yttrium Stabilized Zirconia

Appendix B

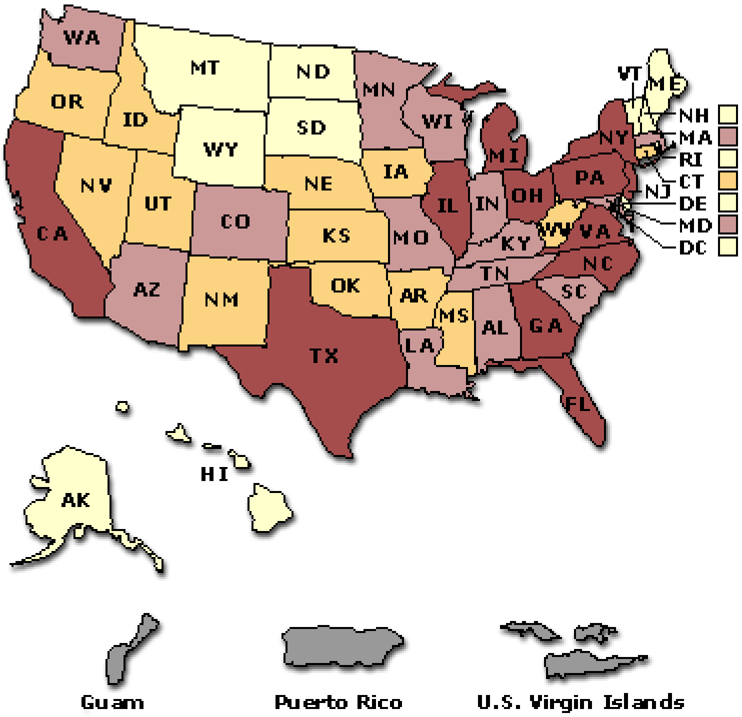
In order to perform a thorough market analysis, the number of specific types of businesses in each state was tabulated. The results are listed in the following table:

State Abbrev.	Hospitals	Banks	Post Offices	Police Stations	Other	Total
AK	36	181	219	80	50	566
AL	168	1360	558	452	100	2638
AR	215	1364	656	349	100	2684
AZ	132	928	277	216	100	1653
CA	1898	8184	2439	1300	300	14121
CO	142	1177	443	255	100	2117
CT	267	1152	321	358	100	2198
DC	34	239	46	41	50	410
DE	29	262	65	48	50	454
FL	541	4408	773	508	200	6430
GA	237	2386	678	516	100	3917
HI	36	260	98	34	50	478
IA	121	1408	906	404	100	2939
ID	55	461	233	119	50	918
IL	532	3639	219	98	100	4588
IN	320	1832	708	539	100	3499
KS	252	1067	615	362	100	2396
KY	173	1620	769	289	100	2951
LA	298	1476	493	455	100	2822
MA	184	1721	544	519	100	3068
MD	146	1647	465	118	100	2476
ME	41	478	440	160	100	1219
MI	419	1941	1008	966	100	4434
MN	177	1500	780	507	100	3064
MO	414	1943	1014	681	100	4152
MS	163	1099	418	333	100	2113
MT	62	363	325	80	50	880
NC	229	2520	856	528	100	4233
ND	56	399	337	108	50	950
NE	109	860	512	203	100	1784
NH	29	377	230	220	50	906
NJ	231	2474	699	771	100	4275
NM	80	483	287	159	100	1109
NV	140	606	250	195	100	1291
NY	643	4079	1904	926	200	7752
OH	544	3162	1166	1125	200	6197
OK	318	926	579	452	100	2375
OR	76	960	365	173	100	1674

PA	456	4065	1744	1174	200	7639
RI	29	198	75	69	50	421
SC	144	1218	423	267	100	2152
SD	60	442	319	130	50	1001
TN	254	1902	598	421	100	3275
TX	1258	5581	1826	1295	200	10160
UT	60	543	208	109	50	970
VA	205	2437	835	315	100	3892
VT	15	263	270	62	50	660
WA	157	1736	503	295	100	2791
WI	222	1293	650	978	100	3243
WV	93	641	702	152	100	1688
WY	25	199	144	75	50	493
TOTAL	**12525**	**81460**	**30992**	**19989**	**5150**	**150116**

Table B-1: Market Analysis by Business[100][101][102]

The following figure shows the population of various states in the United States in 2001:



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[100] Website source: http://www.fdic/gov/bank/analytical/stateprofile/index.html
[101] Website source: http://www.statehealthfacts.kff.org/
[102] Website source: www.smartpages.com

Rank	State	Energy Consumed (Trillion Btu)
1	New York	1253
2	California	1188.8
3	Texas	1161
4	Florida	794.7
5	Illinois	718.7
6	Ohio	622.3
7	Pennsylvania	608.9
8	Michigan	552.7
9	New Jersey	506.1
10	Virginia	454.5
11	North Carolina	434
12	Georgia	429.1
13	Missouri	330.2
14	Massachusetts	328.8
15	Maryland	324.6
16	Washington	321.2
17	Tennessee	316.4
18	Indiana	306.2
19	Wisconsin	276.8
20	Arizona	263.2
21	Colorado	247.3
22	Louisiana	237.5
26	South Carolina	200.9
27	Oklahoma	195.2
28	Connecticut	190.5
29	Oregon	181.6
30	Kansas	168.4
31	Iowa	153.7
32	Mississippi	141.3
33	Arkansas	126.1
34	Utah	119
35	Nebraska	113.8
36	New Mexico	107.7
37	Dist. Of Col.	102.4
38	West Virginia	100
39	Nevada	95.5
40	Idaho	87.9
41	Alaska	62.7
42	Maine	60.7
43	New Hampshire	58.5
44	Montana	54
45	Rhode Island	50.9
46	Delaware	48.1
47	Wyoming	44
48	North Dakota	43.4
49	South Dakota	39.9
50	Vermont	28.5
51	Hawaii	25.7

🟨 Less than 1,299,880
🟧 1,299,880 to 3,969,540
🟪 3,969,550 to 6,290,980
🟥 More than 6,290,980
▨ No data available/NSD

Figure B-2: Total Number of Residents by State 2000-2001[103]

Table B-2: Energy Consumed by State for Commercial Use[104]

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[103] Website source: http://www.statehealthfacts.kff.org/

The following table shows the electricity prices by state for the year 2001:

Rank	State	Electricity Price ($/kWh)
1	Hawaii	15.11
2	Alaska	13.78
3	New York	13.25
4	California	12.78
5	Vermont	11.19
6	Massachusettes	10.36
7	New Hampshire	10.23
8	Connecticut	9.75
9	Rhode Island	9.58
10	New Jersey	9.12
11	Maine	9.12
12	Nevada	8.84
13	Pennsylvania	8.57
14	Illinois	8.15
15	Texas	7.96
16	Maryland	7.93
17	Ohio	7.72
18	New Mexico	7.51
19	Dist. Of Col.	7.49
20	Louisiana	7.46
21	Delaware	7.38
22	Arizona	7.36
23	Michigan	7.33
24	Mississippi	7.17
25	Florida	7.04
26	Wisconsin	6.92
27	Oklahoma	6.91
28	Alabama	6.81
29	South Carolina	6.76
30	Iowa	6.73
31	Georgia	6.62
32	North Carolina	6.60
33	Kansas	6.52
34	South Dakota	6.52
35	Tennessee	6.49
36	Montana	6.44
37	Colorado	6.40
38	Oregon	6.32
39	Minnesota	6.20
40	Washington	6.10
41	Indiana	6.07
42	North Dakota	5.97
43	Missouri	5.92
44	Virginia	5.89
45	Wyoming	5.82
46	Arkansas	5.78
47	Nebraska	5.76
48	Utah	5.61
49	Idaho	5.56
50	Kentucky	5.46
51	West Virginia	5.42

Table B-3: Electricity Prices by State[105]

For the purpose of analyzing transportation costs for each market, and therefore determine the radius that The OUFCC will supply products to, the following table was constructed of possible plant locations and possible market locations:

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[104] Website source: http://www.eia.doe.gov/emeu/states/sep_use/total/pdf/use_all.pdf

[105] Website source: http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_b.html

			Plant Locations												
	State Abbrev.		AZ	CA	FL	MA	MO	NE	NV	NY	OH	OK	TX	WA	WY
		Most Populous City	Phoenix	Los Angeles	Jacksonville	Boston	Kansas City	Omaha	Las Vegas	New York City	Columbus	Oklahoma City	Houston	Seattle	Cheyenne
Market Locations	AK	Anchorage	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	AL	Birmingham	1680	2050	460	1230	730	880	1830	980	570	720	700	2540	1420
	AR	Little Rock	1330	1690	820	1440	420	580	1460	1250	730	340	430	1010	1070
	AZ	Phoenix	0	390	2000	2670	1240	1350	290	2450	1900	980	1160	1470	940
	CA	Los Angeles	390	0	2350	3020	1580	1570	270	2790	2240	1340	1540	1130	1120
	CO	Denver	810	1030	1740	2000	610	540	760	1790	1240	630	1030	1340	100
	CT	Hartford*	2570	2900	1050	110	1340	1370	2660	120	660	1640	1730	2950	1850
	DC		2300	2650	720	450	1040	1140	2420	240	430	1330	1370	2720	1640
	DE	Wilmington***	2440	2775	900	270	1205	1260	2530	160	545	1475	1565	2830	1760
	FL	Jacksonville	2000	2350	0	1160	1140	1320	2240	950	830	1150	890	2970	1750
	GA	Atlanta	1830	2190	310	1110	820	1010	1980	850	590	830	790	2630	1480
	HI	Honolulu	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	IA	Des Moines	1430	1710	1240	1340	200	130	1430	1120	660	550	940	1800	640
	ID	Boise	980	850	2470	2690	1420	1240	670	2490	1970	1440	1820	520	730
	IL	Chicago	1740	2050	1010	1000	540	480	1780	810	360	830	1090	2050	980
	IN	Indianapolis	1730	2060	840	930	500	610	1840	730	180	740	1000	2250	1080
	KS	Wichita	1040	1390	1280	1630	200	300	1180	1420	870	160	620	1860	620
	KY	Louisville*	1750	2180	730	960	510	700	1870	770	210	750	940	2350	1200
	LA	New Orleans	1500	1860	560	1510	840	1030	1730	1340	920	690	350	2590	1380
	MA	Boston	2670	3020	1160	0	1440	1470	2750	210	800	1690	1830	3020	1920
	MD	Baltimore	2310	2650	750	430	1070	1150	2400	200	430	1310	1400	2710	1670
	ME	Portland	2750	3140	1310	110	1560	1530	2860	320	870	1740	1960	3090	2060
	MI	Detroit	2010	2290	1050	800	770	730	2020	650	190	1030	1280	2330	1240
	MN	Minneapolis	1680	1860	1460	1390	440	380	1660	1220	780	790	1180	1650	880
	MO	Kansas City	1240	1580	1140	1440	0	190	1370	1230	680	350	740	1860	680
	MS	Jackson	1460	1820	610	1460	690	870	1630	1220	800	560	420	2540	1270
	MT	Billings	1200	1240	2200	2200	1040	910	1050	2040	1610	1150	1590	830	460
	NC	Charlotte	2030	2410	390	850	970	1140	2200	620	440	1100	1030	2740	1620
	ND	Fargo	1690	1810	1690	1650	620	430	1540	1450	950	870	1300	1420	780
	NE	Omaha	1350	1570	1320	1470	190	0	1300	1250	790	460	860	1690	500
	NH	Manchester***	2670	3020	1160	0	1440	1470	2750	210	800	1690	1830	3020	1920
	NJ	Newark***	2440	2775	900	270	1205	1260	2530	160	545	1475	1565	2830	1760
	NM	Albuquerque	460	810	1640	2220	780	890	590	2000	1460	540	850	1450	540
	NV	Las Vegas	290	270	2240	2750	1370	1300	0	2570	2020	1110	1470	1180	850
	NY	New York City	2450	2790	950	210	1230	1250	2570	0	560	1480	1610	2840	1750
	OH	Columbus	1900	2240	830	800	680	790	2020	560	0	920	1170	2350	1300
	OK	Oklahoma City	980	1340	1150	1690	350	460	1110	1480	920	0	460	1990	690
	OR	Portland	1270	960	2960	3140	1820	1690	1000	2910	2440	1870	2240	170	1180
	PA	Philadelphia	2370	2700	850	320	1170	1200	2480	110	480	1390	1510	2820	1760
	RI	Providence***	2670	3020	1160	0	1440	1470	2750	210	800	1690	1830	3020	1920
	SC	Columbia	2030	2420	300	960	1020	1180	2190	720	530	1060	1030	2790	1660
	SD	Rapid City*	1230	1360	1830	1910	690	530	1110	1720	1240	850	1320	1130	320
	TN	Memphis	1470	1810	690	1340	480	640	1600	1100	590	480	570	2320	1140
	TX	Houston	1160	1540	890	1830	740	860	1470	1610	1170	460	0	2370	1110
	UT	Salt Lake City	650	690	2310	2380	1110	940	420	2190	1680	1100	1440	850	440
	VA	Norfolk*	2350	2690	620	580	1160	1320	2480	370	560	1370	1350	2890	1800
	VT	Burlington***	2670	3020	1160	0	1440	1470	2750	210	800	1690	1830	3020	1920
	WA	Seattle	1470	1130	2970	3020	1860	1690	1180	2840	2350	1990	2370	0	1250
	WI	Milwaukee	1770	2070	1110	1090	560	500	1800	890	470	880	1180	1980	1000
	WV	Charleston	1980	2410	660	750	760	940	2130	550	170	1020	1180	2470	1410
	WY	Cheyenne	940	1120	1750	1920	680	500	850	1750	1300	690	1110	1250	0

*The most populous city was not used.
N/A = driving distance does not apply.
***Distance not listed on website used.

