HOLISTIC ANALYSIS OF FUEL CELLS
FOR RESIDENTIAL APPLICATION

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HOLISTIC ANALYSIS OF FUEL CELLS
FOR RESIDENTIAL APPLICATION

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SUMMARY

A Fuel Cell is an electrochemical device that transforms chemical energy directly into electricity and thermal energy; it has some characteristics such as low environmental impact, high reliability, high efficiency, high scalability from few Kilo Watts (KW) to Giga Watts (GW), that make the system suitable for residential application. On the other hand the construction industry is one of the largest consumers of energy in the world and one of the largest emitters of green house gases and of pollutants in general. Therefore alternative energies have emerged in the last decades to diminish the negative impact that the construction industry is causing to the environment and one of such alternative energies are fuel cells. The purpose of this study is to assess the feasibility of adopting fuel cells for the residential sector of the rural Ohio Appalachian region, comparing this alternative technology to the traditional grid system powered by coal fired power plants. In order to assess the feasibility of the system an index is being developed taking into consideration not only sustainable parameters but also the factors that influence the user's decision making process of adopting an alternative energy.

The index developed throughout this thesis uses a multi-criteria approach to assess each factor in a separate unit and to combine all factors in a single rating. The sustainable factors found in literature are cost, environmental impact, and energy consumption. The factors that influence the user's decision making process of adopting an alternative energy were found through surveys targeted to a sample of possible adopters of alternative energies and to a larger random sample. The factors evaluated on the index are cost, environmental impact, energy consumption, reliability, safety, maintenance, and space.

According to the application of the index, fuel cells rate slightly better than the grid system powered by coal fired power plants assessing the overall factors, making this a feasible

system. However there are some factors such as cost where fuel cells are still too expensive and will not be feasible in the near future.

CHAPTER 1

INTRODUCTION

The construction industry, including the material supply industry, is one of the major exploiters of natural resources in the world (Bentivegna et al., 2002). In the United States this industry constitutes the 40% of the total energy consumption. The residential sector plays an important role because it represents 37% of the national construction activity (Gould and Joyce, 2003). Due to the scarcity of resources and the awareness of the importance of preserving resources for future generations, it is necessary to develop alternative energy systems from renewable sources that have an application in this industry. In addition it is essential to develop tools that allow the comparison of such systems.

There are emerging alternative energies that seek to reduce the negative impacts that the energy sector and in this case the residential sector cause to the environment. Fuel cells are one of those technologies; it consists on the conversion of energy stored in hydrogen, chemical energy, into electricity and thermal energy. The system is very efficient and seems to be adaptable to the requirement of a house.

This study seeks to assess the feasibility of such system on the residential sector in the rural Appalachian region in Ohio. Most of the times the feasibility of any system is assessed just in monetary terms, however, there are two important criteria that should be taken into consideration to assess this kind of system. One is the sustainable criteria, because it is well understood that it is not possible to reach development on the long term if aspects such as the environment and the community are not considered in the decisions that are taken now. Other important criteria are the factors that influence the user’s decision making process of adopting an alternative energy, because in the residential sector, the final users are the ones that have the possibility to make a change on the market patterns and can decide to adopt an alternative energy.

In other to find the sustainable factors an extensive literature review is performed; there are several authors that have widely worked this subject and through different research have identified the factors that are most important to the sustainability of the world. To find the factors that influence the user decision making process of adopting an alternative energy, two surveys are designed and are conducted by researchers from the Voinovich Center at Ohio University to different samples of people, one to possible adopters of alternative energies, and other to a larger random sample. These factors are combined in an index that uses a multi-criteria analysis to compare both systems

In order to find the data from the systems to calculate the index, literature review on the specific systems is performed, using previous researches on fuel cells and commercial data from providers of the system, and using literature regarding coal fired power plants.

This study is important because allows the comparison of fuel cells and the traditional grid system in other terms besides the monetary aspect; and brings to the table another very promising alternative energy technology that has been rarely explored for residential applications.

CHAPTER 2

SUSTAINABLE CONSTRUCTION AND ENERGY

2.1 Sustainable Development

Sustainable development is defined by the World Commission of Environment and Development as “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” (Spence and Mulligan 1995; Bentivegna et al. 2002). Sustainable development seeks not only economic development, as most systems do, but also involves environmental and social issues as equally important factors for development (Hill and Bowen 1997; Barrett et al. 1999). It states that reaching all these priorities (economic development, social and environmental issues) is the only approach to satisfy the needs of the generations of today and tomorrow. Sometimes trade-offs among the priorities are necessary (van Pelt 1994); however, non priority must be attained at expenses of the others. This indicates that it is necessary to address social and economical needs while minimizing the negative impacts on the environment (Spence and Mulligan 1995; van Pelt 1994).

The major idea of sustainability is well understood, but there are varying approaches to it. Some people think of sustainability in a conservative way, which means no resources should be used, or if a resource is used, it is mandatory to replace it. There are other people who have developed a concept of endurance of resources; this concept understands the conservation of non-renewable resources as important, but also understands that the world is in a process of continuous change. For the second group of people, sustainable development is a course of change where exploitation of resources, technological development, direction of investment and all other changes must be in harmony to enhance the present and future generations to meet their own needs (Brandon 1999). A third group of people thinks there are certain ecological principles that have to be addressed in order to achieve sustainable development. First, the pollutant emission must not exceed the earth's assimilative capacity, and wastes must not be discharged to the environment faster than the rate they are assimilated; second, the rate of use of renewable resources must not exceed the rate at which they are renewed; and, third, non-renewable resources may not be consumed faster than the rate that substitutes can be found (Barrett et al. 1999; Bentivegna et al. 2002).

2.2 Sustainable Construction

The construction industry, including the material supply industry, is one of the major exploiters of natural resources (Bentivegna et al. 2002). This industry contributes significantly to global economic development (around 8-12% of the gross domestic product in most of the countries) (Spence and Mulligan 1995). However, this is considered unsustainable development, because its activities cause irreversible transformation of the natural environment. The contributions of the construction industry towards environmental stress are (Spence and Mulligan 1995):

- Loss of soil and agricultural land: soil used as raw materials in construction, and land converted to other uses.
- Loss of forest and wild lands: forests converted to other uses, and forests destroyed to get building timber, bamboo and other raw materials or as energy sources for material production.
- Air pollution: At local scale emission of dust, particulate matter, and toxic gases, both on the jobsite and on the material production process. At regional scale emission of nitrogen and sulfur oxides in material production; and, on a global scale, emission of chlorofluorocarbons, carbon dioxide (38% of the total amount released to the atmosphere is due to the construction industry) and other greenhouse gases (Ding 2005).

- Use of non-renewable energy sources and minerals: Use of fossil fuels for construction activities on-site and for production of raw materials. There are two types of energy within the construction industry: the embodied energy, which is energy used for the production of materials or energy used during the construction process; and the energy used during the lifespan of the building. Also, the construction industry uses some metals that have limited remaining exploitable reserves, such as lead, copper and zinc (Ding 2005).

Increasing the levels of construction activity is fundamental for development. But, if the construction industry continues its activities with the same patterns as it has done in the past, the environmental stresses it is causing will increase. Sustainability is not meant to restrict construction; however, construction activities need to be conceived in a different way. The construction industry could adopt a new pattern toward sustainability in order to reduce the environmental impacts (Spence and Mulligan 1995).

Sustainable construction is a means for the industry to contribute to the achievement of sustainable development. To achieve sustainable construction, there are three main issues. First, a management framework is important to integrate planning, design, construction, monitoring and facility management. It is important to involve the stakeholders in all stages of the project; it is also important to have a protocol for decision-making and that those involved in the decision-making process respond to sustainability in a positive manner (Brandon 1999; Brochner et al. 1999). Second, it is important to think of the whole project in a long-term approach, including the extraction of materials, their successive processing and transportation to the construction site, and the operation and disposal of the facility in the life span of the project. Third, it is important to think in terms of performance, not just on prescriptive design parameters. The team must have the ability to measure performance over time (Brochner et al. 1999).

Besides, there are several good practices that have to be performed in order to achieve sustainable construction that reduce the consumption of nonrenewable resources, minimize emissions and waste (Spence and Mulligan, 1995), and improve the health and well being of the occupants and the communities. These practices are important at the design stage, the construction stage, the occupational and maintenance stage, and the demolition stage (Crawley 1999).

2.3 Energy

2.3.1 Energy and Sustainability

The United States is the largest consumer of energy, consuming approximately 50% of the total energy of the world (Turner 1999), having the highest energy consumption per capita of the world (Gabbard 2007), moreover the construction industry plays an important role because it constitutes the 40% of the total energy consumption in the U.S.; the residential sector represents 37% of the national construction activity (Gould and Joyce, 2003), consuming 17% of the energy of the country.

There is an important relation between energy and sustainable development; because a society that wants to achieve sustainable development should make use of energy sources which cause no environmental impact, that in the long term are available at reasonable cost. However, so far non energy source has been found that causes no environmental impact, consequently two alternatives have emerged, one is to increase the efficiency of the systems to transform and transport energy, and the other is to use renewable sources of energy(Dincer and Rosen 1998).

2.3.2 Characteristics of Adopters of Alternative Energies

Even though there are very few researches about the characteristics of adopters of alternative energies, there are some researches about adopters of solar energy systems. Labay and Kinnear (1981) developed a research about adopters and non adopters of solar energy. They divided the population (N=361) in three groups: consumers of solar energy systems, potential consumers who have knowledge about this technology but who have not installed the system, and potentially consumers who do not have knowledge about this kind of system.

Comparing the adopters with the general population the adopter is younger (mode=35, range 26-45), more highly educated (median= college degree), higher in income (median= $20,410 in 1981), earlier in the family life cycle (mode= full nest I) and higher in occupational status (mode= professional/semi-professional; there are few single adopters, but there are a large amount of adopters in the early marriage stage. Adopters think solar energy offers advantages. They think is less financially risky, less complex, and more compatible with their personal values.

Labay and Kinnear (1981) evaluated some factors of importance in the decision making process of adopting solar technology; from the product stand point the adopters seek quality and reliability of the system, quality and reliability of the installer, service availability, product warranties, relative efficiency of current systems, and the adopters are concerned with installation difficulties. From the economic point of view the adopters are concerned with the rising of future costs of other energy sources; they take into consideration initial cost of the system, payback period, and government incentives. From the social perspective the adopters are concerned with energy conservation, socially responsible behavior, and aesthetic appearance of the system.

CHAPTER 3

FUEL CELLS

3.1 An Introduction to Fuel Cells

A fuel cell (FC) is an electrochemical system that converts chemical energy directly into electricity DC (Direct Current) and thermal energy (Kazim 2001; Ellis et al. 2001; Beausoleil-Morrison et al. 2002; Rahman and Tam 1988; Kordesh and Simader 1995). Fuel cells were invented in the mid 19th century to convert chemical energy to electricity. The evolution of this device has been very slow due to economic factors and material problems (Carrette et al. 2000; Song 2002; Acres 2001; Kordesh and Simader 1996). The process is very efficient because it is direct and does not have to pass through any mechanical energy conversion (Thomas and Zalbowitz 1999). It consists of two electrodes (an anode and a cathode) and an electrolyte, typically platinum based, placed between the electrodes (Song 2002; Thomas and Zalbowitz 1999). The hydrogen fuel is provided to the anode, where it is oxidized and catalytically split into electrons and protons. Electrons go through an external circuit, and the oxidant agent, oxygen, is provided to the cell by the cathode where it is reduced using electrons from the external circuit. Ions go through the electrolyte to balance the flow of electrons and combine (Ellis et al. 2001; Carrette et al. 2000) as shown in Figure 1.

Besides the electricity generated as result of this process, heat and water are produced as byproducts (Rahman and Tam 1988). The DC that is created from the electron flow beginning on the anode to the cathode depends on the chemical activity and on the amount of fuel provided. The production of this current is continuous and lasts until the supply of fuel stops (Song 2002; Kordesh and Simader 1996). Because of their low emission FC can be installed near the place where the power is needed (Kordesh and Simader 1996).

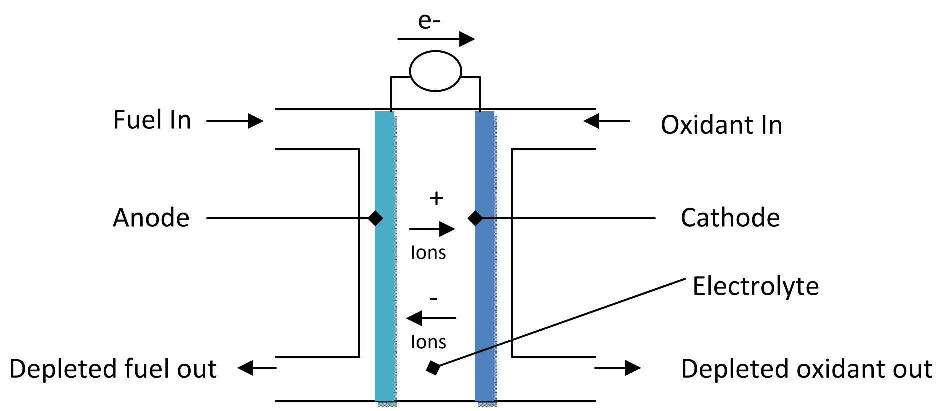

Figure 1 Fuel Cell Device. Adapted from Ellis et. al (2001)

The FC system is composed by the FC stack, the fuel processor, the air management subsystem, the water management subsystem, the converter from DC to Alternating Current (AC) or power conditioning subsystem, and the thermal energy management subsystem (Ellis et al. 2001; Rahman and Tam 1988; Erdmann 2003) as shown in Figure 2.

The FC stack configuration depends on the type of FC used. The voltage delivered by one single fuel cell is not sufficient to supply the energy needed for certain applications, therefore several cells are arranged in series to form the stack (Carrette et al. 2000, Song 2002). This makes the system modular so can be built depending on the power requirements, from hundreds of watts to megawatt size (Kordesh and Simader 1996).

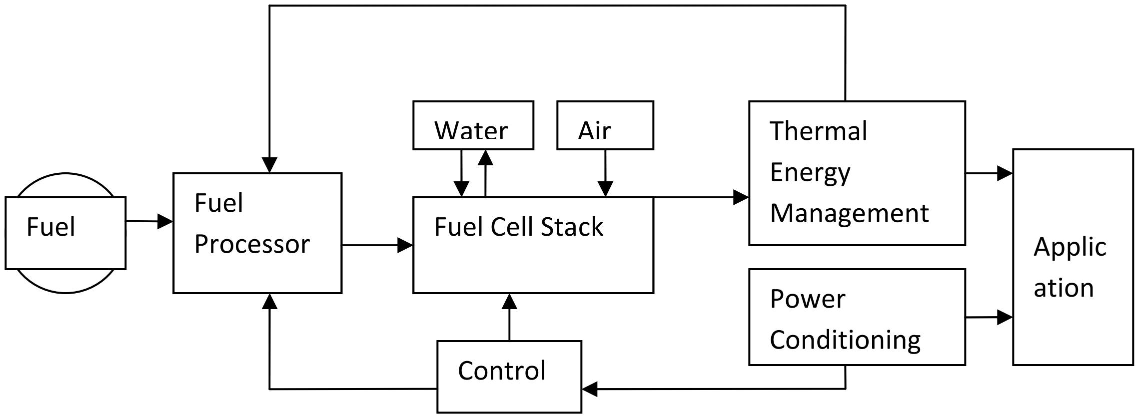

Figure 2 Fuel Cell System

The fuel processor converts the fuel or hydrogen carrier to a hydrogen rich fuel stream. Its complexity depends on the type of FC used and on the hydrogen carrier: a low temperature FC requires a purer hydrogen stream (sulfur and carbon monoxide free) (Song 2002) than high temperature FC. Besides there are FCs that have this process integrated to their system and others that have an external unit (Ellis et al. 2001; Carrette et al. 2000).

The air management subsystem provides oxygen usually found in the form of air, through an air compressor or a blower depending on the needed pressure. The first one consumes larger amounts of power. The water management subsystem removes water produced by the reaction from the exhaust, and then it stores that water and pumps it at the desired pressure to the operation that requires it, that is, fuel processing or humidifying the fuel cell when needed (Rahman and Tam 1988).

The thermal management subsystem recovers the energy released as heat, and distributes it where it is needed. The amount of energy produced depends on the type of fuel cell used (e.g., low temperature or high temperature). For instance, the energy can be distributed to the fuel processing system, to the hot water cogeneration system, to the heat cogeneration system, or if it is not needed, the system releases it to the surroundings (Rahman and Tam 1988).

The power conditioning subsystem converts the electricity generated in the fuel cell to current and voltage that can be used for different applications and also provide the power that is necessary for other subsystems to work properly (Ellis et al. 2001).

Even though FCs were invented in the 19th century, one of the most important and successful applications of them was as a source of energy for space aircrafts, i.e., the Apollo vehicle in 1960s. Non commercial applications had been developed beforehand and the evolution of such market has been very slow (Erdmann 2003; Carrette et al. 2000; Gacciola et al. 2001; Acre 2001). The reasons for the slow evolution are mainly economical, since it is necessary to reduce the cost of the cell stack by raising the effectiveness of the precious metals and other materials, and to improve large scale production. There are also technical problems with some materials; it is necessary to optimize materials to improve durability and resistance of gas impurities, On the other hand, there are safety and technical difficulties with hydrogen storage and with the fuel processing. In addition, wide testing in real circumstances is necessary before operating deficits turn out to be evident (Acres 2001; Song 2002).

