Techno-Economic Analysis of Hydrogen Fuel Cell Systems Used as an Electricity Storage Technology in a Wind Farm with Large Amounts of Intermittent Energy

TECHNO-ECONOMIC ANALYSIS OF HYDROGEN FUEL CELL SYSTEMS USED AS AN ELECTRICITY STORAGE TECHNOLOGY IN A WIND FARM WITH HIGH AMOUNTS OF INTERMITTENT ENERGY

A Dissertation Presented

by

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ABSTRACT

TECHNO-ECONOMIC ANALYSIS OF HYDROGEN FUEL CELL SYSTEMS USED AS AN ELECTRICITY STORAGE TECHNOLOGY IN A WIND FARM WITH HIGH AMOUNTS OF INTERMITTENT ENERGY

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With the growing demand for electricity, renewable sources of energy have garnered a lot of support from all quarters. The problem with depending on these renewable sources is that the output from them is independent of the demand. Storage of electricity gives us an opportunity to effectively manage and balance the supply and demand of electricity. Fuel cells are a fast developing and market capturing technology that presents efficient means of storing electricity in the form of hydrogen. The aim of this research is to study the impact of integrating hydrogen fuel cell storage system with a wind farm to improve the reliability of the grid for allowing higher penetration of renewable energy sources in the power system. The installation of energy storage systems strongly depends on the economic viability of the storage system. We identified four types of fuel cells that could be used in a hydrogen fuel cell storage system. We bring together a range of estimates for each of the fuel cell systems for the economic analysis

that is targeted towards the total capital costs and the total annualized costs for the storage system for individual applications like rapid reserve and load shifting. We performed sensitivity analysis to determine the effect of varying the rate of interest and cost of fuel cell on the total annualized cost of the storage system. Finally, we compared the costs of hydrogen based storage system with other storage technologies like flywheel, pumped hydro, CAES and batteries for the individual application cases.

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CHAPTER 1

OVERVIEW

Energy storage when implemented in a wind farm would allow us to stabilize the grid and at the same time balance the supply and demand of electricity. As per the International Energy Agency, in four years from 2004-2008, there was a 5% increase in world population, 10% increase in annual CO_2 emissions and a 10% increase in gross energy production [1]. High-energy consumption and the ever-increasing population are the main reasons for rapid diminishing of fossil fuels. Also, fossil fuel consumption, especially those based on oil and coal, is the major contributor in increasing carbon dioxide concentration in the atmosphere, thereby increasing the threat of global warming. Climatic change is considered as a serious threat due to its possible impact on the environment and vital processes like food production. Thus, research on reliable renewable energy systems has gained a lot of impetus.

Due to the stochastic nature of wind and solar based electricity production, economically and technologically sound electricity storage systems would help in the widespread deployment of such renewable sources of energy. Hydrogen fuel cells have shown promising results in the research community so far as a way to store electricity. Storage of renewable energy would add value to the electricity supplied by the grid, by making it predictable and by balancing out peaks within a day cycle. Load management would help in extracting the most out of the existing network and making the grid more reliable however the cost of storage has to be considered.

The next section of the report comprises of an overview of fuel cell technology followed by the classification of various hydrogen fuel cells. The third section presents a background and summary of various studies on which this study is built. In the fourth section we discuss how and why fuel cells can be used in conjunction with wind as a kind of energy storage device. The fifth and sixth sections describe the process of production and storage of hydrogen on a wind farm and the characteristics of storage technologies respectively. Section seven consists of the economics related to the storage of electricity using fuel cells followed by the sensitivity analysis to study effect of varying the interest rate and cost of fuel cell system on the total annualized cost of the fuel cell. We also compare the cost of fuel cell storage system to 8 other storage technologies for individual applications like rapid reserve and load shifting in section seven. The conclusions on our findings are summarized in section eight.

CHAPTER 2

FUEL CELL TECHNOLOGY

2.1 Introduction

This section provides an overview of fuel cell technology followed by a classification of hydrogen fuel cells.

A *fuel cell* is a galvanic cell that efficiently converts chemical energy to electrical energy and useful heat. Stationary fuel cells can be used for backup power as well as distributed power. Modularity of fuel cells makes them useful for almost any portable application that typically uses batteries. Fuel cells have proved to be very effective in the transportation sector from personal vehicles to marine vessels.

There are two important types of fuel cells, namely, hydrogen fuel cells and microbial fuel cells. This study will be focused on hydrogen fuel cells. These fuel cells directly convert the chemical energy in hydrogen to electricity. The only by-products of this reaction are pure water and useful heat. Hydrogen fuel cells are more efficient than traditional combustion engines and are pollution free, *given* that one has a source of hydrogen. A traditional combustion power plant is 33% - 35% efficient in generating electricity, whereas fuel cells have been known to be 60% efficient without cogeneration [2]. In addition to that, fuel cell engines have fewer moving parts when compared to a traditional combustion engine, and this helps in their quieter operation.