Table B-4: Driving Distances between Plant and Market Locations[106]
http://www.travelnotes.org/NorthAmerica/distances.htm

This information was used to create the following equation that was used to analyze delivery costs per cell if using a contractor: Transportation Costs= \$100 + \$668 + \$1.45*M, where M represents driving distance in miles.

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[106] Website Source: http://www.travelnotes.org/NorthAmerica/distances.htm

Appendix C

Raw Material Suppliers

PAFC

ElectroChem, Inc.
400 W. Cummings Park
Woburn, MA 01801
Phone: (781) 938-5300
Fax: (781) 935-6966

PEMFC

Ballard Material Product
Two Industrial Avenue
Lowell, MA 01851-5199
USA
Phone: 978.452.8961
Fax: 978.454.5617
Email: materialproducts@ballard.com

Investor Relations
4343 North Fraser Way
Burnaby, BC V5J 5J9
Canada
Phone: 604.412.3195
Fax: 604.412.3100
Email: investors@ballard.com

SOFC

Nextech Materials
404 Enterprise Drive, Lewis Center, OH 43035-9423
Telephone: 614-842-6606
Fax: 614-842-6607
Website: www.nextechmaterials.com

Appendix D

GAMS Code for Deterministic Model

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Sets

i plant locations
        /AZ, CA, FL, MA, MO, NE, NV, NY, OH, OK, TX, WA, WY/

j market locations
        /AL, AR, AZ, CA, CO, CT, DC, DE, FL, GA, IA, ID, IL, IN, KS, KY, LA, MA,
MD, ME, MI, MN, MO, MS, MT, NC, ND, NE, NH, NJ, NM, NV, NY, OH, OK, ORE,
PA, RI, SC, SD, TN, TX, UT, VA, VT, WA, WI, WV, WY/

k fuel cell type
        /PEMFC, SOFC, PAFC/
t time by year
        /2005 * 2014/;

Alias (t, tt);

Table dist (j,i) distance in miles
        AZ      CA      FL      MA      MO      NE      NV      NY      OH
OK      TX      WA      WY
AL      1680    2050    460     1230    730     880     1830    980     570
720     700     2540    1420
AR      1330    1690    820     1440    420     580     1460    1250
730     340     430     1010    1070
AZ      0       390     2000    2670    1240    1350    290     2450
1900    980     1160    1470    940
CA      390     0       2350    3020    1580    1570    270     2790
2240    1340    1540    1130    1120
CO      810     1030    1740    2000    610     540     760     1790
1240    630     1030    1340    100
CT      2570    2900    1050    110     1340    1370    2660    120
660     1640    1730    2950    1850
DC      2300    2650    720     450     1040    1140    2420    240
430     1330    1370    2720    1640
DE      2440    2775    900     270     1205    1260    2530    160
545     1475    1565    2830    1760
FL      2000    2350    0       1160    1140    1320    2240    950     830
1150    890     2970    1750
GA      1830    2190    310     1110    820     1010    1980    850
590     830     790     2630    1480
IA      1430    1710    1240    1340    200     130     1430    1120
660     550     940     1800    640
```

ID	980	850	2470	2690	1420	1240	670	2490	1970	1440	1820	520	730
IL	1740	2050	1010	1000	540	480	1780	810	360	830	1090	2050	980
IN	1730	2060	840	930	500	610	1840	730	180	740	1000	2250	1080
KS	1040	1390	1280	1630	200	300	1180	1420	870	160	620	1860	620
KY	1750	2180	730	960	510	700	1870	770	210	750	940	2350	1200
LA	1500	1860	560	1510	840	1030	1730	1340	920	690	350	2590	1380
MA	2670	3020	1160	0	1440	1470	2750	210	800	1690	1830	3020	1920
MD	2310	2650	750	430	1070	1150	2400	200	430	1310	1400	2710	1670
ME	2750	3140	1310	110	1560	1530	2860	320	870	1740	1960	3090	2060
MI	2010	2290	1050	800	770	730	2020	650	190	1030	1280	2330	1240
MN	1680	1860	1460	1390	440	380	1660	1220	780	790	1180	1650	880
MO	1240	1580	1140	1440	0	190	1370	1230	680	350	740	1860	680
MS	1460	1820	610	1460	690	870	1630	1220	800	560	420	2540	1270
MT	1200	1240	2200	2200	1040	910	1050	2040	1610	1150	1590	830	460
NC	2030	2410	390	850	970	1140	2200	620	440	1100	1030	2740	1620
ND	1690	1810	1690	1650	620	430	1540	1450	950	870	1300	1420	780
NE	1350	1570	1320	1470	190	0	1300	1250	790	460	860	1690	500
NH	2670	3020	1160	0	1440	1470	2750	210	800	1690	1830	3020	1920
NJ	2440	2775	900	270	1205	1260	2530	160	545	1475	1565	2830	1760
NM	460	810	1640	2220	780	890	590	2000	1460	540	850	1450	540
NV	290	270	2240	2750	1370	1300	0	2570	2020	1110	1470	1180	850
NY	2450	2790	950	210	1230	1250	2570	0	560	1480	1610	2840	1750
OH	1900	2240	830	800	680	790	2020	560	0	920	1170	2350	1300

```
OK      980     1340     1150     1690     350      460      1110     1480
920     0       460      1990     690
ORE     1270     960     2960     3140     1820     1690     1000     2910
2440     1870     2240     170     1180
PA      2370     2700     850     320      1170     1200     2480     110
480      1390     1510     2820     1760
RI      2670     3020     1160     0      1440     1470     2750     210      800
1690     1830     3020     1920
SC      2030     2420     300      960      1020     1180     2190     720      530
1060     1030     2790     1660
SD      1230     1360     1830     1910     690      530      1110     1720
1240     850      1320     1130     320
TN      1470     1810     690      1340     480      640      1600     1100
590      480      570      2320     1140
TX      1160     1540     890      1830     740      860      1470     1610
1170     460      0       2370     1110
UT      650      690      2310     2380     1110     940      420      2190
1680     1100     1440     850      440
VA      2350     2690     620      580      1160     1320     2480     370
560      1370     1350     2890     1800
VT      2670     3020     1160     0       1440     1470     2750     210      800
1690     1830     3020     1920
WA      1470     1130     2970     3020     1860     1690     1180     2840
2350     1990     2370     0       1250
WI      1770     2070     1110     1090     560      500      1800     890
470      880      1180     1980     1000
WV      1980     2410     660      750      760      940      2130     550      170
1020     1180     2470     1410
WY      940      1120     1750     1920     680      500      850      1750
1300     690      1110     1250     0
;