3.2 Hydrogen and Hydrogen Carriers

The most important fuel for FCs is hydrogen because it has an excellent electrochemical radioactivity, has no emissions (Thomas and Zalbowitz 1999; Kordesch and Simader 1996), and is the best energy carrier (Turner 1999). It is the most abundant element in the earth, but cannot be found by itself in nature, and instead it is carried and stored by other compounds e.g. hydrocarbons, alcohols, ammonia, hydrazine, metal hydrides, water (Carrette et al. 2000; Thomas and Zalbowitz 1999; Ganley et al. 2004). Then such hydrogen carriers need to be processed into hydrogen rich gas by different methods as catalytic steam reforming, partial oxidation, auto-thermal reforming, electrolytic conversion, etc. Finally for low temperature FCs (less than 250 C), a cleanup process (preferential oxidation, membranes, methanation, etc.) needs to be performed to the gas stream (Carrette et al. 2000). The different paths for hydrogen production are shown in Figure 3.

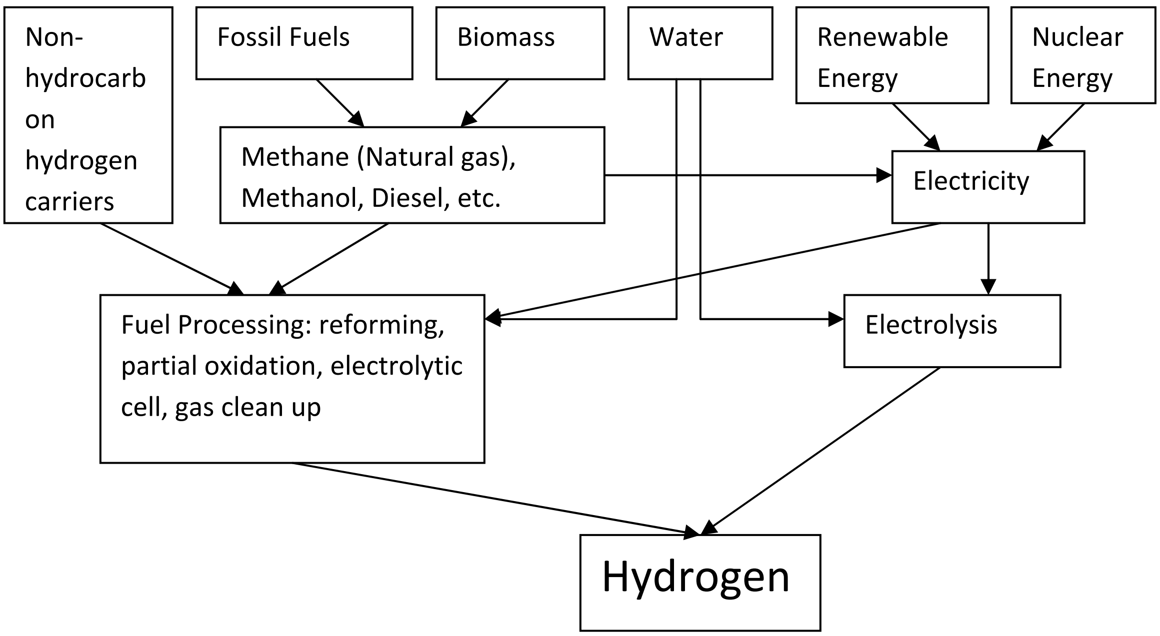

Figure 3 Different paths for the production of hydrogen

Catalytic Steam Reforming is performed to light hydrocarbons and alcohols. It is an endothermic process, and energy needs to be provided to the process. Partial oxidation is an exothermic process usually performed to heavy hydrocarbons; it is similar to a combustion process (Carrette et al. 2000).

The principal hydrogen carriers are:

- Alcohols: Methanol is particularly a good hydrogen-rich fuel because can be easily transported and have little safety constrains. Besides its industrial production is based on natural gas that is already available (Carrette et al. 2000; Kordesch and Simader 1996), even though it is not a renewable source. However, it can be produced from biomass becoming a renewable source (Kordesch and Simader 1996). In MCFC, SOFC, and DMFC could be used without an external reformer (Carrette et al. 2000). To extract hydrogen from methanol, a catalytic steam reformer process, auto-thermal reforming or partial oxidation process can be performed, but the most effective is the catalytic steam reformer, which can take two different pathways. The first one decomposes the methanol into hydrogen and carbon monoxide, this carbon monoxide then reacts with water to form carbon dioxide and more hydrogen; the second pathway can be a reaction of methanol with water to directly form carbon dioxide and hydrogen (Carrette et al. 2000; Kordesch and Simader 1996).

- Hydrocarbons: include oils, coals, coal gas, natural gas, etc. Natural gas is abundant in many places and is easily available because already exists an infrastructure to transport it. Although it is considered a non renewable resource because it is found in nature as fossil fuel, it can be produced as a result of the anaerobic digestion of biomass becoming a renewable resource. To extract hydrogen from hydrocarbons a catalytic steam reforming process, partial oxidation or auto-thermal reforming process need to be performed. Natural gas can be fed directly to the high temperature FC (Carrette et al. 2000). Approximately 95% of the hydrogen produced is by steam reforming of natural gas, because is the most efficient method of production (Thomas and Zalbowitz 1999); 41,280 KJ of energy are consumed to get 1 Kmol of hydrogen (Kordesch and Simader 1996). The natural gas reforming process consists in converting the natural gas in hydrogen and in carbon monoxide, most of the times an additional process is required to convert the carbon monoxide to carbon dioxide, so it does not poison the FC (Wolk 1999; Song 2002).

- Ammonia: is produced industrially by the reaction of methane with steam and air; and is easy to find transport facilities because it is already used in different applications (e.g., fertilizers) and because it can be transported at ambient temperature as liquid (Kordesch and Simader 1996). Besides, ammonia can be found in waste water. Ammonia can be decomposed in nitrogen and hydrogen through a catalytic decomposition process (Ganley 2004; Choudhary et al. 2001; Vitse et al. 2004). The most important advantage of this hydrogen carrier is that it does not have carbonaceous species that poison low temperature FCs (Carrette et al. 2000; Choudhary et al. 2001) and that contribute to the greenhouse effect (Kordesch and Simader 1996). Ammonia can be used in alkaline FC, but it is difficult to use in acid electrolytes because it can have an effect similar to the CO in alkaline FC (Kordesch and Simader 1996). It can be used in acid FC if the unreacted ammonia in the hydrogen stream is removed before it is supplied to the FC (Choudhary et al. 2001). Safety can be an issue, because it is flammable at 16-25% by volume in the air and it is toxic above 25 ppm (Vitse et al. 2004), however the storage and handling are processes that are already solved and standardized (Kordesch and Simader 1996). It has not been proven in many applications, but the Analytical Power Corporation from Boston, MA, uses an ammonia cracker to power a FC power plant (Carrette et al. 2000) and several researchers have been working on the optimization of this process (Choudhary et al. 2001; Vitse et al. 2004; Ganley 2004).

- Water: hydrogen can be produced from water by electrolysis. It is the purest method and can be completely emissions free if the energy used to perform this process is renewable (hydropower, solar energy, or wind energy) (Carrette et al. 2000; Turner 1999), because the only products of the electrolysis of water are hydrogen and oxygen (Thomas and Zalbowitz 1999). Water is split in those products by passing a direct current through water previously made electrically conductive (Kordesch and Simader 1996). Water can be considered as an unlimited source of hydrogen, because, it is also the product of the FC (Kordesch and Simader 1996). The main problem with water electrolysis is the energetic cost because 242,000 KJ of energy are required to produce 1 Kmol of hydrogen (Kordesch and Simader 1996), almost 6 times more than the production of hydrogen from natural gas.

- Algae: there is some type of algae that can be tricked to produce hydrogen as a substitute for oxygen (normal photosynthesis process). However, this process is not well studied yet (Carrette et al. 2000).

Hydrogen can not only be stored in hydrocarbons, or any other hydrogen carrier; it also can be stored as pure compound (gaseous or liquid) or can be bounded to metals and other chemicals (Carrette et al. 2000). Pure hydrogen: safety is a major issue when the hydrogen is stored because the hydrogen-air mixtures are explosive, but not as explosive as other gases. Hydrogen does not present harmful physiological effects, it is not poisonous, but inhalation of the gas produces sleepiness, danger of asphyxiation exists as with other gases. If the oxygen content decreases below 18% because of the hydrogen accumulation, and if there is direct contact with the skin can lead to frost bite (Kordesch and Simader 1996). Besides, storing gaseous hydrogen is not easy, because it is difficult to compress, therefore the size of the tanks would be a problem. On the other hand liquid hydrogen is also a problem because the tanks where it is stored have to be much insulated and the amount of energy necessary to convert gaseous hydrogen into liquid is extremely high (Carrette et al. 2000).

3.3 Types of Fuel Cells Stacks

The fuel cells can be classified depending on the electrolyte used, the operating temperatures and the required fuel (Erdmann 2003; Carrette et al. 2000).

3.3.1 Proton Exchange Membrane Fuel Cell (PEM or PEMFC)

The PEMFC consists of porous carbon electrodes bounded to a solid polymer membrane or electrolyte, which is located between two collector plates that offer an electrical path from the electrodes to the external circuit (Ellis et al. 2001; Carrette et al. 2000; Song 2002). The use of a solid electrolyte prevents the corrosion and leakage associated with liquid electrolytes FC (Song 2002). The fuel has to be hydrogen and any traces of other compounds such as CO can poison the cell; the oxidant is air (Erdmann 2003; Cleghorn et al. 1997), that is why it is one of the most environmental friendly FC, as the fuel has to be pure hydrogen, the only byproduct is water (Kazim 2001). The water management is crucial in this kind of cell because the membrane needs to be wet to maintain high conductivity; even though water is produced as byproduct of the reactions in the cell it is difficult to retain in the membrane (Carrette et al. 2000), to avoid this problem the inlet gas must be heated to the operating temperature and humidified to 80-90% (Ellis and Burak-Gunes 2002).

The efficiency of PEMFC is around 50% (Ellis et al. 2001). The cell operates at low temperature 85^{o} -105^{o} C (Ellis et al. 2001; Carrette et al. 2000; Burak-Gunes 2001), and the usable temperature is less than 70^{o} C (Erdmann 2003) as a result the cell can reach the operating temperature quickly. Considering these characteristics and that the power density is high, this type of FC is the most promising one to replace the automobile engine; the technology can also be suited for small residential and commercial applications (Song 2002; Kazim 2001; Prater 1996). As the temperature of this FC is lower compared to other FCs, precious metals such as platinum need to be used to enhance the reactions (Ellis et al. 2001; Carrette et al. 2000), but the start up is instantly (Song 2002; Kazim 2001; Cleghorn et al. 1997). The fuel cell capacity is between 2 to 250 KW (Erdmann 2003). These FCs were the first to be used in the space, but the system was unstable, so NASA opted for the Alkaline FC (AFC) as better fit for their applications (Carrette et al. 2000).

3.3.2 Direct Methanol Fuel Cells (DMFC)

The DMFC uses a polymer membrane as electrolyte. The fuel is methanol, which can be obtained from natural gas or from renewable biomass, and can be easily transported, in the existing infrastructure to transport petrol. The methanol is dissolved in water and directly supplied to the anode, so this kind of fuel cell system does not need a fuel processor. The oxidant used is air (Ellis et al. 2001, Erdmann 2003). It is a low temperature FC, similar to

PEMFC, even though it can operate at slightly higher temperatures (Carrette et al. 2000). The efficiency and the power density of the DMFC is low compared to the efficiency of other type of fuel cell, but it can be comparable with batteries, due to its simplicity and portability, its most promising application is as replacement of batteries in portable devices (Ellis et al. 2001; Carrette et al. 2000).

3.3.3 Phosphoric Acid Fuel Cell (PAFC)

The PAFC consists of a porous matrix that holds the liquid phosphoric acid electrolyte surrounded by porous carbon electrodes and carbon collector plates on both sides of the assembly. The matrix may present leakage problems. The PAFC has (Ellis et al. 2001; Carrette et al. 2000). The efficiency is around 50%, but the power density is low. The operating temperature is 200^{o} C (Ellis et al. 2001; Carrette et al. 2000), and the usable temperature is 60 ^{o} – 120^{o} C (Erdmann 2003). With this temperature, the process of heat recovery can be performed, thereby allowing for water and space heating in building applications (Ellis et al. 2001). However, the temperature is still low so the use of precious metals for catalysis is still needed. The principal fuel used is natural gas using an external reformer, and the oxidant is air (Erdmann 2003). There are no problems associated with this FC regarding water management and it has some tolerance to hydrocarbons (unlike other low temperature FC) (Song 2002).

PAFCs were the first FC commercially available (Ellis et al. 2001; Carrette et al. 2000), because their construction is very simple, are stable thermal, chemical and electrochemically, and the volatility of the electrolyte is low (Carrette et al. 2000). The application of these cells has been shown through the U.S. Department of Defense Demonstration program. By 2001 had placed more than 30 fuel cells for boiler plants, hospitals, dormitories, and office buildings, besides other applications include the First National Bank of Omaha and the Conde Nast Building in Times Square New York (Ellis et. al 2001). These projects have demonstrated technical feasibility, but for this system to be economically feasible the cost needs to be reduced by a factor of three (Ellis et al. 2001). By 2002 more than 70 projects using PAFC had been built around the world, particularly in the United States, Europe, and Japan, to supply electricity, hot water, and heat to cities, malls and hospitals (Song 2002). The capacity of this FC is between 50 KW and 20 MW (Erdmann 2003).

3.3.4 Molten Carbonate Fuel Cell (MCFC)

The MCFC consists of a porous substrate that holds the molten carbonate electrolyte surrounded by a nickel and nickel-oxide electrodes (Song 2002). The collector plates are made of stainless steel, that are less expensive that the materials used for other type of FCs. This cell operates at 650^{o} C (Ellis et al. 2001; Carrette et al. 2000) and the usable temperature is 400^{o} C (Erdmann 2003). Catalysts are not required and heat can be used for cogeneration applications in buildings (what makes the system very efficient). At these high temperatures an internal reforming process can be performed, therefore different fuel gases (usually natural gas) can be directly injected to the cell stack without any previous fuel processing (Ellis et al.2001; Erdmann 2003; Carrette et al. 2000; Acres 2001), thereby facilitating the use of natural gas directly from the available distribution system. Carbon dioxide and carbon monoxide are not a problem because they do not interfere with the correct functioning of the FC (Carrette et al. 2000). The efficiency of this FC is between 50-60%, but using also the heat in a cogeneration system can reach efficiencies of 85% (Song 2002).

MCFCs are used for mid to large size stationary power applications, whereas the target market includes distributed generation systems and building cogeneration systems (0.1 – 3.0 MW) (Ellis et al. 2001; Erdmann 2003).

3.3.5 Solid Oxide Fuel Cell (SOFC)

The SOFC consists of a ceramic solid electrolyte that can be modeled in different configurations (tubular, segmented tube, flat plate, and monolithic). The most common is the tubular. Because of its solid materials the electrolyte is more stable; neither has a leakage problem nor water management difficulties (Carrette et al. 2000; Song 2002). It Operates at temperatures between 800^{o} - 1000^{o} C (Ellis et al. 2001; Song 2002) and the usable temperature is 300^{o} – 600^{o} C (Erdmann 2003), what makes the system very simple and allows an internal reforming process. It does not need fuel compressor, and can use natural gas or heating oil as direct fuels. Carbon dioxide or carbon monoxide do not poison the cell. This avoids the delivery or storage of hydrogen, besides high temperatures facilitate the cogeneration systems (Ellis et al. 2001; Erdmann 2003; Beausoleil-Morrison et al. 2002). Even heat can be used as electricity by conventional thermal conversion. However, it is difficult to select the appropriate materials that can provide the thermal and chemically stability needed (Carrette et al 2000). The efficiency of this FC is between 50-60%, but with a combined system for heat use the efficiency can be as high as 85% (Song 2002).

The most important development efforts are based on lowering the temperature to 650^{o} C, therefore the cogeneration systems are still possible, and there are still not many problems with the materials used. There are a wide range of possible applications of this kind of FC, which go from small applications like residential applications, vehicle applications to large utility scale applications (Ellis et al. 2001). The capacity of this FCl is between 2 KW to 300 MW (Erdmann 2003).

3.3.6 Alkaline Fuel Cell (AFC)

The AFC uses an aqueous solution of KOH (potassium hydroxide) as electrolyte at concentrations between 30 – 45 wt% retained in a solid matrix (Carrette et al. 2000; Song 2002). The main advantage of this cell is that it has the highest electrical efficiency, the oxygen reduction in alkaline media is much faster than in acid media, and the system design is very simple (Carrette et al. 2000). The most important disadvantage is that the hydrogen supplied to the cell needs to be pure, because impureness poison the cell, and the oxidant needs to be oxygen because if traces of carbon enters the system carbonates are formed and destroy the electrolyte (Erdmann 2003; Carrette et al. 2000). The operating temperature is usually less than 100^{o} C (Carrette et al. 2000), and the usable temperature is 60^{o} – 90^{o} C. The capacity of this FC is between 20 – 100 KW (Erdmann 2003). It was the first FC used successfully in the space applications e.g. Apollo lunar mission (Carrette et al. 2000; Acres 2001) and by 2002 it was the only use so far (Song 2002). This kind of fuel cell can be applicable when fuel processing systems are well developed for other compounds and processes such as water electrolysis (Acres 2001).

3.3.7 Regenerative Fuel Cell

The regenerative FC is a does not have an external fuel processor, it splits water in hydrogen and oxygen through an electrolysis process, and then it uses that hydrogen to generate electricity. This is the cleanest FC but the energetic and economic cost of making the process reversible is extremely high. When this system is used with a renewable energy as initial source of energy, the emissions from the FC is considered zero (Thomas and Zalbowitz 1999).