2.2 Working of Fuel Cell

Figure 1 shows the basic working principle of a hydrogen fuel cell. It consists of two electrodes separated by an electrolyte. When hydrogen gas, in channels, flows to the

anode, a catalyst (usually platinum based) causes the hydrogen molecule to split into protons and electrons. These electrons follow an external circuit to the cathode, whereas the protons get conducted through the electrolyte. This flow of electrons through the external circuit is the produced electricity that can be used to do work.

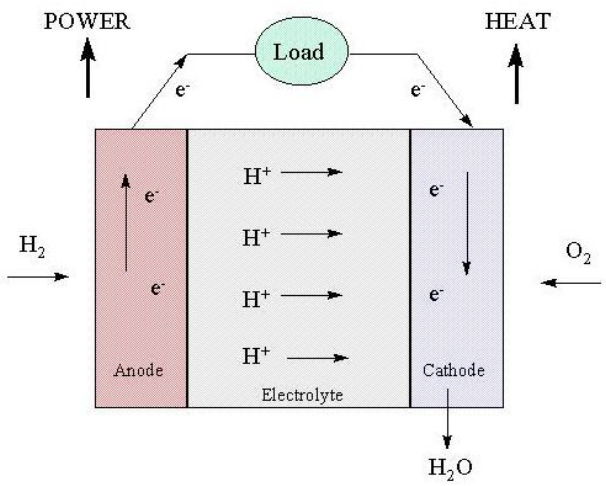

Figure 1: Working of a fuel cell (www.grc.nasa.gov)

2.3 Classification of Hydrogen Fuel Cells

In this section, we will be discussing the classification criterion of hydrogen fuel cells followed by a detailed description of each hydrogen fuel cell. Table 1 provides us with the classification of the types of hydrogen fuel cells that are currently in use and development. Fuel cells are usually classified depending on the electrolyte that is used in them, with one exception: the *direct methanol fuel cell* in which methanol is directly fed to the anode in the course of the reaction. Methanol acts as a fuel in these types of fuel

cells eliminating the need to reform the fuel to hydrogen. Fuel cells can also be classified on the basis of operating temperature for the fuel cell. Alkaline fuel cells, Polymer electrolyte membrane fuel cell, direct methanol fuel cell and Phosphoric acid fuel are low temperature fuel cells: the operating temperature is below 220°C. Molten carbonate fuel cells and Solid oxide fuel cells are high temperature fuel cells, with an operating temperature of around 600-1000°C.

Table 1: Classification of fuel cells [3]

Fuel Cell Type	Operating Temperature (°C)	System Output	Efficiency	Application
Polymer Electrolyte	50-100	1kW – 250kW	53-58% (transportation) 25-35% (stationary)	Backup Power, Portable Power, Transportation, Small Distributed, Generation
Direct Methanol	60-90	1W – 100W	25-35%	Small Portable Power
Alkaline	90-100	10kW – 100kW	60%	Military, Space
Phosphoric Acid	150-200	50kW – 1MW	>40%	Distributed Generation
Molten Carbonate	600-700	1kW – 1MW	45-47%	Large Distributed Generation, Electric Utility.
Solid Oxide	600-1000	1kW – 3MW	35-43%	Auxiliary Power, Large Distributed Generation, Electric Utility

All the fuel cells mentioned above follow the same working principle as explained in section 2.1. For example in a PAFC, when hydrogen (fuel) and air (oxygen) are introduced at the anode and cathode gas chambers, they dissolve in the electrolyte and diffuse to the electrocatalyst (Polytetrafluoroethylene) sites in the electrodes where the following reactions take place. The catalyst strips the electrons from the hydrogen at the anode. Positively charged hydrogen ions migrate to the cathode through the electrolyte and electrons follow the external circuit where they can be used to perform useful work.

Table 2 below shows us the electrochemical reactions that take place in the fuel cell. A discussion of these fuels is presented later in this section.

Table 2: Electrochemical reactions in fuel cells

Fuel Cell	Anode reaction	Cathode reaction	Overall reaction
Polymer Electrolyte	$H_2 \rightarrow 2H^+ + 2e^-$	$^1/_2\, O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$H_2 + {}^1/_2\, O_2 \rightarrow H_2O$
Direct Methanol	$CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$	$^3/_2\, O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$	$CH_3OH + {}^3/_2\, O_2 \rightarrow 2H_2O$
Alkaline	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$	$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$	$2H_2 + O_2 \rightarrow 2H_2O$
Phosphoric Acid	$H_2 \rightarrow 2H^+ + 2e^-$	$^1/_2\, O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$H_2 + {}^1/_2\, O_2 \rightarrow H_2O$
Molten Carbonate	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$^1/_2\, O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	$H_2 + {}^1/_2\, O_2 + CO_2(cathode) \rightarrow H_2O + CO_2(anode)$
Solid Oxide	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	$^1/_2\, O_2 + 2e^- \rightarrow O^{2-}$	$H_2 + {}^1/_2\, O_2 \rightarrow H_2O$

2.3.1 Polymer electrolyte membrane fuel cell (PEMFC)

In this section we discuss the polymer electrolyte membrane fuel cell (also known as proton exchange membrane fuel cell). We start with a basic introduction of the fuel cell followed with the specifics of the electrodes and electrolyte used in the PEMFC.