Table demand(j,k,t)  demand for each type of fuel cell in each state

PAFC.2005  PEMFC.2005  SOFC.2005PAFC.2006  PEMFC.2006  SOFC.2006
PAFC.2007  PEMFC.2007  SOFC.2007  PAFC.2008   PEMFC.2008   SOFC.2008
PAFC.2009 PEMFC.2009  SOFC.2009  PEMFC.2010  PAFC.2010  SOFC.2010
PAFC.2011  PEMFC.2011  SOFC.2011  PAFC.2012 PEMFC.2012 SOFC.2012
PAFC.2013  PEMFC.2013 SOFC.2013 PAFC.2014  PEMFC.2014  SOFC.2014

AL      1       0      0        1         0      1      1        1        1        2         1
1       2       1      2      2          2      2      3          3      3         3         3
3      3          4      3      3        5        3
```

```
AR    1    0    0    1    0    1    1    1    1    2    1
1     2    1    2    2    2    2    3    3    3    3    3
3     3    4    3    3    5    3
AZ    0    0    0    1    2    0    1    0    1    1    1
1     1    1    1    1    1    1    2    2    2    2    2
2     2    3    2    2    3    2
CA    6    6    1    5    0    4    6    3    5    8    5
8     11   7    10   1    13   12   14   14   14   16
18    16   17   23   17   18   29   17
CO    0    0    0    1    0    1    1    0    1    1    1
1     2    1    2    2    2    2    2    2    2    2    3
2     3    3    3    3    4    3
CT    1    0    0    1    0    1    1    0    1    1    1
1     2    1    2    2    2    2    2    2    2    2    3
2     3    4    3    3    4    3
DC    0    0    0    0    0    0    0    0    0    0    0
0     0    0    0    0    0    0    0    0    0    0    1
0     0    1    0    1    1    0
DE    0    0    0    0    1    0    0    0    0    0    0
0     0    0    0    0    0    0    0    0    0    1    1
1     1    1    1    1    1    1
FL    1    1    1    2    1    2    3    1    2    4    2
4     5    3    5    5    6    6    7    6    6    7    8
7     8    10   8    8    13   8
GA    1    1    0    1    1    1    2    1    1    2    1
2     3    2    3    3    4    3    4    4    4    4    5
4     5    6    5    5    8    5
IA    1    1    0    1    0    1    1    1    1    2    1
2     2    2    2    2    3    3    3    3    3    3    4
3     4    5    3    4    6    4
ID    0    0    0    0    0    0    0    0    0    1    0
1     1    0    1    1    1    1    1    1    1    1    1
1     1    1    1    1    2    1
IL    1    1    0    2    1    1    2    1    2    3    2
3     3    2    3    3    4    4    5    4    5    5    6
5     6    7    5    6    9    6
IN    1    1    0    1    1    1    1    1    1    2    1
2     3    2    3    3    3    3    4    3    4    4    4
4     4    6    4    4    7    4
KS    1    0    0    1    0    1    1    1    1    1    1
1     2    1    2    2    2    2    2    2    2    3    3
3     3    4    3    3    5    3
KY    1    1    0    1    0    1    1    1    1    2    1
2     2    2    2    2    3    3    3    3    3    3    4
3     4    5    4    4    6    4
```