3.4 Characteristics of a Fuel Cell

A FC has some characteristics that make it a unique device to transform energy such as modularity, efficiency, environmental impact, maintenance, cost, ramping capability, reliability, noise, size, and safety that will be explained below:

- Modularity: a FC stack can be easily scaled to different configurations depending on the amount of power required for certain application, increasing or decreasing the number of cells that are composing the stack (Ellis et al. 2001; Rahman and Tam 1988; Song 2002; Cleghorn et al. 1997). However, there are authors who state that the development of small capacity power generation is still a problem, and needs further research (Gacciola et al. 2001).

- Efficiency: the conversion from chemical energy to electricity efficiency of the FC can be around 50%, and can reach over 80% when the heat is used as part of the system and is not released to the atmosphere (Ellis et al. 2001; Rahman and Tam 1988; Carrette et al. 2000; Burak-Gunes 2001; Song 2002; Cleghorn et al. 1997; Gacciola et al. 2001). Besides, FC consumes low fuel when idle (Rahman and Tam 1988). This makes the FC almost three times more efficient than the internal combustion engine (Song 2002); therefore, even when the FC is fueled with fossil fuels there is a significant reduction of fossil fuels utilization and of greenhouse gases emission (Kordesh and Simader 1995). An important characteristic is that the efficiency is not affected by the load, so the efficiency is going to be the same no matter if the FC is operating at full load or at a lower load (Wolk 1999).
- Environmental impact: if hydrogen is produced from renewable resources, the only emission found in the system is water, eliminating the carbon dioxide production, as well as byproducts such as carbon monoxide, NOX, and SOX of the combustion engine (DOE 2007). On the other hand when methane or other fossil fuel is used to produce the hydrogen, as the efficiency is larger than the efficiency of the combustion engine, the amount pollutant byproducts is much smaller per watt of power generated (Ellis et al. 2001; Carrette et al. 2000; Wolk 1999; Cleghorn et al. 1997; Gacciola et al. 2001).

As the emission from the FC is just water during operation, the dominant factor to assess its environmental impact lies on the manufacturing process. Phent (2001) performed a Life Cycle Assessment (LCA) of the production of a 75 KW PEMFC for vehicles and a 275 KW PEMFC for stationary applications at Ballard. The investigated system consisted of an array of two stacks, these included membrane electrode assemblies (MEA) and graphite flow fields. The elements of the MEA were the cathode and the anode; the graphite that allowed the feeder of the hydrogen and oxygen and conducted the generated electricity. In addition there were platinum group metals (PGM) that catalyzed or enhanced the kinetics of the reaction. The LCA encompassed the materials and the production steps.

The PGM is produced mainly in South Africa by mining processes, which results in significant environmental impact due to the emission of sulfur dioxide. The graphite has two different production paths, natural graphite existing in several locations, being China the main producer, or manufactured graphite, typically produced from coke and coal. Both types consume significant amounts of energy for the production process. The proton exchange membrane production is based on tryfluorostyrene that needs very strong solvents.

The PEMFC production process has the following steps: production of the gas diffusion electrode including the application of the catalyst, production of the membrane, joining the electrode and the membrane, fabrication of the bipolar plate, assembly of the stack, and testing.

The energy necessary to produce a stationary FC is 5,100 MJ/KW if no recycled materials are used and 1,446 otherwise; the global emissions in Kg/KW for FC with recycled materials and with non recycled materials are respectively CO_2 78 and 275, CH_4 0.2 and 0.5, N_2O 0.014 and 0.019; the local emissions are SO_2 0.17 and 0.73, CO 0.10 and 0.14, NO_x 0.14 and 0.74, Dust and Particles 0.03 and 0.14, NH_3 2.0E-03, and 2.5E-03. (Pehnt 2001).

Most researchers affirm that the environmental impact of the FC during it operation is almost negligible, because the only byproducts are water and heat; however there are few researchers that have addressed possible problems that could be caused to the environment due the intensive use of FC. Tromp et al. (2003) state that the widespread use of FC could have an unknown environmental impact because of emissions of molecular hydrogen, according to them H_2 is a trace constituent of the atmosphere and contribute to the chemical cycle of H_2O, greenhouse gases and other pollutants. It is difficult to forecast the real impact of FC on the environment; however it is possible to affirm that losses of H_2 to the atmosphere on the order of 10% are going to be presented because of the production, storage, and transport. One important impact is the moisturizing of the stratosphere which would result in cooling of it and would delay the recovery of ozone layer.

- Maintenance: as the FC stack does not have any moving parts, the maintenance required is minimal (Kordesh and Simader 1995, Pehnt 2001). The cell stack needs to be replaced after 40,000 hours of operation or 5 years approximately for stationary applications (McEntee 2005). The other components of the system require a routine maintenance typical of compressors, fans, controls etc; the expected life of such mechanisms is around 20 years (Ellis et al. 2001; Wolk 1999). The entire maintenance of the system can be performed by semi skilled manpower, once or twice a year (Rahman and Tam 1988).
- Cost: The maintenance cost is around $0.03/ kWh, and the installed cost is approximately $5,600/ KW of capacity. To be competitive with conventional systems the installed cost must not be above $1,000/KW - $1,500/KW of capacity (Ellis et al. 2001; Wolk 1999).
- Fast ramping capability: a fuel cell can go from idle to full load capacity in milliseconds (Rahman and Tam 1988; Cleghorn et al. 1997).
- High reliability: as long as the supply of fuel is constant, the generation of power is continuous (Carrette et al. 2000; Song 2002). And due to its low maintenance the system will not be stopped more than twice a year (Rahman and Tam 1988).
- Quiet: a 40 KW has a sound of 68 dB at a distance of 10 Ft (Rahman and Tam 1988), which makes a FC a noiseless device (Song 2002; Kordesh and Simader 1995).
- Size: compared with other sources of power generated or stored on site, such as batteries, solar power, wind power etc; fuel cells are smaller and lighter (Thomas and Zalbowitz 1999). A 1 KW FC manufactured by Ballard that is being used for the residential market in Japan is 43 cm long, 17 cm wide * 23 cm high, the dry weight is 20.5 Kg and occupies a volume of 0.017 m^3 (Ballard 2007).
- Safety: If hydrogen is handled appropriately it is as safe as any other common fuel. It has some properties that are advantageous; is much lighter than air therefore it flows up very

quickly, its molecular weight is 2.02, while methane is 16.04 and gasoline is 100, has high diffusivity (20 m/sec) therefore in an open environment it disperses very fast and is very difficult that it reaches flammable concentrations (4%-75%), the auto ignition temperature is high compared with other fuels (hydrogen=585 C, methane= 540 C, and gasoline= 230-480 C). Hydrogen is non toxic and non poisonous, its solubility in water at normal atmospheric conditions is low; therefore it does not contaminate water reservoirs. Hydrogen is odorless, colorless, and tasteless. (DOE 2007)

As hydrogen burns with a blue almost invisible flame, leak detector sensors have to be installed on the system to eliminate the hazard of any undetected flame. On the other hand hydrogen by itself can not explode, an oxidizer such as oxygen has to be present, thus the system has to be very tight to not allow any air in before the oxidation process.

3.5 Fuel Cells for Buildings

FCs are a promising technology for buildings because they offer the potential of cogeneration, therefore the efficiency of the system can be augmented by an extra 30 to 40% (Ellis and Burak-Gunes 2002; Ellis et al. 2001) utilizing the FC not only to generate the electricity needed in the building, but also providing the heat and hot water required (Beausoleil-Morrison et al. 2002;Carrette 2000), as the FC needs to operate continuously the start up time is not a criterion (PAFC y PEMFC have a quickly start up, but MCFC and SOFC not) (Ellis et al. 2001). The FC system specifically for buildings does not differ much from the system previously described. However, the power conditioning subsystem depends on the application of the FC in the building system. In a grid independent application the FC needs to provide the entire power load, therefore all energy generated has to be transformed from DC to AC. In a backup power application, two or more power systems are needed to improve reliability. For example, the grid can be the primary source and the fuel cell can be used when the grid presents failure, or the

FC can serve as primary supply of power and the energy from the grid can be used when the amount of energy supplied by the FC is not enough to satisfy the energy requirements. Regardless of the situation, both systems are not going to act simultaneously. The power conditioning system must monitor the grid or the FC supply and initiate to provide the backup power whenever it is necessary. In parallel power applications the FC and the grid supply the power at the same time; the power conditioner has to synchronize the voltage and the waveforms of both systems and must include interlock relays to avoid energy from the FC going into the grid. Finally in utility interconnected applications the FC supplies power to the building and also can provide power to the grid, requires features to measure the flow of power to the grid (Ellis and Burak-Gunes 2002).

Usually FC systems are located in typical equipment spaces such as parking lots, rooftops, and basement mechanical rooms (Ellis and Burak-Gunes 2002). By 2002 the cost of a 200 KW PAFC was $5,500/ KW. To be competitive a cogeneration system cost needs to be reduced to $1,500/KW (Ellis and Burak-Gunes 2002).

In the case of FCs for stationary applications there are three main groups. The first one is large size FCs (250 KW – 10 MWe) appropriate for power stations. The second is medium size (10 KW – 300 KW) designed to supply the energy requirements of large buildings and commercial applications; and the third is the small size (1-10 KW) FC more suitable for residential and small commercial applications (Cacciola et al. 2001). Thus MCFC, PAFC, DMFC, and SOFC are more suitable for large and mid size applications (Carrette et al. 2000), while PEMFC, SOFC (Erdmann 2003; Carrette et al. 2000; Burak-Gunes 2001), and PAFC (Carrette et al. 2000) are more appropriate for small size applications. For the third group each FC has different advantages and disadvantages. The SOFC operates at higher temperatures so more heat can be used for cogeneration applications. It does not necessarily need a fuel compressor and can use natural gas without any external reforming. On the other hand, this FC has lower capacity to adapt to changes in the demand. The PEMFC has better capacity to adapt to changes in demand and can be more compatible with mobile applications, but the operating temperature is still very low for cogeneration systems (Erdmann 2003; Carrette 2000). The usable temperature must be increased over 100C for the system to be more suitable for cogeneration application (Cacciola et al. 2001). The PAFC operating temperature can make it suitable for cogeneration (Carrette 2000).

By 2001 SOFCs had been demonstrated in hospitals, boiler plants, telecommunications facilities, and other buildings (Ellis et al. 2001). Beausoleil-Morrison et al. (2002) developed a model of a cogeneration system within residential buildings. They modeled a SOFC fed by natural gas; due the high temperature of the FC the fuel processing is made by internal reformer, therefore avoiding the storage of hydrogen in the building. The system provided thermal energy for space and water heating. The FC system consisted of the internal reformer SOFC, a power conditioning system to convert DC to AC, and a heat exchanger to extract thermal energy from exhaust gases and provide it to cover the house thermal requirement. A comprehensive simulation tool was developed to model the thermal performance of the building serviced by the system. In the model, the thermal output of the system is transferred to a water storage tank, which supplies the hot water requirements of the building and is connected through a pump to a fan coil system that provides the space heat necessities. There is a gas burning system to provide heat whenever the temperature drops a set point (50^{o} C) and a safety device to extract heat whenever the temperature exceeds a safety point (65^{o} C). For a typical size house of four people located in Montreal an annual simulation was performed with a five minutes interval. For the full year the system meets 99% of the house electrical demand and 36% of the house thermal requirements. The total efficiency of the system, including electrical conversion and thermal supply was 68%.

Burak-Gunes (2001) developed a model for a total energy system which provides electricity and thermal energy to meet the energetic requirement of a 2100 SF, 4 people house in the United States. The system consists of a PEMFC, an electric heat pump and a thermal storage tank. The thermal energy of the fuel cell is transferred to the thermal storage tank, which principal objective is to store thermal energy during low thermal energy demand period, and supply it during high demand period, lowering peak demand. The tank is also used for domestic water and space heating, when the thermal energy is not enough, so heat is supplied electrically. During the cooling season electricity is used to operate a heat pump in air conditioning mode; lights and appliances are powered by electricity all the time. The model output determined that the FC must be sized 4 KW for southern locations and 5 KW for northern locations, the cogeneration efficiency was 78%, the optimum size of the storage tank is 300 L. This system represents 32 to 51% primary energy savings over conventional systems.

By 2001 Sanyo was developing a 2-3 KW PEMFC cogeneration system fuelled by natural gas (Cacciola et al. 2001); Plug Power formed a joint venture with General Electric to develop a 7 KW PEMFC for domestic use not connected to the energy grid (Cacciola et al. 2001; Burak-Gunes 2001; Hoogers 2003); Siemens-Westinghouse was commercializing a 5 KW SOFC prototypes (Cacciola et al. 2001); Sulzer-Hexis was commercializing 3-5 KW SOFC prototypes (Cacciola et al. 2001; Hoogers 2003); Avista Corporation, United Technologies, ReliOn, and H Power Corporation, were working in similar residential applications (Burak-Gunes 2001); Ballard Generation System was working with Ebara Ballard from Tokyo to develop a natural gas reformer as part of a 1 KW PEMFC for the Japanese market, besides they were testing a 10 KW natural gas fuelled for industrial application (Hoogers 2003); Teleydene Energy Group and Energy Partners announced the development of a 3 KW PEMFC for residential grid connected applications (Burak-Gunes 2001; handbook); IdaTech was targeting a 3 KW PEMFC methanol powered residential FC (Burak-Gunes 2001; Hoogers 2003); General Motors presented a 5.3 KW PEMCFC for residential application based in automotive technology (Hoogers 2003).

After the 2001's research boom of FCs for residential applications, a strong drawback emerged. According to Ben Kroposki (2006) from the National Renewable Energy Laboratory, most of the applications were based on PEMFC and after testing those FCs, a problem became more evident regarding electrolyte poison due to CO traces in the reformed gas, and the costs of the system did not drop as expected. The companies that were performing research in this field in the United States postponed their research and have been exploring other different applications. According to Amy Anderson Clem (2006), IdaTech's marketing communications manager, that company is currently working in markets such as telecommunications, utilities and uninterruptible power supply (UPS) for applications from critical backup to industrial remote power requirements, residential fuel cells are undergoing significant additional development before future field deployments, therefore residential fuel cell systems are not offered at this time. Residential applications represent longer term opportunities, anywhere between 3 to 5 years. According to Sandra Saathoff (2006) from the ReliOn's media relations, marketing and communication department, their company targets mostly communications applications within the telecommunications, government and utility sectors; they do not focus in residential applications at this time. Engle (2005) explains what happened with Plug Power's developments: their 5 KW PEMFC (GenSys) came to the market for the adoption in homes and small business but it was too expensive, so it was installed where heavy subsides from agencies with clean energy ideas were provided; when they tried to sell their FC to unsubsidized customers their crunch began. After facing this problem their marketing strategy drastically changed, in 2003 they developed the Gen Core that is more suitable for industrial and telecommunication applications.

On the other hand, according to the marketing department of Ballard Power Systems (2006), a partnership with a Japanese joint venture, Ebara Ballard Corporation, they have been developing a residential cogeneration system for several years. Their cogeneration system is the result of strong technology development, marketing collaboration and hundreds of thousands of hours of validation and field trials. The system integrates Ballard's Mark 1030 1 KW liquid cooled cogeneration stack, Ebara Ballard's balance of plant, and fuel processing technology developed by Tokyo Gas and Nippon Oil Corporation (NOC). The Tokyo Gas designed reformer converts natural gas from the pipeline into hydrogen to power the fuel cell cogeneration system, while the NOC reformer technology converts kerosene. They have gained success in the Japanese residential market, now they want to expand their market to other parts of the world. In the United States the system is still not available.

3.6 Codes and Regulations for Fuel Cells for Buildings

The code that refers to installation of stationary fuel cells power systems is the NFPA 853 (NFPA 2007). It states that the FC should be installed over a firm foundation, anchored and protected from rain, snow, ice, freezing temperatures, wind, seismic events, and lighting, above the base flood elevation, should not block exits, the exhaust should not be near doors, windows, outdoor air intakes, and other openings. It has to have access, should be located far from combustible material and to any product that present fire hazards, during construction should comply with NFPA 241 standard for safeguarding construction, alteration, and demolition operations. For outdoor installation the FC has to be specified to be so, the intake should be far from the exhausts of the facility, the exhaust of the FC should be located 15 ft of any air intake or opening of the facility, the exhaust should not be heading walkways, non natural or artificial barriers should interfere with the air intake system, the FC should not be located near areas where chemicals, or hazardous or flammable materials are going to be stored. For indoor installation the FC should not be located in areas used for industrial purpose, it should be placed in a room separated by a 1 hour rating floor, walls, door, and ceiling. The penetrations to the room should be sealed with a 1 hour rating sealant. For roof installation the FC should be installed according to installation for outdoors and the roofing material should not be combustible.

For fuel supply and storage, the NFPA 853 (NFPA 2007) states that all piping should be marked and depending on the type of fuel the respective regulation and code shall apply. For ventilation and exhaust with the exception of outdoor installed FC, all systems have to have a source of ventilation, exhaust and makeup air designed to provide a negative pressure in the room. In terms of fire protection, the storage of any combustible should have a hydrant with a water supply of 946 L/min for two hours and the FC should have automatic fire detection and alarm system.

In addition to the requirements for all stationary FC, there are certain requirements or modifications for FC of 50 KW and less. For instance, the exhaust of the system should be placed at least 10 ft from any air intake or opening of the building for outdoor FCs. For indoor installed FC, if the fuel is natural gas, propane, methanol, ethanol, or fuel oil the partitions do not have to be rated. However most FCs that use a flammable liquid as fuel have to be installed outdoors with the exception of systems that contain less than 5 gal of liquid during operation including piping. The indoor piping should be solid pipe or tube insulated from the outdoor bulk fuel supply, and have a leakage detection system. A gas detection system should be installed except when the gas is odorized or is listed for indoor use (NFPA 2007)

CHAPTER 4

COAL FIRED POWER PLANT

4.1 Power Plant

Historically, the electricity in the U.S. is extremely linked to the use of coal as it has been the leading single source of electricity (Spath et al. 1999). In addition the U.S. has the largest reserves of coal of the world (DOE 2007). The world has 1,500 years of coal reserve at the current use rate (Gabbard 2007). More than half of the electricity produced in the U.S., between 52% and 56%, is generated from coal fired in thermal power plants (Gabbard 2007, Schneider 2004, Spath et al. 1999), and 87% of all coal consumed is used in coal fired power plants (Spathe et al. 1999); therefore there are about 600 coal fired power plants in the U.S. (UCSUSA 2005).

A thermal power plant converts chemical energy derived from the combustion of coal into electrical energy, passing through thermal energy and mechanical energy (Elliot et al. 1997). Before the combustion process, coal is prepared by crushing it to pieces less than 2 inches, and after it is crushed it is fed into a coal pulverizer. Then, throughout the combustion process the coal is combined with oxygen producing heat, carbon dioxide, sulfur dioxide, oxides of nitrogen, some trace compounds and water. The heat is used to heat up re-circulated water into steam in a steam boiler transferring the energy of burning coal to mechanical energy of the spinning steam turbine. The turbine generator consists of some steam turbines connected to a generator on a shaft that spins at 3,600 RPM generating 21,000 amps at 24,000 volts. The electricity then flows to a distribution net where transformers, transform it to usable voltage (Elliot et al. 1997, Spath 1999). The complete process has an efficiency of approximately 32% to 33% (DOE 2007, Spath et al. 1999).

4.2 Environmental Impact of a Coal Fired Power Plant

Coal-fired power plants are the single largest source of air pollution. Coal pollutes when it is mined, transported to the power plant, stored and burned (UCSUSA 2005). However, the environmental impacts of power plants are dominated by fuel production and combustion, thus the construction of the plant is 10 times less relevant than the operation in terms of environmental impact (Pehnt 2001).

The first step for the generation of electricity from coal combustion is coal extraction. 60% of coal mining is extracted from surface mines; the other 40% is extracted from underground mines (UCSUSA 2005). During coal mining, significant amounts of methane are released to the atmosphere, as methane is created by anaerobic digestion while coal formation takes place and is stored in the coal seams or surrounding rocks (Spath et al. 1999). Surface mining alters the landscape, produces great quantities of particulate matter and high emissions of airborne ammonia (0.001g NH_3 / Kg of coal) because of the production of ammonium nitrate explosives. On the other hand, underground mining releases greater amount of methane to the atmosphere (underground mining releases 1.91 g of CH_4/Kg of coal, while surface mining releases 4.23 g of CH_4/Kg of coal) because of higher pressures, and is a very hazardous occupation because of deaths and injuries caused by accidents, and by chronic health problems caused by methane exposure (UCSUSA 2005, Spath et al. 1999). After the coal is mined it is transported to the power plant. Coal transportation also causes great stress over the environment. To transport 1.4 million tons per year, it is necessary to use 14,600 railroad cars that rely on diesel fuel. The emissions from these locomotives encompass 1 million tons of nitrogen oxide and 52,000 tons of coarse and small particles per year in the U.S (UCSUSA 2005). When the coal gets to the power plant it is stored. Typically coal is stored onsite in uncovered piles, and dust and particulate matter are blown from those piles causing irritation to people lungs. In addition, rainfall causes runoff from these coal piles already contaminated with pollutants, to reach surface water and ground water (UCSUSA 2005).

Within the power plant the most significant impact is the combustion of coal (DOE 2007). The main byproducts of coal combustion are: i) carbon dioxide, being 38% of the carbon dioxide produced in the U.S. caused by electricity generation. 98% of the total emissions by weight of power plants is carbon dioxide at a production rate of 1,022 g/kWh, (Spath et al. 1999) ii)sulfur oxides; two thirds of the sulfur dioxide produced in the U.S is caused by power plants, 90% of this sulfur dioxide is from coal fired power plants, and 93.4% el the sulfur dioxide emitted in the U.S. is from coal (Schneider 2004, Spath et al. 1999); and iii) nitrogen oxides; 80.2% of the total nitrogen oxides emissions in the U.S. are from coal (Gabbard 2007, Spath et al. 1999). The most important global pollution problems are acid precipitation, stratospheric ozone depletion and the green house effect. The combustion of coal in power plants plays an important role on each of these problems. The acids produced after the combustion of coal are transported over great distances throughout the atmosphere and are then deposited as acid precipitation. This phenomenon is mainly attributed to the emissions of SO_x and NO_x. Coal power plants account for 70% of the SO_2 in the world (Dincer and Rosen 1998); In addition there is strong evidence that acid precipitation is also caused by volatile organic compounds, chlorides, ozone, and trace metals that are byproducts of coal combustion as well. On the other hand, energy related activities are partially responsible for emissions that cause ozone depletion, which is caused by emissions of chlorofluorocarbons, halons, and N_2O. Energy activities account for 75% of anthropogenic N_2O emissions (Dincer and Rosen 1998). Finally, the most important environmental problem related to coal fired power plants is the global climate change or greenhouse effect. As the concentration of CO_2, CH_4, CFC, halons, and N_2O increases, the heat radiated from the earth's surface gets trapped in the atmosphere (Dincer and Rosen 1998, DOE 2007). In average a coal fired power plant in the U.S. produces 3,039 kg of NO_x /GWh, 6,400 Kg of SO_x /GWh, 134 Kg of CO/GWh, 969,925 Kg of CO_2 /GWh, 135 Kg of N_2O /GWh, 16 Kg of VOCs/GWh, and 35,685 Kg of moisture free ash/GWh (Spath 1999).

A 500 Megawatt coal fired power plant burns more than 1.4 million tons of coal each year, it produces 3,700,000 tons of carbon dioxide (main cause of global warming), 10,000 tons of sulfur dioxide (main cause of acid rain), 500 tons of small airborne particles (cause of respiratory diseases and obstruction of visibility), 10,200 tons of nitrogen oxides (causes formation of tropospheric ozone and smog which burns lung tissue), 720 tons of carbon monoxide (cause headaches and intoxication), 220 of volatile organic compounds (causes formation of tropospheric ozone), 170 pounds of mercury (causes poisoning of fish and problems on the nervous system of humans), 225 pounds of arsenic (causes cancer), 114 pounds of lead, 4 pounds of cadmium, 125,000 tons of ash and 193,000 tons of sludge that contains arsenic, mercury, chromium and cadmium. It also consumes 2.2 billion gallons of water (UCSUSA 2005, Schneider 2004). In the year 2005 the electricity produced in the U.S was 4,054,688 thousand megawatt hour, of which 2,013,179 thousand of megawatts hour were generated by coal fired power plants. The total amount of emissions from power plants were 2,513,934 thousand metric tons of carbon dioxide, 10,340 thousand metric tons of sulfur dioxide, and 3,961 thousand metric tons of nitrogen oxides (DOE 2006).

The embodied energy of the system is defined as the energy consumed by the system. Excluding the energy content of coal, the embodied energy of a 500 Megawatt coal fired power plant is approximately 0.8 MJ/kWh (Spath 1999).

Although it is not well known, releases from coal combustion contain radioactive materials. Gabbard (2007) states that Americans living close to coal-fired power plants are exposed to higher radiation than those living near to nuclear plants meeting governmental regulations, and that the major source of radioactive materials released to the atmosphere are coal-fired power plants. Coal ash is composed of oxides of silicon, aluminum, iron, calcium, magnesium, titanium, sodium, potassium, arsenic, mercury, sulfur and small quantities of uranium and thorium. The amount of uranium contained in coal ranges from 1 part per million (ppm) to 10 ppm, and the amount of thorium is 2.5 times greater than the amount of uranium. A 1000 Megawatt power plant, burning around 4 million tons of coal each year, releases 5.2 tons of uranium and 12.8 tons of thorium. According to the National Council on Radiation Protection and Measurements the average radioactivity of coal is 0.00427millicuries/ton. The volume of coal is reduced by over 85% during combustion, therefore the concentration of uranium and thorium in the fly ash is several times greater than the original concentration because their content is not reduced due to combustion. Although these quantities are almost negligible in one year, the accumulated quantities over 150 years can have a significant impact on the environment and could have health effects.

These environmental impacts may cause huge stress on human health asthma attacks, respiratory diseases, heart attacks, and premature deaths. National power plants cause 23,600 deaths, 21,850 hospitality admissions, 26 emergency room visits for asthma, 38,200 heart attacks, 16,200 chronic bronchitis, 554,000 asthma attacks, and 3,186,000 lost work days per year. The total health cost of power plants in the U.S. is around $167.3 billion each year (Schneider 2004).

4.3 Coal fired power plants In Ohio

90% of the electricity in Ohio is generated by coal fired power plants. Almost all sulfur dioxide, nitrogen oxides, carbon dioxide and mercury comes from those plants. In addition, Ohio power plants are one of the dirtiest of the U.S. In 2002, Ohio scored highest in sulfur dioxide and nitrogen oxides emissions among all other states, and placed second for carbon dioxide emissions (Clear the Air 2007). Each year in Ohio, there are 1,743 deaths, 1,638 hospital admissions, 2,873 heart attacks, 227,521 lost work days, 39,703 asthma attack, 2,268 emergency room visits for asthma, associated to pollution from power plants (Schneider 2004, Clear the Air 2007).

The electrical generation system in Ohio has several major problems regarding reliability due to different factors such as lightning, ice storms, animals, and especially because of tree limbs falling across power lines (American Electric Power 2007). According to the Department of Energy (2007) within the year 2007, there were 58 hours of power outage that affected 367,500 costumers from the total of 11,478,006 habitants of the state (US Census Bureau 2006).

CHAPTER 5

PROJECT APPRAISAL TECHNIQUES

5.1 Project Appraisal

5.1.1 Cost-Benefit Analysis

Most projects are evaluated using cost-benefit analysis (Joubert et al. 1997; Ding 2005; van Pelt 1994), based on the use of a monetary unit to compare project alternatives. This tool is used to show whether the total benefits of the project exceed the total costs. The larger the obtained value, the better the project is considered. This is a good estimate of the project appraisal in economic terms, but it does not take into consideration the values of the environmental goods, services and impacts, nor the social impacts or benefits (Ding 2005). This analysis reduces the problem to a net present value, and it discounts the cost and benefits over time. Subsequently, it shows the economic return of a project, but it does not necessarily seek for the maximization of the social or environmental welfare. The outcome of this analysis is in the hands of an analyst and does not consider stakeholders' opinions (Joubert et al. 1997).

5.1.2 Externalities

There are techniques that give a monetary value to environmental goods and impacts as externalities, costs that are not accounted by the price system and constitute an external cost; therefore, they allow the decision-maker to involve these items in a cost benefit analysis. There has been a lot of progress in the evaluation techniques, but still there are many uncertainties and methodological difficulties (Mirasgedis and Diakoulaki 1997; Joubert et al. 1997; van Pelt 1994).

Environmental goods or impacts can be classified as traded or non-traded goods. For traded goods, such as crops or materials, a monetary value is estimated based on the price used in the world market, and, consequently, the value is quite accurate. However, for non-traded goods, a monetary value is given using techniques such as willingness to pay or willingness to accept risks; by contrast, these techniques are very inaccurate (Mirasgedis and Diakoulaki 1997). Even though the techniques are inaccurate, their outcome is not subjective (Mirasgedis and Diakoulaki 1997).

5.1.3 Multi-criteria Analysis

This analysis is an appraisal technique that involves different criteria measured as weighted scores. It takes into consideration the point-of-view of different parties in society (van Pelt 1994; Nijkamp et al. 1990; Joubert et al. 1997). It allows the decision-maker to assess trade-offs and impacts on different stakeholders.

In a multi-criteria analysis, each criterion or dimension of the problem is measured in a different unit, i.e. the unit that best fit each criterion, and not necessarily in a monetary unit. Then, all values are converted to a dimensionless unit by dividing the value by the highest value in that specific criterion; finally, the dimensionless value is multiplied by the weight of the criterion, and all weighted scores are added for each alternative (Nijkamp et al. 1990; Ding 2004). This analysis is used to compare different alternatives, not to give a single ranking to one possibility.

5.1.4 Cost-Benefit Analysis and Multi-criteria Analysis

Some authors (Ding 2005; Joubert et al. 1997; Nikkamp et al. 1990; Mirasgedis and Diakoulaki 1997) suggest that a better way to assess projects by combining the cost-benefit analysis with a multi-criteria analysis, which allows social and environmental issues to be measured in non-monetary terms. Substituting a monetary market approach with non-monetary methods has limitations, since the multi-criteria analysis alone may overlook the financial return, and one of the principles of sustainable development is the economic development. However, using just the cost-benefit analysis might ignore the social and environmental problems regarding the project. The cost-benefit analysis can be used to measure a criterion on financial revenue involved in a multi-criteria analysis (Ding 2005); in this manner, financial considerations and social and environmental issues are part of the decision-making framework.

5.1.5 Life Cycle Assessment (LCA)

The LCA is a tool for the assessment of the environmental impact of products and services along their life cycle. It consists of four steps (Pehnt 2001):

- Goal and Scope Definition: where the boundaries for the system are established
- Inventory Analysis: where data are collected and calculations to quantify inputs and outputs take place
- Impact Assessment: where the potential impacts of those inputs and outputs are determined using some established categories such as global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, human health, smog, ozone depletion, and ecological toxicity. The global warming potential is measured using Kg equivalents of CO_2 calculated using Table 1:

Table 1 Carbon Dioxide Equivalents

Compound	Carbon Dioxide Eq.
Carbon Dioxide	1
Methane	23
Nitrous Oxide	296
Carbon Tetrafluoride	5,700
CFCs	10,600
Halon	6,900
HCFC	1,700

The acidification potential is measured using equivalents of Hydrogen ions using Table 2:

Table 2 Hydrogen Ion equivalents

Compound	Hydrogen Ion Eq
Ammonia	95.49
Hydrogen Cloride	44.70
Hydrogen Cyanide	60.40
Hydrogen Fluoride	81.26
Hydrogen Sulfide	95.90
Nitrogen Oxides	40.04
Sulfur Dioxide	50.79
Sulfiric Acid	33.30

- Interpretation: where the results from the inventory analysis are combined with the results from the impact assessment to reach conclusions and provide recommendations

5.2 Index Developed to Assess Sustainability

5.2.1 Sustainability index

This index uses monetary and non-monetary approaches to rank projects by their contribution to sustainability. To develop the index, the most important environmental and economic criteria from the literature were identified, and a survey to construction industry professionals was developed to rank these criteria, and to identify major sustainable development determinants. Those criteria were analyzed and ranked according to building professionals and environmentalists' opinions. After the ranking process, the most important criteria were selected: financial return, environmental impact, and energy consumption. The other criteria were also important and were grouped in a criterion named external benefits (performance bases criteria: functional layout, heritage preservation, maintenance/durability, project life span, recycling potential, and productivity; and intangibles: aesthetic impact and social benefits). The model is stated as follows (Ding 2004; Ding 2005):

- Financial return: Measures the total project costs and benefits discounted over time, this is the ratio of the discounted value of benefits to the discounted value of costs (cost-benefit analysis). The grater the ratio the more efficient the proposal.

$$BCR = \frac{\sum_{t=0}^{n} \frac{Bt}{(1+r)^t}}{\sum_{t=0}^{n} \frac{Ct}{(1+r)^t}}$$ **Equation 1**

BCR= benefit / cost ratio

r= selected discount rate

t= period (t=0,1,…,n)

B= benefit

C=cost

- Energy consumption: Includes both embodied energy and operational energy consumption over the project life span. It can be measured as annualized gigajoules per square meter (GJ/m2).

$$EC = E_e + E_o$$ **Equation 2**

$$E_e = E_m + E_t + E_p$$ **Equation 3**

EC = energy consumption

E_e = embodied energy

E_o = operational energy

E_m = manufacturing energy of building materials

E_t = energy for transportation

E_p = energy used in various processes

- External benefits: Reflects the positive contribution of a project in terms of improving living standards arising over the operational life of a project. It is evaluated using weighted scores. High scores reflect significant external benefits.

$$EB = \sum_{j=1}^{I} B_{ji} W_j$$ **Equation 4**

EB= external benefits

i = alternatives

j= sub-criteria

B=benefit

W= weight of criterion j

- Environmental impact: Measures the long term negative impact of a development on the environment. It is evaluated using weighted scores. Lower scores indicate that environmental impact is less significant.

$$EI = \sum_{j=1}^{I} R_{ji} W_j$$ **Equation 5**

EI= environmental impact

i= alternatives

j= sub-criteria

R= impact

W_j = weight of criterion j

These criteria are assembled using multi-criteria approach. Criteria are individually weighted to reflect particular client motives and community requirements.