```
LA   1  1  0  1  0  1  1  1  1  2  1
2  2  1  2  2  3  2  3  3  3  3  4
3  3  5  3  4  6  3
MA   1  1  0  1  0  1  1  1  1  2
1  2  2  2  2  2  3  3  3  3  3  3
4  3  4  5  4  4  6  4
MD   1  0  0  1  0  1  1  1  1  1
1  1  2  1  2  2  2  2  3  2  2  3
3  3  3  4  3  3  5  3
ME   0  0  0  0  0  0  1  0  0  1  0
1  1  1  1  1  1  1  1  1  1  1  2
1  1  2  1  2  2  1
MI   1  1  0  2  1  1  2  1  2  3  2
2  3  2  3  3  4  4  5  4  4  5  6
5  5  7  5  6  9  5
MN   1  1  0  1  0  1  1  1  1  2
1  2  2  2  2  2  3  3  3  3  3  3
4  3  4  5  4  4  6  4
MO   1  1  0  1  1  1  2  1  2  2
1  2  3  2  3  3  4  4  4  4  4  5
5  5  5  7  5  5  8  5
MS   0  0  0  1  0  1  1  0  1  1  1
1  2  1  2  2  2  2  2  2  2  2  3
2  3  3  3  3  4  3
MT   0  0  0  0  0  0  0  0  0  1  0
0  1  0  1  1  1  1  1  1  1  1  1
1  1  1  1  1  2  1
NC   1  1  0  1  1  1  2  1  2  3  1
2  3  2  3  3  4  4  4  4  4  5  5
5  5  7  5  5  9  5
ND   0  0  0  0  0  0  0  0  0  1  0
1  1  0  1  1  1  1  1  1  1  1  1
1  1  2  1  1  2  1
NE   0  0  0  1  0  1  1  0  1  1  1
1  1  1  1  1  2  2  2  2  2  2  2
2  2  3  2  2  4  2
NH   0  0  0  0  0  0  0  0  0  1  0
0  1  0  1  1  1  1  1  1  1  1  1
1  1  1  1  1  2  1
NJ   1  1  0  2  1  1  2  1  2  3  1
2  3  2  3  3  4  4  4  4  4  5  5
5  5  7  5  5  9  5
NM   0  0  0  0  0  0  0  0  0  1
0  1  1  1  1  1  1  1  1  1  1  1
1  1  1  2  1  1  2  1
```

NV	0	0	0	0	0	0	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	2	1	2	2	2	2	3	2
NY	4	1	1	3	1	2	3	2	3	5	3	4	6	4	6	6	7	7	8	8	8	9	10	9	9	13	9	10	16	9
OH	1	1	1	2	1	2	3	1	2	4	2	3	5	3	4	4	6	5	6	6	6	7	8	7	7	10	7	8	13	8
OK	1	0	0	1	0	1	1	0	1	1	1	1	2	1	2	2	2	2	2	2	2	3	3	3	3	4	3	3	5	3
ORE	0	0	0	1	0	0	1	0	1	1	1	1	1	1	1	1	2	1	2	2	2	2	2	2	2	3	2	2	3	2
PA	4	1	1	3	1	2	3	2	3	5	3	4	6	4	6	6	7	7	8	7	8	9	10	9	9	12	9	10	15	9
RI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	1	1	1
SC	0	0	0	1	0	1	1	0	1	1	1	1	2	1	2	2	2	2	2	2	2	2	3	2	3	3	3	3	4	3
SD	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	1
TN	1	1	0	1	0	1	1	1	1	2	1	2	2	2	2	2	3	3	3	3	3	4	4	4	4	5	4	4	7	4
TX	4	4	2	4	2	3	4	2	4	6	4	6	8	5	7	7	9	9	10	10	10	11	13	11	12	16	12	13	21	12
UT	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	1
VA	1	1	0	1	1	1	2	1	1	2	1	2	3	2	3	3	4	3	4	4	4	4	5	4	5	6	5	5	8	5
VT	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
WA	1	1	0	1	0	1	1	1	1	2	1	2	2	1	2	2	3	2	3	3	3	3	4	3	3	5	3	4	6	3

WI 1 1 0 1 0 1 1 1 1 2 1
2 2 2 2 2 3 3 3 3 3 4 4
4 4 5 4 4 7 4
WV 0 0 0 1 0 1 1 0 1 1
1 1 1 1 1 1 2 1 2 2 2 2
2 2 2 3 2 2 3 2
WY 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 1 0 0 1
1 1 1 1 1 1 1 1;

Table maxcap(k,t) Capacity of Fuel Cells Produced per Year

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
PAFC	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
PEMFC	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
SOFC	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000;

Parameters

Time(t) Number of years
/2005 1, 2006 2, 2007 3, 2008 4, 2009 5, 2010 6, 2011 7, 2012 8, 2013 9, 2014 10/

Tax(i) corporate income tax rate (state and federal)
/CA .4384, NY .425, FL .405, OH .435, AZ .4597, OK .41, TX 0.35, WA 0.35, NE .4281, NV 0.35, WY 0.35, MO 0.415, MA .445/

Wage(i) median hourly wages
/CA 14.68, NY 15.32, FL 11.80, OH 13.36, AZ 12.58, OK 11.24, TX 12.32, WA 15.31, NE 11.90, NV 12.66, WY 12.07, MO 12.50, MA 15.94/

ElecCost(i) cost of electricity in $ per kwh
/CA 12.78, NY 13.25, FL 7.04, OH 7.72, AZ 7.36, OK 6.91, TX 7.96, WA 6.10, NE 5.76, NV 8.84, WY 5.82, MO 6.44, MA 10.36/

WaterCost(i) cost of water in $ per 1000 gallons
/CA 1.80, NY 1.40, FL 1.70, OH 1.72, AZ 1.76, OK 1.60, TX 1.96, WA 1.60, NE 1.76, NV 1.84, WY 1.82, MO 1.44, MA 1.63/

EqCost(k) equipment cost for each fuel cell in $
/PEMFC 644000, SOFC 2426100, PAFC 918000/

RawCost(k) cost of raw materials for each fuel cell
/PEMFC 576600, SOFC 375000, PAFC 524800/

PowReq (k) Power requirement to make each fuel cell in kwh
/PEMFC 226.67, SOFC 619.52, PAFC 216.54/

Table Sell(k,t) selling price per fuel cell

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
PEMFC	1200000	1188000	1176120	1164359	1152715	1129661	1107068	1084926	1063227.8	1041963.3
PAFC	1000000	990000	980100	970299	960596	941384.1	922556.4	904105.3	886023.2	868302.7
SOFC	1100000	1089000	1078110	1067329	1056656	1035522	1014812	994515.8	974625.5	955133.0

Scalar

work	number of workers /71/
trans	transportation cost per mile /1.45/
handling	Shipping and handling costs (fixed) /768/
hours	hours per year worked by employees /8760/
WC	working capital percentage of FCI /0.15/
elecbldg	Electricity needed to run the rest of the plant in $ /100000/
CoolWat	The amount of cooling water needed per fuel cell in gallons /500/
CWCost	The cost of cooling water in $ per 1000 gallons /.20/
DIWater	The amount of deionized water needed per specific fuel cell in gallons /3/
DIWCost	The cost of deionizing water in $ per 1000 gallons /.80/
n	Service life of the equipment in years /10/
int	Assumed Interest rate for NPW /0.08/
infl	Assumed inflation rate per year /0.05/
Dep	Depreciation /.10/
gamma	Larger than maximum capacity /100000000/

**The following fractions were used to calculate the FCI and are based on the equipment costs*

installation	cost of equipment installation /0.45/
controls	cost of instrumentation and controls /.09/
piping	cost of installing piping /0.16/
wiring	cost of electrical installations /0.10/
buildings	cost of building facilities /0.25/
yardimprov	cost of yard improvements /0.13/
servfact	cost of installing service facilities excluding electricity /.30/
construct	cost of maintenance and operation of temp. facilities /0.39/
contingency	cost of contingency /0.39/
landcost	estimated cost for 10 acres for land /500000/
truckcost	cost of buying a fleet of trucks /23283100/
advert	advertising expenses in $ /2000000/

*The following is used to calculate the total product cost:

maintain	Maintenance and repairs percentage of FCI /0.07/
supplies	Operating supplies percentage of FCI /0.0105/
permits	permits needed for plant in $ per year /1000/
patents	patents and royalities in $ per year /10000/

```
     Vs                   Salvage value percentage of total equipment cost /0.10/
     initialinvestment  Initial investment put into the bank/60000000/
     insurance            health-building-equipment insurance in $ per year /1000000/;

Parameter
     labor(i)       the total labor cost for number of workers at a Wage(i) wage;
     labor(i) = work*hours*Wage(i);

Parameter
     shipping (i)  transport costs per unit;
     shipping (i) = trans*sum(j,dist(j,i))+handling;


Variables
     x(i,j,k,t)                Number of fuel cells produced
     y(i,k,t)                  Variable
     z(i,t)                    Decision Variable 2 - decides plant location
     cap(i,k,t)                capacity
     AddProd(i,k,t)            Add production lines
     TotalEqCost(i,k)          Total equipment cost in $
     TotalRawCost(i,t)         Total raw material cost in $
     TotalElecCost(i,t)        Total electricity cost in $
     TotalWaterCost(i,t)       Total cost of cooling and process water
     FxCost(i,t)               Fixed costs
     FCI(i,t)                  Fixed capital investment in $
     TCI(i,t)                  Total capital investment in $
     TOC(i,t)                  Manufacturing costs & general expenses
     Rev(i,t)                  Revenue in $ per year
     CF(i,t)                   Cash flow over time in $ per year
     NPW                       Net present worth in $ after 10 years
     amtbank(t)
     produce(i,t)
     newdemand(j,k,t)          new demand;

Binary variable z, y ;

Integer variable x ;
Positive variable CF, AddProd, amtbank;

AddProd.fx(i,k,'2006')=0;
AddProd.fx(i,k,'2008')=0;
AddProd.fx(i,k,'2010')=0;
AddProd.fx(i,k,'2012')=0;
AddProd.fx(i,k,'2014')=0;