The sustainability index can be expresses as follows:

$$SI_i = \sum_{j=1}^{J} e_{ji} W_j \qquad \textbf{Equation 6}$$

(i=1,2,…,I)

$$e_{ji} = f\{BCR, EC, EB, EI\} \qquad \textbf{Equation 7}$$

SI_i = Sustainability index for alternative I

W_j = Weight of criterion j

e_{ij} = Value of alternative I for criterion j

5.2.2 Sustainable Index Process (Krotscheck and Narodoslawsky 1996)

This index measures the feasibility of processes under sustainable economic conditions (Krotscheck and Narodoslawsky 1996). The authors stated that, even though the index was developed for industrial processes, the index can be applied universally. The index is a ratio between the area needed to produce a good or a service and a reference area. The area is calculated as the area needed to transform the raw materials and to provide the energy demands for the good or service.

CHAPTER 6

METHODOLOGY

To evaluate the feasibility of fuel cells compared to the traditional grid system, an index that includes the sustainable performance criteria and the factors that influence the users' decision making process for its adoption is developed following three phases: Analysis of Domain, Index Definition, and Evaluation. Each phase has several steps as shown in Figure 4

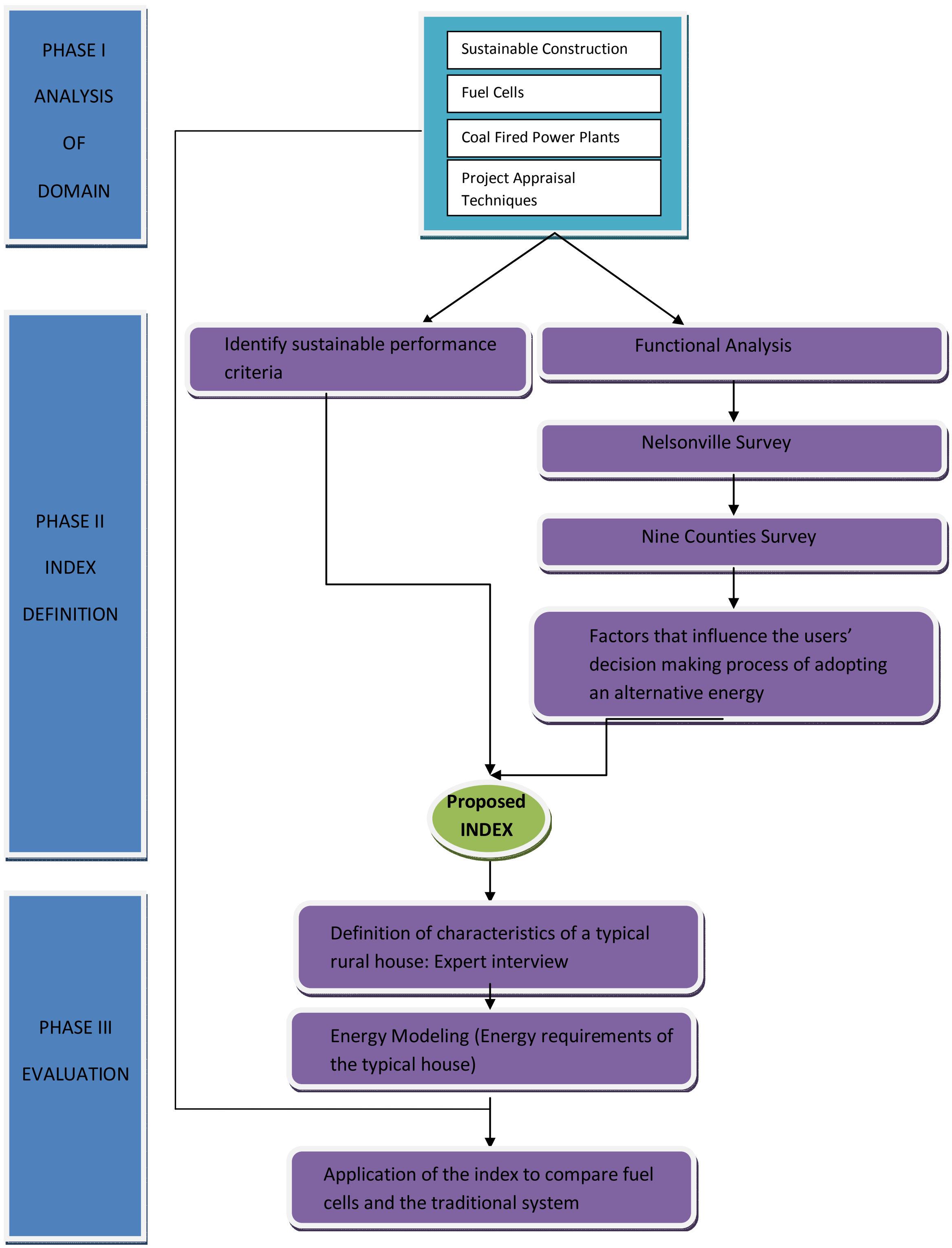

Figure 4 Thesis Methodology

Phase I: Analysis if domain

The first step of this thesis is an extensive literature review, to understand the principles of sustainable construction and sustainability, to define the most relevant characteristics of the two systems that are to be compared, (i.e., fuel cells and the coal fired power plants as the traditional grid system), and to determine the best way to evaluate projects of this nature.

Phase II: Index Definition

The second step is to identify the most important criteria of sustainable performance. These criteria are identified as result of literature review.

The third step is to determine the factors that may influence the decision-making process of adopting an alternative energy source. In order to find those factors a Functional Analysis System Technique (FAST Diagram) is used to define the basic function of the system and the attributes that support the system.

The fourth step is to define the factors that influence the decision-making process of adopting an alternative energy source and the weights users assigned to those factors. In order to define the factors and their weights, the factors found in the FAST Diagram are used to advise researchers from the Voinovich Center at Ohio University to design a survey that is conducted to two different samples: one to possible adopters of alternative energies, and the other to a larger random sample of people from nine counties of the Appalachian region in the state of Ohio (Athens, Gallia, Hocking, Jackson, Meigs, Morgan, Perry, Vinton and Washington).

The factors identified in the literature review and through the surveys are used to develop an index that aids the process of comparing different sources of energy as fifth step. The index is used to compare fuel cells and the traditional grid system powered by coal fired power plants. Furthermore, it can also be used to appraise any source of energy.

Phase III Evaluation

The sixth step is to identify the characteristics of a typical rural house in the Ohio Appalachian region though interviewing an expert on the residential market of the region. The materials and systems typically used in this type of houses are identified on this step.

The seventh step is to calculate the energy requirements of the typical house defined on the last step. In order to perform such calculation the energy modeling program eQuest is used. The program uses historic climate data from the last 30 years.

The eighth step is to apply the developed index to compare fuel cells with the traditional energy supply system powered by coal fired power plants. This step uses data calculated on the energy modeling of the house and data found in literature to define the characteristics of both systems.

CHAPTER 7

SUSTAINABLE INDEX

Some authors suggest that the best procedure to assess projects of this nature is by combining a monetary technique such as cost-benefit analysis or lifecycle cost analysis, with a multi-criteria analysis, which allows social and environmental issues to be measured in non-monetary terms (Ding, 2005; Joubert et al., 1997; Nikkamp et al., 1990; Mirasgedis and Diakoulaki, 1997). Therefore this index is based on a multi-criteria analysis. Every single parameter will be measured in the appropriate unit and will be standardized to a dimensionless unit that can be added within the index by dividing by the largest value within each criterion.

7.1 Sustainable Criteria

Ding (2004; 2005) identified that the most important criteria to assess sustainable performance were economic performance or financial return, energy consumption, and environmental impact. Those criteria will be included in the index.

- Economic Performance

A lifecycle cost analysis (LCCA) will be used to find the economic performance of the alternatives. The analysis permits to evaluate the costs incurred during the lifespan of the system discounted at an interest rate over the time; includes not only the initial cost, but also evaluates the maintenance and operation costs. To perform the LCCA, the present worth of the system is calculated using equations 7 to 11, bringing all costs that are spent in time zero, and all costs that are going to be spent during the different stages of the life of the system to the present in current dollars (Blank and Tarquin 2005).

$$PW = F * \frac{1}{(1+i)^n}$$ **Equation 8**

$$PW = A * \frac{(1+i)^n - 1}{i * (1+i)^n}$$ **Equation 9**

$$PW = G * \frac{(1+i)^n - i * n - 1}{i^2 * (1+i)^n} + A_1 * \frac{(1+i)^n - 1}{i * (1+i)^n}$$ **Equation 10**

$$PW = \frac{A_2 * \left[1 - \left(\frac{1+g}{1+i}\right)^n\right]}{i - g} \quad \text{if} \quad g \neq i$$ **Equation 11**

$$PW = A_2 * \frac{n}{1+i} \quad \text{if} \quad g = i$$ **Equation 12**

PW= Present worth of the system

F= Single cost in time n

A= Uniform series cost starting on time 1 going to time n

G= Constant arithmetic gradient cost starting on time 2 going to time n

A_1 = Uniform series cost used with constant arithmetic gradient starting on time 1 going to time n

g= Constant rate of change of a geometric gradient cost starting on time 2 going to time n

A_2 = Uniform series cost used with geometric gradient starting on time 1 going to time n

i= interest rate

n= time

- Energy Consumption

There are two types of energy associated to a construction project, the embodied energy and the operational energy. The embodied energy is the energy needed to produce the material and components. For this case, it is the energy required to produce the system evaluated. The operational energy is energy needed to operate the system (Ding, 2004). It is important to evaluate not only the operational energy but also the embodied energy. The embodied energy will be calculated from indexes found in literature, that state the Mega Joules required to build a system that provides a KW of energy. The operational energy will be calculated using the expected efficiency of the system during the operation stage, because the efficiency displays the energy required in KW to provide one KW of energy.

- Environmental Impact

A Lifecycle Assessment of the system should be performed in order to find the environmental impact of a system. However, for the purposes of this thesis and due to the scarcity of experimental data on both systems, just the inventory phase and a preliminary impact assessment will be taken into consideration. Besides, only two categories of the impact assessment will be evaluated, global warming potential and the acidification potential, because those are the areas that are more affected by the energy generation system. The lifecycle of the systems is going to be divided into two stages, the construction and manufacturing of the system, and the operation of the system. The global warming potential is going to be determined in terms of Kg of CO_2, CO, N_2O, and CH_4 produced during the lifespan of the system and the acidification potential is going to be determined in terms of Kg of SO_2, NO_x, and NH_3. For this study, the global warming potential is going to have a weight of two while the acidification potential is going to have a weight of one because global warming is the most important environmental problem associated with energy generation.

7.2 FAST Diagram

In order to identify the factors that that are involved in the energy supply system that might be factors that influence the user's decision making process of adopting an alternative energy, a Functional Analysis System Technique diagram is developed. This technique makes it possible to identify the primary basic functions, secondary functions and supporting functions, as shown in Figure 5. The first order function was identified as providing electricity or energy for the house. To provide energy it is necessary to transfer it from the place it is generated to the final users. To transfer the energy it is essential to transform energy i.e. direct current (as it is generated) to alternate current (for suitability). But to transform energy it is important to convert energy to a usable form. And finally a sustainable source is needed to generate continuous power supply. There are other important characteristic that bring significant attributes to the principal function, for instance, to be easy to maintain, ability to reduce losses, reduce heat, low noise, safe (low emissions), and high reliability, which are considered as secondary functions. And finally, restrict space is an attribute of the system. The primary function, the secondary function and its attributes are grouped in reliability, environmental impact, maintenance, safety, and space.

The ratings of ‘very important’, ‘important’, and ‘not important or unimportant’ when the users are thinking on adopting an alternative energy of these factors, and the factors cost and governmental incentives are given as a suggested question to the researchers of the Voinovich Center at Ohio University, to be included in two surveys that are conducted by them to two samples of people, one to attendants to an event on alternative energies, and the other to a larger random sample. The results of these surveys are analyzed later on this thesis.

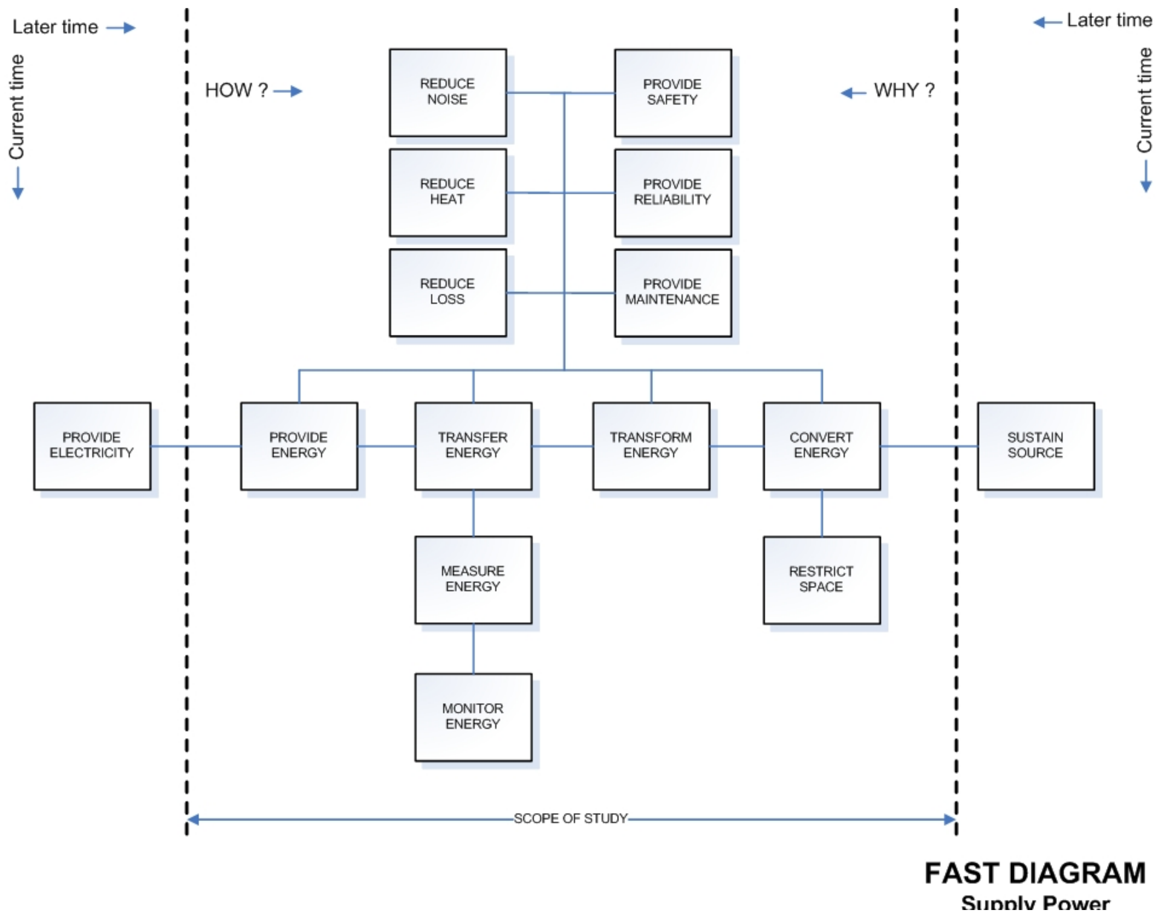

Figure 5 FAST Diagram for the Electricity Supply System

7.3 Factors that Influence the Users' Decision Making Process of Adopting an Alternative Energy: Surveys

To define the factors that influence the users' decision making process of adopting an alternative energy two surveys were conducted, one to a sample of possible adopters of alternative energies and another to a random sample of people who live in the rural Appalachian region.

7.3.1 Nelsonville Survey

The Nelsonville survey was completed by 76 people. The age ranges were: 19-23 (34%); 23-34 (34%); 35- 44 (17%); 45-54 (6%); 55-65 (5%); and, 65 and older (5%). Their education level was: less than high school (6%); some college (20%); associate degree (8%); bachelor's degree (20%); and master's degree (45%). From this sample, 7% are people who are currently using an alternative energy in their home, 74% are people who are willing to adopt alternative energies in their home, 8% are people who are not willing to adopt alternative energies in their home, and 11% are people who do not know. Regarding the understanding of the term "fuel cell", 27% of the people had a little understanding, 56% had a general sense, and 17% had a clear understanding. This sample was younger and highly educated, and was attending an event on alternative energies, leading to the conclusion that, for the most part, this is a sample of people who could potentially adopt an alternative energy as their source of energy for their house.

7.3.2 9 Counties Survey

The second survey was responded by 294 people: 10% from Athens County; 11% from Gallia County; 11% from Hocking County; 10% from Jackson County; 15% from Meigs County; 15% from Morgan County; 9% from Perry County; 10% from Vinton County; and 9% from Washington County. Their education level was: less than high school diploma (10%); high school diploma (45%); some college (20%); associate degree (9%); bachelor's degree (8%);

and master's degree (8%). Their age ranges was: 18-24 (6%); 25-34 (10%); 35-44 (17%); 45-64 (37%); and 65 and older (30%). From the sample, 5% of the people have adopted an alternative energy for their home, and 95% have not.

7.4 Factors that Influence the Users' Decision Making Process of Adopting an Alternative Energy: Comparison between the Two Surveys

The following bar charts (Figure 6) display the ranking given by each sample of people to the factors cost, reliability, environmental impact, maintenance, safety, space, and governmental impact.

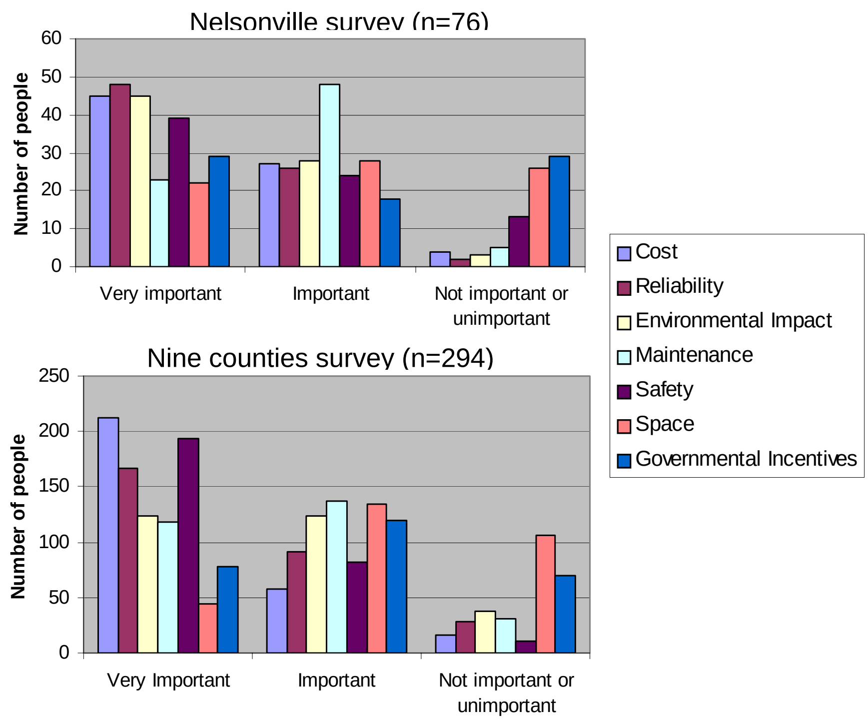

Figure 6 Bar charts of responses from both surveys

A numeric value was assigned to each category, giving a value of 2 when the respondents ranked the factor as 'very important', a value of 1 when the people ranked the factor as ‘important’, and a value of 0 when the people ranked the factor as ‘not important or unimportant’’. Table 3 presents a comparison between the mean and mode of the two surveys.

Table 3 Comparison between the two surveys

Survey	Statistic	Environmental Impact	Reliability	Safety	Space	Cost	Maintenance	Governmental Incentives
9 Counties Survey	Mean	1.35	1.55	1.66	0.86	1.71	1.33	1.03
	Mode	2.00	2.00	2.00	1.00	2.00	1.00	1.00
Nelsonville Survey	Mean	1.55	1.61	1.34	0.96	1.54	1.24	1.00
	Mode	2.00	2.00	2.00	1.00	2.00	1.00	0.00

Both groups of people ranked environmental impact, reliability, safety, cost and maintenance between ‘very important’ and ‘important’; space and governmental incentives between ‘not important or unimportant’ and ‘important’. Environmental impact, reliability, safety, and cost have a mean between 1 and 2 (important – very important) and their mode is 2 (very important) for both surveys; maintenance and space have similar means and their mode is 1 (important), and governmental incentives have a different behavior for each survey. Even though the mean is very similar in both cases, the mode differs from one survey to the other; for the Nelsonville survey, the mode is 0 (not important), while, for the nine counties survey, the mode is 1 (important). These results address the conclusion that, despite the factor governmental incentives, all the factors have been ranked similar for both samples.

7.5 Factors and Weights within the Index

The first sample can be categorized as potential adopters of alternatives energy for housing, because of their demographic information (i.e., younger people, highly educated and somehow informed about alternative energies), their attendance at an event on alternative energies at the moment the survey was conducted, and because 74% of the people stated that they are willing to adopt an alternative energy source for their homes and 7% have already adopted such kind of energy. The sample of the second survey can be categorized as people who do not necessarily have an interest in alternative energies, because their demographic information does not match the profile of adopters of alternative energies, and they seem to have little knowledge regarding alternative energies.

The data found in the first survey (Nelsonville survey) is going to be used to weight each factor in the index, because the index is being designed to compare different sources of energy by measuring its sustainable performance and by measuring the factors that influence the users' decision-making process for its adoption. Therefore, the opinion of people who certainly could adopt an alternative energy is more important.

For the first survey, some of the factors were ranked very similar, so it is important to observe statistically if they are significantly different or if their difference is random. If they are statistically different, they can be used to rank the factors and to give a weight to the factors in the index. The variance analysis uses an F distribution to probe if the null hypothesis can be rejected or not.

Ho= the media of all factors are equal Ha= the media of all factors are not equal

$$F = \frac{\sigma_1^2}{\sigma_2^2}$$ **Equation 13**

$$\sigma_1^2 = N * S^2$$ **Equation 14**

$$S^2 = \frac{\sum_1^n (\overline{X_n} - \overline{X})^2}{n-1}$$ **Equation 15**

$$\sigma_2^2 = \frac{1}{n}(\sum_1 S_n^2)$$ **Equation 16**

σ_1^2 = variance based on the variance between means

σ_2^2 = variance based in the variance of each sample

N= sample size

n= number of factors

$\overline{X_n}$ = media of the factor n

$\overline{X}$ = media of the media of all factors

S_n^2 = variance of the factor n

Table 4 Variance test of Nelsonville Survey. Results 1

Mean of Mean	1.32
Variance	0.07045
Variance 1	5.35401
Variance 2	0.47153
F	11.35

Table 5 Variance test of Nelsonville Survey. Results 2

Degrees of freedom of the numerator	n-1=7-1	6
Degrees of freedom of the denominator	n*(N-1)=7*(76-1)	525
F for a significance level of 0.001	3.81	11.35>3.81
The null hypothesis can be rejected		

The variance analysis uses an F distribution to probe if the null hypothesis can be rejected or not. An F value of 11.35 was obtained from the data analyzed; for 6 degrees of freedom on the numerator, 525 degrees of freedom on the denominator, and a significance level of 0.001, the value of the test F is 3.81. As 11.35>3.81, the null hypothesis (i.e., the media of all factors are equal) can be rejected. The results display that statistically all the means are different. Subsequently, the results show what respondents dissent when deciding to adopt an alternative energy source, and the difference between means is not due to randomness.

The best approach to identify the weight of each factor in the index is through its mode, since these are discrete responses; as a result, a chi square test was performed in order to observe if the frequencies assigned to each factor are statistically different and to affirm that the factors with higher modes have higher weight in the decision-making process of adopting an alternative energy.

$$\chi^2 = \sum_1^3 \sum_1^7 \left(\frac{(Observfreq_i - Expecfreq_i)^2}{Expecfrq_i} \right)_j = 105.14 \qquad \textbf{Equation 17}$$

A Chi Square of 105.14 was obtained for the data of the first survey. For 12 degrees of freedom and a significance level of 0.001 the Chi square is 32.91. As 105.14>32.9 the null hypothesis (the frequency of all factors are equal) can be rejected. As a result the mode data from the Nelsonville survey can be used to give a weight value to each factor as follows:

Environmental Impact	2	Reliability	2
Safety	2	Space	1
Cost	2	Maintenance	1
Governmental Incentives	0		

The factor “governmental incentives” is not going to be used as a factor in this index, because the study is focused on possible adopters of the system; however, if the index is going to be used to evaluate other systems or other population it might be included with a weight of 1.

Two of the sustainable parameters, economic performance (cost) and environmental impact are also part of the factors that people take into consideration when they are deciding to adopt an alternative energy; therefore, their weights are already assigned. For the parameter energy consumption, a weight of 2 (very important) is going to be given, because the factor directly relates to the system assessed.

$$Index = 2CF + 2EIF + 2RF + 2SaF + 2ECF + 1SpF + 1MF$$ **Equation 18**

CF=Cost Factor

EIF=Environmental Impact Factor

RF=Reliability Factor

SaF=Safety Factor

EF= Energy Consumption Factor

SpF=Space Factor

MF=Maintenance Factor

- Maintenance: The maintenance will be evaluated as the number of times the system is going to need maintenance per year from the final user's point of view.
- Safety: The safety of the system will be given a rating according to an analysis of safety implications to the final user.
- Reliability: The reliability of the system is going to be measured as hours per year that the system will be down from the final user's point of view.
- Space: The space of the system is going to be measured as volume occupied by the system at the house.

CHAPTER 8

DEFINITION OF THE ENERGY REQUIREMENTS OF A TYPICAL RURAL HOUSE IN THE OHIO APPALACHIAN REGION

8.1 Definition of the Characteristics of a Typical Rural House in the Ohio Appalachian Region

Information related to typical characteristics of a house, including materials and systems, in the rural Appalachian region of Ohio was obtained through an expert interview with Mr. Wil Chandler (2006). Mr. Chandler is owner of a full service real estate company representing buyers and sellers in Athens, Ohio. The results from the interview are presented on Table 6.

Table 6 Characteristics of a Typical House in the Rural Appalachian Region of Ohio

General	
House Area	1500
Numbers of floors below grade	1
Number of floors above grade	2
Floor to floor height	9'
Floor to ceiling height	7'10''
Doors	
Number of exterior doors	3
Height exterior doors	6'8"
Width exterior doors	32"
Above grade walls	
R Exterior insulation	0
R Interior insulation	R11
Construction	Wood frame 2 x 4, 16 in o.c.
Exterior finishes	Wood/plywood
Wall type	Frame
Ceiling	
R batt insulation	0
Interior finishes	Drywall finish
HVAC system	
Cooling equipment	DX coils
Heating equipment	Furnace
Return air path	Ducted
Roof	
Roof color	gray
R exterior insulation	0
R batt insulation	R19
Construction	Wood standard frame
Exterior finishes	Wood/plywood
Windows	
Windows frame	0
Windows glass type	Double pane
Ground floor	
R Exterior insutation	0
R Interior insulation	R11
Construction	Concrete 4 in
Exposure	Over unconditioned space
Finishes	Carpet with rubber pad

Table 6 (Continued)

Floor	
R rigid insulation	0
Construction	1 in plywood/underlayment
Interior finishes	Carpet with rubber pad
Water heater	
Water heater	Natural gas

8.2 Energy Modeling

To assess the energy requirements of the house the simulation program eQuest was used. Information of materials and design characteristics of the house, as shown in Table 6, was used as input. The climate data for the last 30 years of this region was also considered. The simulation consists of a single family house located in the Appalachian region in Ohio, in Athens County. The results from the simulation are presented below:

Table 7 Annual energy requirements of the house

Month	Average (kWh)	Max KW
January	869	2.2
February	781	2.6
March	918	2.8
April	1014	3.6
May	1250	4.4
June	1551	5.6
July	1677	5
August	1665	5.1
September	1282	4.6
October	1037	3.8
November	853	3.1
December	850	2.4

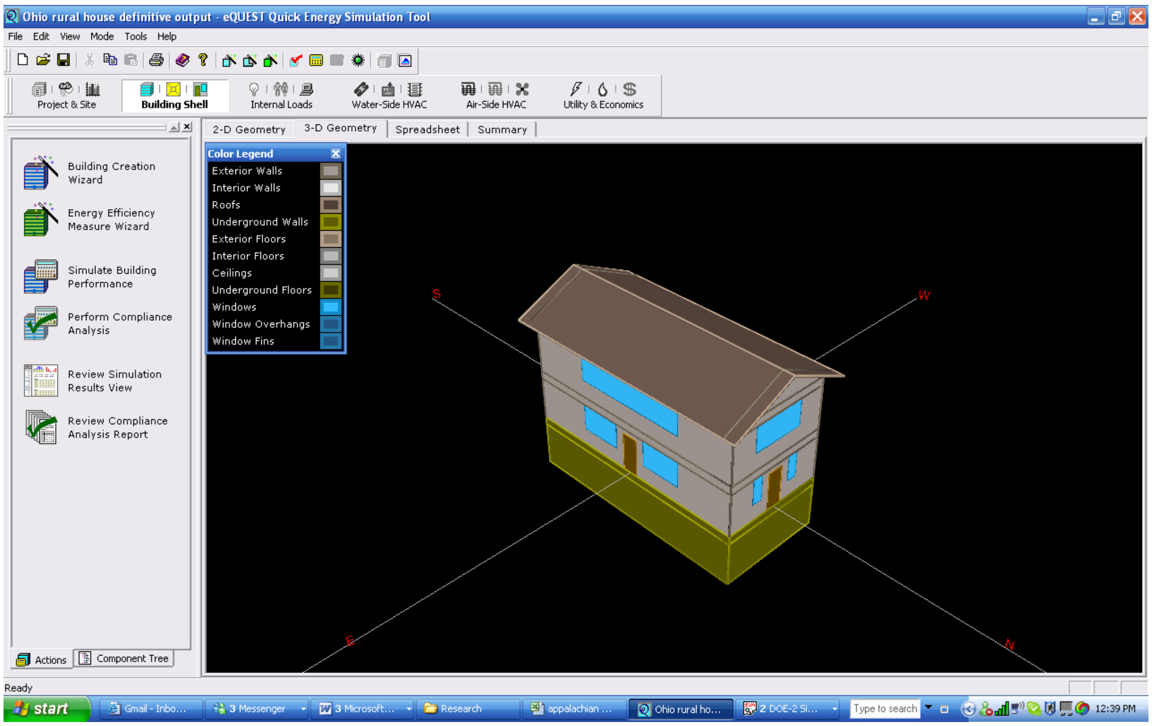

Figure 7 Energy modeling of the house

CHAPTER 9

COMPARISON BETWEEN FUEL CELLS AND THE TRADITIONAL GRID SYSTEM

As has been stated earlier in this thesis there are several types of fuel cells that differ from each other according to their electrolyte. For the purpose of this thesis, the Proton Exchange Membrane Fuel Cell (PEMFC) is going to be used because it is the one that better suits the small residential applications. In addition it is well known that the hydrogen source is another major difference between fuel cells. The hydrogen carrier that will be assessed is the water because is the only one that is completely renewable and is the cleanest mean to produce hydrogen. On the other hand, to evaluate the traditional grid system, electricity from a coal fired power plant will be evaluated because 90% of the electricity generated in Ohio is by using this source.

9.1 Cost

The cost of each system will be evaluated using a lifecycle cost analysis from the final user point of view, because the cost that the user has to finally pay is the cost that affects their decision making process of adopting an alternative energy.

9.1.1 Fuel Cell

There is data in the literature that permits to approximate the costs of the system. Song (2002) states a cost of US$4,000/KWh for a complete fuel cell system, while Erdmann (2003) presents a cost of €10,000/KWh (US$9,000 of 2003), and Ellis and Burak-Gunes (2002) cite a cost of US$5,500/ KWh. An initial investment of US$5,500/KWh will be used for the purpose of this thesis. A 5.6 KW system is needed to fulfill the energy requirements of the house in the month of June (peak energy month). An annual maintenance cost of $0.03/KWh (Ellis and

Burak-Gunes 2002) will be used. The monthly costs associated to the annual maintenance are presented on Table 8.

Table 8 Monthly cost analysis of fuel cell system

Month	Consumption (KWH)	Monthly Charges
January	869	$ 26.07
February	781	$ 23.43
March	918	$ 27.54
April	1014	$ 30.42
May	1250	$ 37.50
June	1551	$ 46.53
July	1677	$ 50.31
August	1665	$ 49.95
September	1282	$ 38.46
October	1037	$ 31.11
November	853	$ 25.59
December	850	$ 25.50
		$ 412.41

The lifecycle cost over 20 years using the prime rate of 8.25% per year is presented in Table 9.

Table 9 Lifecycle cost of fuel cell system

Annual Cost	$	412.41
New infrastructure	$	31,350.00
Years		20
i		0.0825
PW	$	35,324.87
CC	$	36,348.91

9.1.2 Coal Fired Power Plant

The Standard Tariff (2007: Residential use) from the Columbus Southern Company was used to calculate the initial cost for the new development and its annual cost. The changes in tariff depends on the station (winter October-May, summer June-September, as establish in its standard tariff) and consumption (if the monthly energy consumption is higher of 800 kWh). The annual cost of the grid system for the final user is presented in Table 10.