Equations
```

```
         expansion1             Capacity expansion
         expansion2             Capacity expansion
         expansion3             Capacity expansion
         expansion4             Capacity expansion
         expansion5             Capacity expansion
         expansion6             Capacity expansion
         rawmaterialcost        The total cost of raw materials
         electricitycost        The total cost of electricity for the process and running the
                                building
         watercosts             The total cost of water for the process and other miscellaneous
                                activities
         decision1              Tells us that if there is no "i" then x = 0
         capacity1              The total number of fuel cells which can be produced
         capacity2              The lowest number of fuel cells that meets capacity
         marketdemand           The maximum number of each fuel cell that can be sold to a
                                market in the first year
         fixedcosts             Fixed costs
         fixedcapitalinvestment   Fixed capital investment for first year
         totalcapitalinvestment   Total capital investment for first year
         totaloperatingcost       Manufacturing costs & general expenses
         revenue                Revenue in $ per year
         cashflow0              Cash flow in $ per year
         cashflow1              Cash flow in $ per year
         amtbankinitial
         amtbankfinal
         netpresentworth          Net present worth in $ after 10 years
         amtproduced(i,t)
;

*Constraints
         decision1(i,t)          ..     sum((j,k),x(i,j,k,t))-gamma*sum(tt $(ord(tt) le
                                         ord(t)),z(i,tt)) =l= 0;
         capacity1(k,t)          ..     sum((i,j), x(i,j,k,t))=l= maxcap(k,t);
         capacity2(i,k,t)        ..     cap(i,k,t) =g= sum(j,x(i,j,k,t));
         marketdemand(j,k,t)  ..     sum(i,x(i,j,k,t)) =l= demand(j,k,t);
         amtproduced(i,t)        ..     produce(i,t) =e= sum((j,k),x(i,j,k,t));

         equipmentcost(i)          ..     TotalEqCost(i) =e= z(i)*sum(k, EqCost(k));
         expansion1(i,k,t)$(ord(t)gt 1) ..     cap(i,k,t) =e= cap(i,k,t-1)+ AddProd (i,k,t);
         expansion2(i,k)           ..     cap(i,k,"2005") =e= AddProd (i,k,"2005");
         expansion3(i,k,t)         ..     AddProd (i,k,t) -y(i,k,t)*gamma=l= 0;
         expansion4(i,k,t)         ..     y(i,k,t) =l= sum(tt$(ord(tt) le ord(t)), z(i,tt));
         expansion5(i)             ..     sum(t,z(i,t))=l= 1;
         expansion6                ..     sum((i,t),z(i,t))=l= 1;
         rawmaterialcost(i,t)      ..   TotalRawCost(i,t) =e= sum((j,k),RawCost(k)*
                                         (1+infl)**ord(t)* x(i,j,k,t));
```

```
    electricitycost(i,t)          ..      TotalElecCost(i,t)=e= sum((j,k),(PowReq(k)*
    ElecCost(i)+ (1+infl)**ord(t)*ElecCost(i))* x(i,j,k,t));
    watercosts(i,t)               ..      TotalWaterCost(i,t) =e= sum((j,k),x(i,j,k,t)*
      (CoolWat/1000)*(CWCost + (1+infl)**ord(t)*CWCost) +
    (x(i,j,"PEMFC",t)*(DIWater/1000)*(DIWCost + (1+infl)**ord(t)*DIWCost)) +
    (x(i,j,"PAFC",t)*(DIWater/1000)*(DIWCost+(1+infl)**ord(t)*DIWCost)));
    fixedcosts(i,k,t)             ..      FxCost(i,t) =e=z(i,t)*(6400000*
   (piping + controls +contigency + wiring + buildings + yardimprov + servfact +
      construct)+landcost+truckcost);
    fixedcapitalinvestment(i,t)   ..      FCI(i,t) =e=  FxCost(i,t) + Sum(k,2400* AddProd
                                          (i,k,t));
    totalcapitalinvestment(i,t)   ..      TCI(i,t) =e= FCI(i,t)+(FCI(i,t)*WC);
    totaloperatingcost(i,t)       ..      TOC(i,t) =e= TotalRawCost(i,t) +
                                       TotalElecCost(i,t) + TotalWaterCost(i,t);
    amtbankinitial         ..     amtbank('2005')=e=initialinvestment -sum(i,TCI(i,'2005'));
    amtbankfinal(t)$(ord(t)gt 1)  ..      amtbank(t)=e=sum(i,CF(i,t-1))+sum(i,Rev(i,t))-
                                          sum(i,TOC(i,t))-sum(i,FCI(i,t));
    revenue(i,t)                  ..      Rev(i,t)=e=sum((j,k),Sell(k,t)*x(i,j,k,t));
    cashflow0(i,t)$(ord(t)gt 10)  ..      CF(i,t) =e= Rev(i,t) - (Rev(i,t) -(Dep*
                                          sum(tt$((ord(tt) gt ord(t)-10) AND (ord(tt) le
                                          ord(t))), FCI(i,tt))))*Tax(i)-TOC(i,t);
    cashflow1(i,t)                ..      CF(i,t) =e= Rev(i,t) - (Rev(i,t)-(Dep* sum(tt$(ord(tt) le
                                          ord(t)), FCI(i,tt))))*Tax(i)-TOC(i,t);
    netpresentworth        ..     NPW =e= sum((i,t),(CF(i,t)-TCI(i,t))/((1+int)**Time(t)));


model fuelcell /all/ ;

solve fuelcell using mip maximizing NPW ;
display x.l,z.l,FxCost.l,TotalRawCost.l,TotalElecCost.l,
AddProd.l,TCI.l,FCI.l, TOC.l,Rev.l,CF.l,NPW.l,cap.l,y.l;
```

GAMS code for Stochastic Model

The beginning of this model is the same as the deterministic model. The following was added to determine the uncertainty.