Table 10 Monthly cost analysis of the grid system

Month	Consumption (KWH)	First 800 KWH	After 800 KWH	Customer charge	Energy Charge First 800 KWH Generation ($/KWH)	Energy charge first 800 KWH generation	Energy Charge First 800 KWH distribution ($/KWH)	Energy charge first 800 KWH distribution	Energy Charge after 800 KWH generation ($/KWH)	Energy charge after 800 KWH generation	Energy Charge after 800 KWH distribution ($/KWH)	Energy charge after 800 KWH distribution
January	869	800	69	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0142588	$ 0.98	$ 0.0203132	$ 1.40
February	781	781	0	$ 4.75	$ 0.0543107	$ 42.42	$ 0.0261615	$ 20.43	$ 0.0142588	$ -	$ 0.0203132	$ -
March	918	800	118	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0142588	$ 1.68	$ 0.0203132	$ 2.40
April	1014	800	214	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0142588	$ 3.05	$ 0.0203132	$ 4.35
May	1250	800	450	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0142588	$ 6.42	$ 0.0203132	$ 9.14
June	1551	800	751	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0543107	$ 40.79	$ 0.0261615	$ 19.65
July	1677	800	877	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0543107	$ 47.63	$ 0.0261615	$ 22.94
August	1665	800	865	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0543107	$ 46.98	$ 0.0261615	$ 22.63
September	1282	800	482	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0543107	$ 26.18	$ 0.0261615	$ 12.61
October	1037	800	237	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0142588	$ 3.38	$ 0.0203132	$ 4.81
November	853	800	53	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0142588	$ 0.76	$ 0.0203132	$ 1.08
December	850	800	50	$ 4.75	$ 0.0543107	$ 43.45	$ 0.0261615	$ 20.93	$ 0.0142588	$ 0.71	$ 0.0203132	$ 1.02

Table 10 (continued)

Universal service fund rider	Energy efficiency fund rider	KWH tax rider ($/KWH)	KWH tax rider	Gross receipts tax reider (% of total charges without the riders)	Gross receipts tax reider	Property tax credit rider ($/KWH)	Property tax credit rider	Municipal Income tax rider generation ($/KWH)	Municipal Income tax rider generation	Municipal Income tax rider distribution ($/KWH)	Municipal Income tax rider distribution	Franchise tax rider ($/KWH)	Franchise tax rider
$ 0.60	$ 0.0895	$ 0.004650	$ 4.040850	4.87829%	$ 3.49	$0.0015193	$ 1.32	$ 0.0000816	$ 0.07	$ 0.0000436	$ 0.04	$0.0009673	$ 0.84
$ 0.54	$ 0.0895	$ 0.004650	$ 3.631650	4.87829%	$ 3.30	$0.0015193	$ 1.19	$ 0.0000816	$ 0.06	$ 0.0000436	$ 0.03	$0.0009673	$ 0.76
$ 0.63	$ 0.0895	$ 0.004650	$ 4.268700	4.87829%	$ 3.57	$0.0015193	$ 1.39	$ 0.0000816	$ 0.07	$ 0.0000436	$ 0.04	$0.0009673	$ 0.89
$ 0.70	$ 0.0895	$ 0.004650	$ 4.715100	4.87829%	$ 3.73	$0.0015193	$ 1.54	$ 0.0000816	$ 0.08	$ 0.0000436	$ 0.04	$0.0009673	$ 0.98
$ 0.86	$ 0.0895	$ 0.004650	$ 5.812500	4.87829%	$ 4.13	$0.0015193	$ 1.90	$ 0.0000816	$ 0.10	$ 0.0000436	$ 0.05	$0.0009673	$ 1.21
$ 1.06	$ 0.0895	$ 0.004650	$ 7.212150	4.87829%	$ 6.32	$0.0015193	$ 2.36	$ 0.0000816	$ 0.13	$ 0.0000436	$ 0.07	$0.0009673	$ 1.50
$ 1.15	$ 0.0895	$ 0.004650	$ 7.798050	4.87829%	$ 6.82	$0.0015193	$ 2.55	$ 0.0000816	$ 0.14	$ 0.0000436	$ 0.07	$0.0009673	$ 1.62
$ 1.14	$ 0.0895	$ 0.004650	$ 7.742250	4.87829%	$ 6.77	$0.0015193	$ 2.53	$ 0.0000816	$ 0.14	$ 0.0000436	$ 0.07	$0.0009673	$ 1.61
$ 0.88	$ 0.0895	$ 0.004650	$ 5.961300	4.87829%	$ 5.26	$0.0015193	$ 1.95	$ 0.0000816	$ 0.10	$ 0.0000436	$ 0.06	$0.0009673	$ 1.24
$ 0.71	$ 0.0895	$ 0.004650	$ 4.822050	4.87829%	$ 3.77	$0.0015193	$ 1.58	$ 0.0000816	$ 0.08	$ 0.0000436	$ 0.05	$0.0009673	$ 1.00
$ 0.59	$ 0.0895	$ 0.004650	$ 3.966450	4.87829%	$ 3.46	$0.0015193	$ 1.30	$ 0.0000816	$ 0.07	$ 0.0000436	$ 0.04	$0.0009673	$ 0.83
$ 0.58	$ 0.0895	$ 0.004650	$ 3.952500	4.87829%	$ 3.46	$0.0015193	$ 1.29	$ 0.0000816	$ 0.07	$ 0.0000436	$ 0.04	$0.0009673	$ 0.82

Table 10 (Continued)

Regulatory assetcharge rider ($/KWH)	Regulatory assetcharge rider	Provider of last resort charge rider ($/KWH)	Provider of last resort charge rider	Monogahela power litigation termination rider ($/KWH)	Monogahela power litigation termination rider	Power acquisition rider ($/KWH)	Power acquisition rider	Transmission cost recovery rider ($/KWH)	Transmission cost recovery rider	IGCC Cost recovery charge rider ($/KWH)	IGCC Cost recovery charge rider	Major storm cost recovery rider (% of distribution charges)
$0.0029829	$ 2.59	$0.0008192	$ 0.71	$0.0001229	$ 0.11	$0.0007945	$ 0.69	$0.0053822	$ 4.68	$ 0.0007670	$ 0.67	3.7622%
$0.0029829	$ 2.33	$0.0008192	$ 0.64	$0.0001229	$ 0.10	$0.0007945	$ 0.62	$0.0053822	$ 4.20	$ 0.0007670	$ 0.60	3.7622%
$0.0029829	$ 2.74	$0.0008192	$ 0.75	$0.0001229	$ 0.11	$0.0007945	$ 0.73	$0.0053822	$ 4.94	$ 0.0007670	$ 0.70	3.7622%
$0.0029829	$ 3.02	$0.0008192	$ 0.83	$0.0001229	$ 0.12	$0.0007945	$ 0.81	$0.0053822	$ 5.46	$ 0.0007670	$ 0.78	3.7622%
$0.0029829	$ 3.73	$0.0008192	$ 1.02	$0.0001229	$ 0.15	$0.0007945	$ 0.99	$0.0053822	$ 6.73	$ 0.0007670	$ 0.96	3.7622%
$0.0029829	$ 4.63	$0.0008192	$ 1.27	$0.0001229	$ 0.19	$0.0007945	$ 1.23	$0.0053822	$ 8.35	$ 0.0007670	$ 1.19	3.7622%
$0.0029829	$ 5.00	$0.0008192	$ 1.37	$0.0001229	$ 0.21	$0.0007945	$ 1.33	$0.0053822	$ 9.03	$ 0.0007670	$ 1.29	3.7622%
$0.0029829	$ 4.97	$0.0008192	$ 1.36	$0.0001229	$ 0.20	$0.0007945	$ 1.32	$0.0053822	$ 8.96	$ 0.0007670	$ 1.28	3.7622%
$0.0029829	$ 3.82	$0.0008192	$ 1.05	$0.0001229	$ 0.16	$0.0007945	$ 1.02	$0.0053822	$ 6.90	$ 0.0007670	$ 0.98	3.7622%
$0.0029829	$ 3.09	$0.0008192	$ 0.85	$0.0001229	$ 0.13	$0.0007945	$ 0.82	$0.0053822	$ 5.58	$ 0.0007670	$ 0.80	3.7622%
$0.0029829	$ 2.54	$0.0008192	$ 0.70	$0.0001229	$ 0.10	$0.0007945	$ 0.68	$0.0053822	$ 4.59	$ 0.0007670	$ 0.65	3.7622%
$0.0029829	$ 2.54	$0.0008192	$ 0.70	$0.0001229	$ 0.10	$0.0007945	$ 0.68	$0.0053822	$ 4.57	$ 0.0007670	$ 0.65	3.7622%

Table 10 (Continued)

Major storm cost recovery rider	Monthly line extention fee	Monthly Charges
$ 0.84	$ 8.00	$ 100.28
$ 0.77	$ 8.00	$ 94.45
$ 0.88	$ 8.00	$ 103.02
$ 0.95	$ 8.00	$ 108.38
$ 1.13	$ 8.00	$ 121.56
$ 1.53	$ 8.00	$ 174.68
$ 1.65	$ 8.00	$ 187.81
$ 1.64	$ 8.00	$ 186.56
$ 1.26	$ 8.00	$ 146.65
$ 0.97	$ 8.00	$ 109.66
$ 0.83	$ 8.00	$ 99.39
$ 0.83	$ 8.00	$ 99.22
	Annual cost	$ 1,531.68

The lifecycle cost over 20 years using the prime rate of 8.25% (April 2007) per year is presented in Table 11. The prime rate is used because it is the rate usually used by banks to calculate most loans.

Table 11 Lifecycle cost of the grid system

Annual Cost	$	1,531.68
New infrastructure fee	$	375.00
Years		20
i		0.0825
PW	$	15,137.52
CC	$	18,940.76

9.1.3 Cost factors

$$CF_{FuelCell} = \frac{35{,}324.87}{35{,}324.87} = 1.00$$ **Equation 19**

$$CF_{GridSystem} = \frac{15{,}137.52}{35{,}324.87} = 0.43$$ **Equation 20**

9.2 Environmental Impact

The environmental impact of the systems will be evaluated using the first few stages of a lifecycle assessment. Each system is going to be divided in two main phases: the first one is going to be construction and manufacturing and the second one is going to be operation; within each phase there are several sub-phases.

The inputs and outputs from each phase will be identified and the impacts will be quantified using the global warming potential that gives the impact of the system in equivalent Kg of CO_2 and the acidification potential that gives the impact of the system in equivalent Kg of H ions. It is important to take into consideration that the largest impacts of FC are in the manufacturing process, while the largest impacts of the coal fired power plant grid system are during operation.

9.2.1 *Fuel Cell*

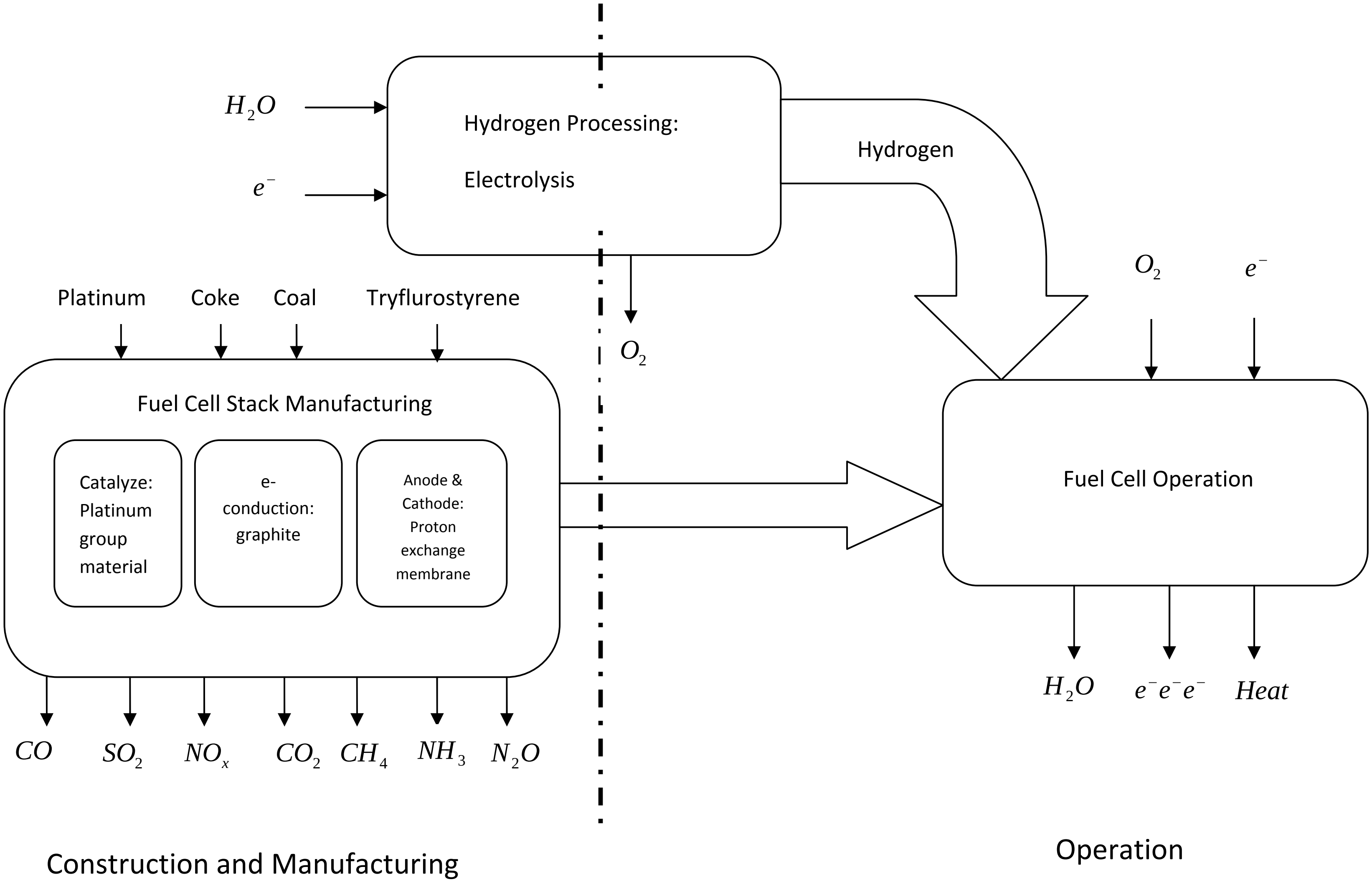

Figure 8 Lifecycle of a Fuel Cell System

9.2.1.1 Construction and Manufacturing

Global Warming Potential

According to table 1 and to data found in literature review that states that the manufacturing of fuel cell stack emits 275 Kg CO_2/KW, 0.2 Kg CH_4/KW and 0.014 Kg N_2O/KW (Phent 2001). The global warming potential is:

$$GWP/KW = 275KgCO_2/KW * \frac{1KgCO_{2eq}}{KgCO_2} + 0.2KgCH_4/KW * \frac{23KgCO_{2eq}}{KgCH_4} + 0.014KgN_2O/KW * \frac{296KgCO_{2eq}}{KgN_2O}$$

Equation 21

GWP/KW= 283.74 $KgCO_{2eq}$/KW **Equation 22**

GWP= $283.74\frac{KgCO_{2eq}}{KW} * FC_{capacity}$ **Equation 23**

GWP= $283.74\frac{KgCO_{2eq}}{KW} * 5.6KW$ **Equation 24**

GWP=1588.97 $KgCO_{2eq}$ **Equation 25**

Acidification Potential

According to Table 2 and to data found in literature review, the manufacturing process of a fuel cell stack produces 2.5E-03 Kg NH_3/KW, 0.74 Kg NO_x/KW, and 0.73 Kg SO_2/KW (Phent 2001), and the acidification potential is:

$$AP/KW = 0.73KgSO_2/KW * \frac{50.79KgHion_{eq}}{KgSO_2} + 2.5E-03KgNH_3/KW * \frac{95.49KgHion_{eq}}{KgNH_3} + 0.74KgNO_x/KW * \frac{40.04KgHion_{eq}}{KgNO_x}$$

Equation 26

AP/KW= 66.95 $KgHion_{eq}$/KW **Equation 27**

AP= $66.95\frac{KgHion_{eq}}{KW} * FC_{capacity}$ **Equation 28**

AP= $66.95\frac{KgH_{eq}}{KW} * 5.6KW$ **Equation 29**

AP=374.92 $KgHion_{eq}$ **Equation 30**

9.2.1.2 Operation

Global Warming Potential

GWP= 0 **Equation 31**

Acidification Potential

AP= 0 **Equation 32**

9.2.2 Coal Fired Power Plant: Grid System

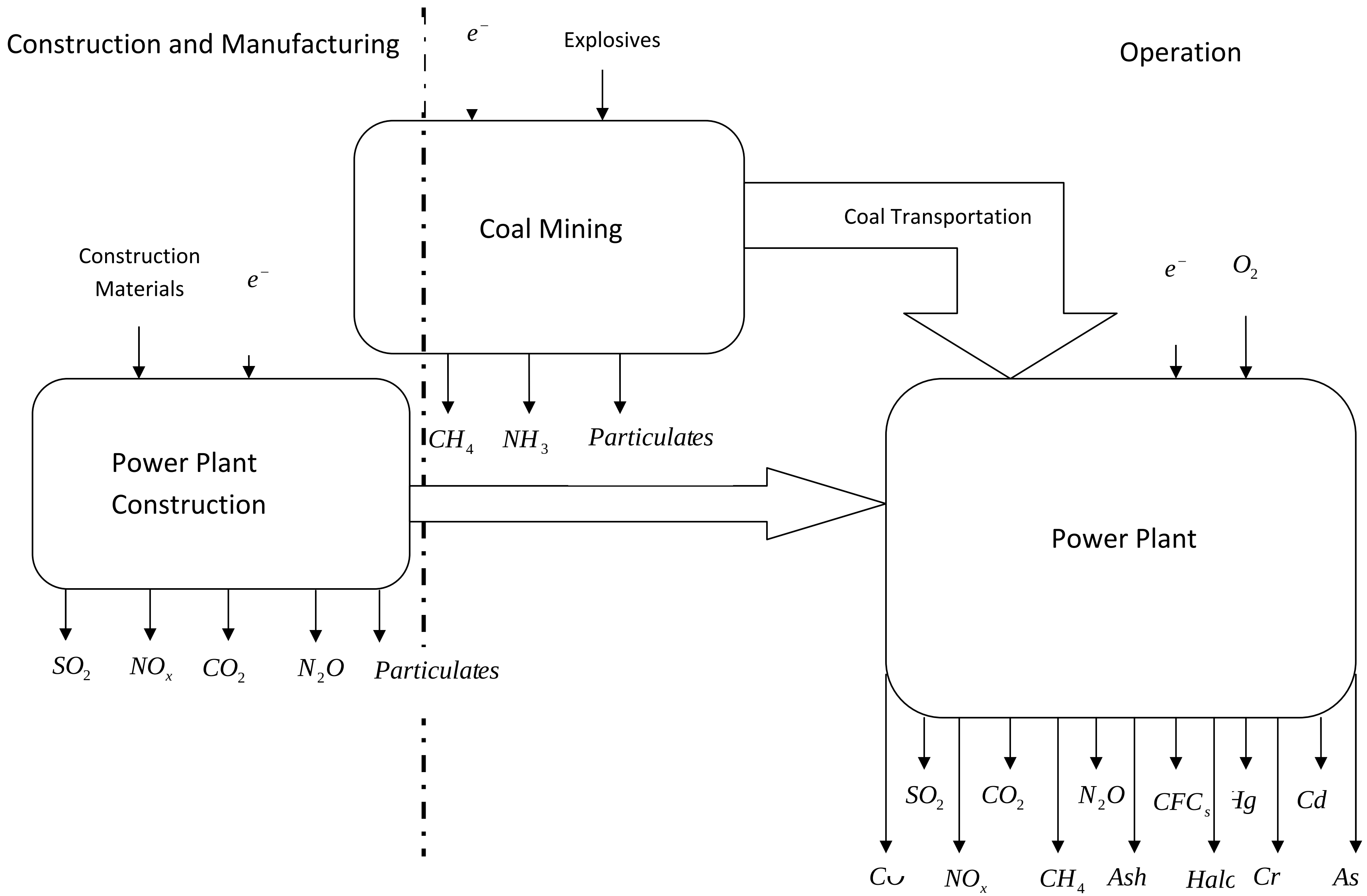

Figure 9 Lifecycle of a Coal Fired Power Plant

In the literature it was found that the impacts during construction of a power plant are 10 times less than the impacts during operation, therefore the impacts during construction are 10% of the impacts during operation (Pehnt 2001). Thus the impacts during operation are going to be assessed first.

9.2.2.1 Operation

Global Warming Potential

According to Table 1 and to data found in literature that states that the operation of a coal fired power plant emits 0.96 Kg CO_2/kWh, 0.012 Kg CH_4/kWh and 0.00014 Kg N_2O/kWh (Spath 1999). The global warming potential is:

$$GWP/kWh = 0.96 KgCO_2/kWh * \frac{1KgCO_{2eq}}{KgCO_2} + 0.012 KgCH_4/kWh * \frac{23KgCO_{2eq}}{KgCH_4} + 0.00014 KgN_2O/kWh * \frac{296KgCO_{2eq}}{KgN_2O}$$

Equation 33

GWP/kWh= 0.97 $KgCO_{2eq}$/kWh **Equation 34**

GWP/year= $0.97 \frac{KgCO_{2eq}}{kWh} * EnergyConsumption$ **Equation 35**

Table 12 Global Warming Potential in 20 Years

Month	Consumption (kWh)	GMP CO2eq.
January	869	842.93
February	781	757.57
March	918	890.46
April	1014	983.58
May	1250	1212.5
June	1551	1504.47
July	1677	1626.69
August	1665	1615.05
September	1282	1243.54
October	1037	1005.89
November	853	827.41
December	850	824.5
Total GMP in KgCO2Eq. per year		13334.59
Total GMP in KgCO2Eq. in 20 years		266691.8

Acidification Potential

According to Table 2 and to data found in literature review, the operation of a coal fired power plants produces 2.8E-06 Kg NH_3/kWh, 0.0030 Kg NO_x/kWh, and 0.0064 Kg SO_2/kWh, (Spath 1999) and the acidification potential is:

$$AP/kWh = 0.0064 KgSO_2/kWh * \frac{50.79 KgHion_{eq}}{KgSO_2} + 2.8E-06 KgNH_3/kWh * \frac{95.49 KgHion_{eq}}{KgNH_3} + 0.0030 KgNO_x/kWh * \frac{40.04 KgHion_{eq}}{KgNO_x}$$

Equation 36

AP/kWh= 0.45 $KgHion_{eq}$/kWh **Equation 37**

AP= $0.45 \frac{KgHion_{eq}}{kWh} * EnergyConsumption$ **Equation 38**

Table 13 Acidification Potential of Grid System in 20 Years

Month	Consumption (kWh)	AP Hion eq.
January	869	391.05
February	781	351.45
March	918	413.1
April	1014	456.3
May	1250	562.5
June	1551	697.95
July	1677	754.65
August	1665	749.25
Septembe	1282	576.9
October	1037	466.65
November	853	383.85
December	850	382.5
Total GMP in HionEq.Kg Per Year		6186.15
Total GMP in HionEq.Kg in 20 years		123723

9.2.2.2 Construction and Manufacturing

Global Warming Potential

GWP= 266,691.80 * 0.1 = 26,669 $KgCO_{2eq}$ **Equation 39**

Acidification Potential

AP= 123,723.00 * 0.1 = 12,372 $KgHion_{eq}$ **Equation 40**

9.2.3 Environmental Impact factors

$$EIF_{FuelCell} = \frac{2*\frac{1{,}588.97 KgCO_{2eq}}{(266{,}691.80+26{,}690.18)KgCO_{2eq}} + \frac{374.92 KgHion_{eq}}{(123{,}723+12{,}372.30)Hion_{eq}}}{3} = 0.0045$$

Equation 41

$$EIF_{GridSystem} = \frac{2*\frac{(266{,}691.80+26{,}690.18)KgCO_{2eq}}{(266{,}691.80+26{,}690.18)KgCO_{2eq}} + \frac{(123{,}723+12{,}372.30)KgHion_{eq}}{(123{,}723+12{,}372.30)KgHion_{eq}}}{3} = 1.00$$

Equation 42

9.3 Energy Consumption

The energy consumption of both systems will be assessed in terms of embodied energy of the system and in terms of efficiency of the system.

9.3.1 Fuel Cell

According to literature the embodied energy of a fuel cell system is 5,100 MJ/KW (Phent 2001) and its efficiency when cogeneration is considered around 50% (Ellis et al. 2001; Rahman and Tam 1988; Carrette et al. 2000; Burak-Gunes 2001; Song 2002; Cleghorn et al. 1997; Gacciola et al. 2001).

$EmbodiedEnergy = 5{,}100 MJ / KW * FCcapacity$ **Equation 43**

$EmbodiedEnergy = 5{,}100 MJ / KW * 5.6 KW$ **Equation 44**

$EmbodiedEnergy = 28{,}560 MJ$ **Equation 45**

$$Efficiency = 50\%$$ **Equation 46**

9.3.2 Coal Fired Power Plant

According to literature the embodied energy of the grid system powered by coal fired power plants is 0.8 MJ/kWh (Spath 1999) and its efficiency is 33% (DOE 2007, Spath et al. 1999).

$$EmbodiedEnergy = 0.8MJ / kWh * EnergyConsumption$$ **Equation 47**

Table 14 Embodied Energy of the Grid System

Month	Consumption (kWh)	Embodied Energy (MJ)
January	869	695.2
February	781	624.8
March	918	734.4
April	1014	811.2
May	1250	1000
June	1551	1240.8
July	1677	1341.6
August	1665	1332
September	1282	1025.6
October	1037	829.6
November	853	682.4
December	850	680
Total Embodied Energy per year		10997.6
Total Embodied Energy in 20 years		219952

$$Efficiency = 33\%$$

9.3.3 Energy Consumption Factors

$$ECF_{FuelCell} = \frac{\frac{28,560MJ}{219,952MJ} + \frac{(1-0.50)}{(1-0.33)}}{2} = 0.44$$ **Equation 48**

$$ECF_{GridSystem} = \frac{\frac{219,952MJ}{219,952MJ} + \frac{(1-0.33)}{(1-0.33)}}{2} = 1.00$$ **Equation 49**

9.4 Reliability

The reliability factor will be assessed in terms of system downtime hours per year.

9.4.1 Fuel Cell

A fuel cell is a very reliable source of power because the generation is continuous and the maintenance is very low. Therefore it will not be stopped more than twice a year (Rahman and Tam 1988). Assuming that the fuel cell is stopped for three hours two times a year, the hours per year that the system is down are 6 hr/yr.

9.4.2 Coal Fired Power Plant

In Ohio there are major problems regarding reliability, within the year 2007 there has been 58 hours of power outage (DOE 2007). Assuming that there will not be any power outage this year, the hours per year that the system is down are 58 hr/yr.

9.4.3 Reliability factor

$$RF_{FuelCell} = \frac{6h/year}{58h/year} = 0.10$$ **Equation 50**

$$RF_{GridSystem} = \frac{58h/year}{58h/year} = 1.00$$ **Equation 51**

9.5 Maintenance

System maintenance is going to be assessed in terms on number of times per year the user has to make any maintenance to the system.

9.5.1 Fuel Cell

The maintenance required on a fuel cell is minimal and can be performed by semi skilled manpower twice a year (Rahman and Tam 1988).

9.5.2 Coal Fired Power Plant

As the energy gets to the house through the grid system the final user does not have to perform any maintenance. When the system presents an outage the utility company fixes the problem without even going to the house.

9.5.3 Maintenance factor

$$MF_{FuelCell} = \frac{2times / year}{2times / year} = 1.00$$ **Equation 52**

$$MF_{GridSystem} = \frac{0times / year}{2times / year} = 0.00$$ **Equation 53**

9.6 Space

The space of the system will be assessed in terms of the volume occupied by the system at the house of the final user.

9.6.1 Fuel Cell

From the different sources of alternative energies, fuel cells are the system that occupies less space; they are very small and very light. The size of a fuel cell is 43 cm long (18 in), 17 cm wide (7 in), and 23 cm high (9.6 in) (Ballard 2007). Its volume is:

$$Vol = length * width * height$$ **Equation 54**

$$Vol = 18in * 7in * 9.6in$$ **Equation 55**

$$Vol = 1{,}209.6in^3$$ **Equation 56**

9.6.2 Coal Fired Power Plant

The use of the grid system does not imply any allocated space for the final user of the system.

9.6.3 Space factor

$$SpF_{FuelCell} = \frac{1{,}209.6in^3}{1{,}209.6in^3} = 1.00$$ **Equation 57**

$$SpF_{GridSystem} = \frac{0.0in^3}{1{,}209.6in^3} = 0.00$$ **Equation 58**

9.7 Safety

Safety is going to be addressed from the point of view of the final user, in terms of the risks that using the systems generate to the user of the house.

9.7.1 Fuel Cell

The highest risks of fuel cells are associated to hydrogen storage. However, when hydrogen is handled appropriately is as safe as any other common fuel. In addition, hydrogen properties are advantageous because it is very light (flows up very quickly), has high diffusivity (in open space it disperses fast and it is difficult that it reaches flammable concentrations), and the auto ignition temperature is high. Moreover it is not toxic and non poisonous. However, there are some risks associated, for instance when hydrogen burns the flame is blue (almost invisible), in addition hydrogen is odorless. Therefore leak detectors are installed to prevent undetected flames and leakages. On the other hand hydrogen can explode in the presence of oxygen; therefore the systems have to be very tight. On the following table the risks to the final users and the possibility of occurrence are presented:

Table 15 Risk and possibility of occurrence associated to fuel cells

Risk	Possibility of Occurrence
Leakage	Low
Flame	Low
Explosion	Very Low

Taking into consideration the risk and its possibility of occurrence, giving a rate between 0 and 10, being 10 high risk with high possibility of occurrence and 0 no risk, the fuel cell has a rating of 3 on safety.

9.7.2 Coal Fired Power Plant

Coal Fired Power Plants represent an enormous risk to people who live near the plant in terms of health problems, because it causes asthma attacks, respiratory diseases, heart attacks, and premature deaths. However from the perspective of the final user, the grid system powered by a coal fired power plant represents very few risks (if the final user does not live near the power plant). On the following table the risks associated to this system and the possibility of occurrence are presented:

Table 16 Risks and possibility of occurrence associated to the grid system

Risk	Possibility of Occurrence
Electromagnetic radiation from heavy duty power lines	Very Low
Sudden changes in voltage	Very low

Taking into consideration the risk and its possibility of occurrence, giving a rate between 0 an 10, being 10 high risk with high possibility of occurrence and 0 no risk, the grid system has a rating of 1 on safety.

9.7.3 Safety Factor

$$SaF_{FuelCell} = \frac{3}{3} = 1.00$$ **Equation 59**

$$SaF_{GridSystem} = \frac{1}{3} = 0.33$$ **Equation 60**

9.8 Index Calculation

The factors of each system are presented on the following table:

Table 17 Summary of Factors for Each System

Factor	Fuel Cell	Grid System
Cost (CF)	1.00	0.43
Environmental Impact (EIF)	0.0045	1.00
Energy Consumption (ECF)	0.44	1.00
Reliability (RF)	0.10	1.00
Maintenance (MF)	1.00	0.00
Space (SpF)	1.00	0.00
Safety (SaF)	1.00	0.33

According to the factors calculated in this chapter and the weights found in previous chapters the indexes are:

$$Index = 2CF + 2EIF + 2RF + 2SaF + 2ECF + 1SpF + 1MF$$ **Equation 61**

$$Index_{FuelCell} = 2*1.00 + 2*0.0045 + 2*0.10 + 2*1.00 + 2*0.44 + 1*1.00 + 1*1.00$$ **Equation 62**

$$Index_{FuelCell} = 7.09$$ **Equation 63**

$$Index_{GridSystem} = 2*0.43 + 2*1.00 + 2*1.00 + 2*0.33 + 2*1.00 + 1*0.00 + 1*0.00$$ **Equation 64**

$$Index_{GridSystem} = 7.52$$ **Equation 65**

According to Equation 61 and Equation 63 fuel cells have a slight better rating than the grid system powered by a coal fired power plant; in spite that both numbers are very similar, the factors rated very different. Therefore the fuel cell still needs further development in terms of cost reduction and in duration of its components to be competitive with the conventional grid system.

CHAPTER 10

CONCLUSIONS

- The factors that should be included in the assessment of an alternative source of energy were identified for the Appalachian region of Ohio in the United States. Cost, Environmental Impact, Energy Consumption, Reliability, and Safety are considered very important for the evaluation; therefore a weight of two is given within this index. Maintenance and Space are important in this framework; consequently a weight of 1 is given. Governmental Incentives presents a different behavior depending on the target population. For possible adopters it is not important while for the rest of the population it is important. For the purpose of this study that factor will not be considered as criteria in the index because the study focuses in possible adopters. However, if the index will be used in any other study it is important to reconsider whether the criterion should be included or not.
- The study has a statistical significance demonstrated through the hypothesis tests and though the validation with the larger random sample of non-necessary adopters of alternative energies.
- Multi-criteria analyses that combine all the criteria selected to compare the different kinds of alternative energies using a dimensionless unit are important for the assessment. The factors and weights can vary from one community to another, and can be defined according to the community's necessities. Nevertheless, it is important to address the assessment of alternative energies from different points-of-view, taking into consideration the sustainability performance and the opinion of the final users, not only the economic factors.
- Regarding the factor cost, fuel cells have an enormous disadvantage compared to the traditional grid system for the final user, because the initial investment is very large and because it is not possible to recover such investment within the lifecycle of the system. As long as the cost of the fuel cell technology remain that expensive and the cost of fossil fuels continue being

inexpensive, this technology is not going to be feasible for the residential market or for the building market in general.

- From the environmental impact perspective, the fuel cell is more advantageous than the traditional grid system powered by coal fired power plants, because the coal combustion in one of the largest producer of green house gases that are causing global warming. Besides it has a considerable contribution to the acidification of waters and soils. In addition, this source of energy plays an important role in non-renewable sources consumption and fossil fuel depletion. On the other hand, the fuel cell is a very clean technology; the emissions from the actual fuel cell are almost negligible. Most of the emissions are caused on the hydrogen production process depending on the hydrogen carrier used. For instance, if natural gas is used, some amounts of carbon dioxide and carbon monoxide are going to be emitted. However when water is used as hydrogen carrier the final byproducts are limited to water and heat.
- In terms of energy consumption the fuel cell is more advantageous than the grid system because it has less embodied energy and because the conversion of energy in the operational phase of the system is much more efficient, requiring less energy to produce the same amount of energy.
- In regard to reliability, fuel cells are a very good alternative compared to the grid system, which in Ohio has very serious problems concerning outages caused by several natural phenomena such as storms, snow, trees, etc. The fuel cell provides a constant power that is interrupted just when regular maintenance is needed. Besides, fuel cells are considered as one of the most reliable energy conversion techniques.
- From the safety point of view, both technologies have some risks associated. However if they are handled properly, the possibility of occurrence of such risks is very low. Even though both technologies are fairly safe for the final user, fuel cells present a higher risk compared to

the grid system, because the actual conversion system is on site and special considerations should be considered according to the NFPA code.

- The maintenance factor plays an important role in the final calculation of the index, because there is no maintenance on the traditional grid system from the final user point of view. Therefore, even though the maintenance associated to the fuel cell is very limited, the final user would have to do some kind of effort to operate the system.

- The situation with the space factor is very similar to the maintenance factor, because the grid system does not require any additional space. However, even the installation of the fuel cell at the house requires much less space than any other alternative energy such as solar panels or wind turbines.

- Taking into consideration the overall factors and the weight users assigned to those factors, the fuel cell is slightly more advantageous than the grid system powered by a coal fired power plant. However, the results show that both systems rate very similar because there are some tradeoffs. Probably as the surveys just asked to rank the factors on a three level scale the weights cannot express what the final users really prefer and need. Probably the results could differentiate the systems in a better way. For instance, if the scale to rank the importance of each factor was larger, it would allow the user to express this in a better way. This is the case for, the factor space, which resulted as being two times less important than environmental impact or cost, but it could be actually more times less important. In addition, there might be other several factors that could be important for the final users that were not asked on the surveys. Therefore results of the index could be better if a small sample would be asked which factors users take into consideration when they are thinking on adopting an alternative energy in order to design the surveys with those factors.

- The fuel cell is feasible if all factors are taken into consideration. However, there are factors such as cost that make the adoption of this system very difficult to the final users and are slowing down the process of adopting alternative energies.
- Further research is needed to establish the weights with more differentiation of the factors. Also, it is important to find experimental data on the assessed systems that can feed the model, thereby having more certainty on the results and not just relying in data found in literature.

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