```
Table  c1(s,k)     uncertainty in fuel cell price

         PEMFC          SOFC           PAFC
1       1127944.282     1235633.718     1135277.332
2       893356.0396     767222.2551     855042.0059
3       1258621.754     1268293.718     969721.3298
4       1506353.65     1282374.97      864645.5879
5       1487604.053     1347828.53      1211442.966
6       1615951.945     1495687.675     1000374.712
```

```
7      675938.9665      852457.0972      1426662.154
8      1143796.502      1161872.47      922401.0026
9      1462805.406      1255301.95      724172.0848
10      939191.8441      1074742.286      698813.5536


;

Table   c2(s,k)      uncertainty in raw material cost

         PEMFC            SOFC            PAFC
1      695693.5171      417395.3566      538996.4178
2      588048.2995      406521.58      491977.7943
3      675885.3271      348343.7335      487619.4229
4      497215.6843      379510.3974      536689.9712
5      489822.7488      359041.6081      579918.8103
6      494609.0813      379524.8498      487722.5204
7      582270.4956      377303.5653      550128.8497
8      490244.6404      347592.3772      540514.1811
9      478889.4901      349790.3416      490832.5062
10      463249.8721      328375.6636      567143.5617
;

Table   c3(s,k)      uncertainty in equipment cost

        PEMFC            SOFC            PAFC
1      282212.1423      2437207.519      222189.7608
2      230058.2486      2559139.381      210931.3987
3      299823.9388      2279190.909      251019.0148
4      288464.691      2214060.902      220671.2684
5      266460.433      2324228.905      182779.8092
6      243358.1591      2523253.267      214254.1012
7      237254.8528      2375363.971      213837.0979
8      234783.1873      2210822.192      208928.4185
9      290794.589      2504914.579      215313.7989
10      262950.2951      2046642.755      213294.0386
   ;



option solprint = off;
option limcol = 0;
option limrow = 0;
option optcr = 0.00;

parameter Xc(s),sc,scn ;
```

```
for{sc = 1 to 10,
* this 'for' statement allows performing the deterministic problem under different
scenarios
    Xc(s) = 0 + 1$(ord(s)= sc);
    Sell(k,t) = sum[s,Xc(s)*c1(s,k)];
    RawCost(k) = sum[s,Xc(s)*c2(s,k)];
* here we fix the value of cc with the correspondent values of c(s) for each scenario
    solve fuelcell using mip maximizing NPV;
    y.fx(i,k,t) = y.l(i,k,t);
    z.fx(i,t) = z.l(i,t);
* we fix the solution found to obtain the NPV for each scenario under that solution found
    display y.l,z.l;
    for[scn = 1 to 100,
       Xc(s) = 0 + 1$(ord(s)= scn);
       Sell(k,t) = sum[s,Xc(s)*c1(s,k)];
       RawCost(k) = sum[s,Xc(s)*c2(s,k)];
       solve fuelcell using minlp maximizing NPV;
       display NPV.l, y.l,z.l;
   put NPV.l put/;]
   put ' ' , put/;

   y.lo(i,k,t) = 0;
   y.up(i,k,t) = 1;

   z.lo(i,t) = 0;
   z.up(i,t) = 1;
}   ;


display x.l,z.l,FxCost.l,TotalRawCost.l,TotalElecCost.l,produce.l,
Addcap.l,TCI.l,FCI.l,Rev.l,CF.l,NPV.l,cap.l,y.l;
```

Appendix E

Power Requirement Calculations for 250 kW PEMFC

Calculations for the power requirements for the manufacturing of the MEA and Bipolar Plates[107] I took the given values in the reference and converted them to out needs and production rate. Each individual 5 kW cell has 2 electrodes and a 250 kW fuel cell is made up of 50 of these cells.

Process	Calculation	Power Requirement X (kW/Fuel Cell)
(M1) *Shear Mixing*	$\frac{500\text{ electrodes/FC}}{0.417\text{ kW}} = \frac{100\text{ electrodes/FC}}{X}$	.0834
(M2) *Constant Volume Displacement Distillation & Viscosity Reduction*	$(.026\text{ kW/hr/electrode})(100\text{ electrodes})(8\text{ hr}) = X$	20.8
(M3) *Screen Printing*	$\frac{480\text{ electrodes/hr}}{0.55\text{ kW}} = \frac{12.5\text{ electrodes/hr}}{X}$	.014
(M4) *Drying*	$(.00071\text{ kW/hr/electrode})(100\text{ electrodes})(8\text{ hr}) = X$	.568
(M5) *Die Cutting Catalyst Coated Carbon Paper*	$\frac{6600\text{ electrodes/hr}}{4.35\text{ kW}} = \frac{12.5\text{ electrodes/hr}}{X}$	.00824
(M6) *Medium Size Low Temperature Pressing*	$\frac{392.7\text{ electrodes/hr}}{33.33\text{ kW}} = \frac{12.5\text{ electrodes/hr}}{X}$	1.06
(M7) *Final Die Cutting of MEA*	$\frac{3300\text{ MEAs/hr}}{4.35\text{ kW}} = \frac{6.25\text{ MEAs/hr}}{X}$	.0082
(M8) *Injection Molding Bipolar Plates*	$\frac{(6461643\text{ pieces/yr})}{(341\text{ days})(24\text{ hr})} = 789.55\text{ pieces/hr}$ $\frac{789.55\text{ pieces/hr}}{79\text{ kW}} = \frac{100\text{ pieces/8 hr}}{X}$	1.25

---

[107] http://www.dti.gov.uk/energy/renewables/publications/pdfs/f100164.pdf Table A-2

	Assume a "piece" is a bipolar plate (2 for each 5 kW cell, 100 for an entire stack for a 250 kW FC)	

Table E.1: Sample Calculations

Calculations for the ancillary components of the ISP and Manufacturing and Power Requirements[108] I took the given values in the reference and converted them to out needs and production rate. I assumed 4 "pieces" for each component, since 4 sides of fuel cell housing

Process	Calculation	Power Requirement X (kW/Fuel Cell)
Structural Foam	$\frac{(475200\text{ pieces/yr})(8\text{ hr})}{(341\text{ days})(24\text{ hr})} = 448.24\text{ pieces/FC}$ $\frac{448.24\text{ pieces/FC}}{65\text{ kW}} = \frac{4\text{ pieces/FC}}{X}$	.58
Aluminium Casting	$\frac{(80000\text{ pieces/yr})(8\text{ hr})}{(341\text{ days})(24\text{ hr})} = 75.46\text{pieces/FC}$ $\frac{75.46\text{ pieces/FC}}{4497\text{ kcal}} = \frac{4\text{ pieces/FC}}{Y}$ $Y = 238.4\text{ kcal} = .277\text{ kWh} = X$	2.26
Die Cutting	$\frac{27871\text{ pieces/FC}}{2\text{ kW}} = \frac{4\text{ pieces/FC}}{X}$	.000287
Aluminium Stamping	$\frac{96.77\text{ pieces/FC}}{22.8\text{ kW}} = \frac{4\text{ pieces/FC}}{X}$	.942
Machining	$\frac{625.6\text{ pieces/FC}}{90\text{ kW}} = \frac{4\text{ pieces/FC}}{X}$	.57

SOFC - Cost of Materials and Material Properties

	YSZ			**ScZ**
Quantity (dry basis)	**Powder**	**Coating**	**Aq. Suspension**	**Powder**
150-g	$95.00	$595.00	$695.00	$745.00
500-g	$175.00	$1,395.00	$1,495.00	$1,795.00
1-kg	$295.00	$1,995.00	$2,295.00	$2,545.00

Table: Cost of Zirconia-based Electrolyte Materials

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[108] http://www.dti.gov.uk/energy/renewables/publications/pdfs/f100164.pdf Table A-6

Quantity (dry basis)	GDC -10			SDC	
	Nanopowder	Ceramic Grade Powders	Suspension	Nanopowder	Ceramic Grade Powders
150-g	$385.00	$460.00	$995.00	$385.00	$460.00
500-g	$850.00	$925.00	$1,995.00	$850.00	$925.00
1-kg	$1,275.00	$1,350.00	$2,995.00	$1,275.00	$1,350.00

Table E.2: Costs of Ceria-Based Electrolytes

Materials	Composition	Electrolyte Material	Operating Temperature (^oC)
LSM15	$(La_{0.85}Sr_{0.15})MnO_3$	YSZ	800 to 1000
LSM20	$(La_{0.80}Sr_{0.20})MnO_3$	YSZ	800 to 1000
LSF20	$(La_{0.80}Sr_{0.20})FeO_3$	YSZ, GDC	750 to 900
LSF40	$(La_{0.60}Sr_{0.40})FeO_3$	GDC	750 to 900
LSCF6428	$(La_{0.60}Sr_{0.40})(Fe_{0.80}Co_{0.20})O_3$	GDC	700 to 750

Table E.3: Types of Cathode Materials

		Quantities in Grams	
Material	Form	500	1000
LSM (15 or 20)	Powder	$445	$665
LSM (15 or 20)	Ink	$2,425	-
LSF (20 or 40)	Powder	$545	$795
LSF (20 or 40)	Ink	$2,425	-
LSCF	Powder	$575	$865
LSCF	Ink	$2,425	-

Table E.4: Cost of Cathode Materials

		Quantities in Grams	
Material	Form	500	1000
NiO/YSZ	Powder	$995	$1,495
NiO/YSZ	Ink	$2815	n/a
NiO/GDC	Powder	$1,095	$1,645
NiO/GDC	Ink	$2815	n/a

Table E.5: Cost of Anode Materials

	Planar Metal Interconnect		**Planar All- Ceramic**	
	$/m^2		**$/m^2**	
	Material	**Process**	**Material**	**Process**
Anode	204.16	8.52	10.03	3.86
Cathode	4.52	5.37	3.43	3.34
Electrolyte	35.69	18.04	190.29	15.63
Interconnect	81.94	15.27	360.07	31.15
Layer Assembly		55.55		135.61
Subtotal	326.31	102.75	563.82	189.59
TOTAL	**$429**		**$753**	

Table E.6: Cost Break-down Based on Active Area for SOFCs

Appendix F

Reformer Design Calculations[109]

The steam reformer was sized using an Excel spread sheet[110] which was created using an industrial case study The design of the reformer assumes that equilibrium is rapidly reached with sufficiently high heat flux (between 17,000 and 21,000 Btu/(hr*ft^2)) provided by a direct-fired furnace. The furnace is fueled by some of the natural gas feed and also by fuel cell exhaust which contains some left over methane and hydrogen. The design procedure is almost exactly similar to that of the case study. However, the Excel spread sheet allows for easier calculation of the two unknowns using the solver add-in to find the mole fractions of CO_2 and CH_4. The inlet temperature was adjusted to achieve a high conversion of CH_4. The inlet gas assumes that all of the sulfur has been removed in a hydrodesulfurization unit. The hydrodesulfurization unit is not sized here, because cobalt oxide-molybdenum oxide-alumina kinetic information had not been located at the time of this writing.

The inlet gas composition[111] is taken as 95% methane, 3% inert, 2% CO. A steam to CH_4 ratio of 4 was used. The inlet temperature was taken to be 50°C lower than the anticipated exit temperature (which was found through a combination of examining literature and trail and error). The void fraction of catalyst bulk volume to reactor volume was assumed to be 0.4 in all of the reactors. Catalyst prices were estimated as $5 per pound . A reactor tube length of 6 ft and a tube diameter of 1 inch was assumed and the number of tubes was determined by calculating the total heat load and dividing it by the tube surface area and chosen heat flux of 17,000 Btu/(hr*ft^2). The results indicate 16 tubes are required for the process. The furnace cost was found using figure 14-38[112] assuming stainless steel, although it is likely that more expensive materials will be required to resist the high temperatures and presence of hydrogen. The furnace cost came to about $150,000 for a heat duty of 5280 Btu/min which makes the cost of the reactor and catalyst inconsequential for cost estimates. Therefore, the cost of the furnace and steam reformer is estimated to be around $150,000.

High Temperature and Low Temperature Water Gas Shift Reactor Sizing[113]

To estimate the costs of the high temperature and low temperature gas shift reactors, once again, an industrial case study was referenced. The high temperature reactor ran at 750 °F, while the low temperature reactor was operated at 400°F. The difference is a result of the different operational temperature ranges of the different catalysts.

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[109] Rase, H., Chemical Reactor Design for Process Plants, Volume Two: Case Studies and Design Data, John Wiley & Sons, NY, 1979, Case Study 111 pp. 133-138

[110] \\garfield\group1\PROJECT FINAL REPORT\References\Steam Reformer.xls

[111] Website Source: www.copper.org/applications/fuelgas/ SoCal%20Gas%20Final%20Report.pdf

[112] Peters, M.S., Timmerhaus K.D., "Plant Design and Economics for Chemical Engineers" 1991, p 692

[113] Rase, H., Chemical Reactor Design for Process Plants, Volume Two: Case Studies and Design Data, John Wiley & Sons, NY, 1979, Case Study 105 pp. 44-60

Polymath was used to setup and solve the reaction kinetics given in the case study[114] The inlet composition for the high temperature reactor was taken from the exit composition of the steam reformer and the inlet composition of the low temperature reactor was taken from the high temperature reactor exit composition.

The high temperature reactor was sized using a 0.4 void fraction, 6 ft length, 1" ID pipes. The catalysts were assumed to be isothermal since the case study indicated that 200 lb increments of catalyst never caused temperature changes greater than 1°C. The high temperature reactor was calculated to require 312 lbs of Chromia-promoted iron oxide catalyst and 339 pipes. The estimated reactor cost was $12,500 and the catalyst cost, based upon the $5 per pound estimate, comes to about $1560. The high temperature reactor reduced the dry CO concentration from 9% to 6.5%.

The low temperature reactor, which employs a copper-zinc oxide catalyst, converts the CO concentration from 6.5% to 0.5%. To do this, it was estimated that 736 pounds of catalyst and 625 tubes would be required. The cost for the reactor and catalyst was estimated at $20,000 and $3,680.

The total estimated cost of the reformer system, including about $20,000 to account the for the heat integration, methenation reactor (to reduce the CO to low ppm levels) and the hydrodesulferization reactor comes out to about $200,000.

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[114] \\garfield\group1\PROJECT FINAL REPORT\References\High T Gas Shift
\\garfield\group1\PROJECT FINAL REPORT\References\Low T Gas Shift