PEMFC are a type of the low temperature fuel cell with an operating temperature in the range of 85°C - 105°C. The low temperature operation delivers high current density and high power density. This allows the cell to have a compact design, lightweight and faster response time when compared to other fuel cells.

- Cell components for PEMFC

As the name suggests, a solid proton exchange membrane is used as electrolyte in a PEMFC. The proton conducting membrane is an important component of the fuel cell. Using a solid electrolyte has its advantages. The sealing of the anode and cathode gases becomes easier, which in turn makes the manufacturing economical. Unlike liquid electrolytes, solid electrolytes are less prone to corrosion allowing the system to have longer cell and stack life. Figure 2 here shows the working of a PEMFC. Platinum impregnated porous gas diffused electrodes are usually used in PEMFC's to ensure the regular supply of reactant gases to the system. The back of the electrodes is coated with polytetrafluoroethylene (PTFE) that provides a waterproof path for diffusion of gas to the catalyst. The gas supply, the catalyst particle, and the ionic conductor form a three-phase boundary.

Membranes usually operate in a very limited temperature range. Nafion®is the most studied membrane in the PEMFCs [3]. Membranes in this fuel cell are generally filled with water that keeps the conductivity high. Thus, water management becomes major issue in the fuel cell. Solidifying the gases coming into the fuel cell can solve this problem.

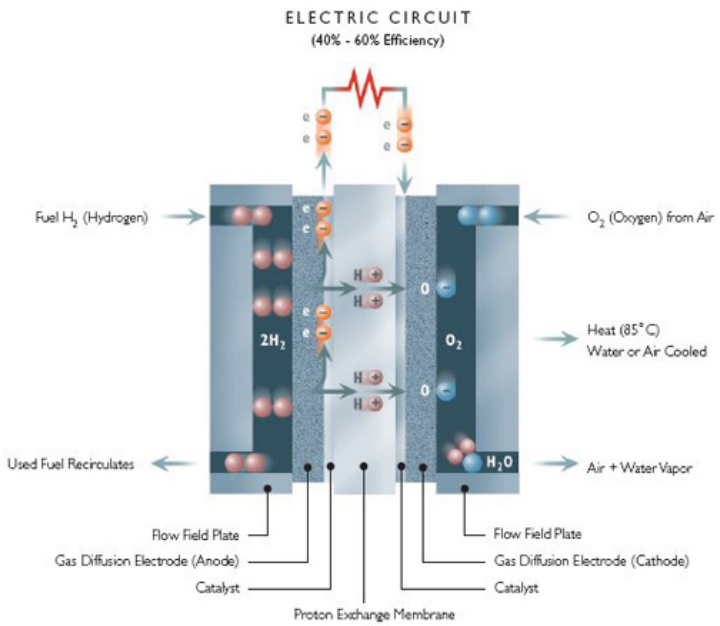

Figure 2: Polymer Electrolyte Membrane Fuel Cell*

*http://www.ballard.com/about-ballard/fuel-cell-education-resources/how-a-fuel-cell-works.aspx

2.3.2 Phosphoric acid fuel cell (PAFC)

In this section we discuss the Phosphoric Acid fuel cell. We start with a basic introduction of the fuel cell followed with the specifics of the electrodes and electrolyte used in a PAFC.

The *phosphoric acid fuel cell* is a low temperature fuel cell with an operating temperature of about 200 ºC. It is the most advanced fuel cell system with its main application in stationary power plants. PAFC is amongst the first few commercialized fuel cell technology with worldwide installed capacity of 75 MW [23]. These cells are expected to find a position in the market for applications of about 1 MW as they are very reliable and can be used for cogeneration of low-temperature steam.

- Cell components for PAFC

Figure 5 below shows the general working of a PAFC. Electrodes of a PAFC are Pt bonded PTFE (Polytetrafluoroethylene). At the cathode, relatively higher loading of Pt is necessary for the oxygen reduction reaction [3, 55]. It was the development of supported platinum electrocatalysts that helped to reduce the platinum loading. In recent times, platinum supported carbon black electrodes are also used along with the porous PTFE electrode structure as electrocatalyst [25]. The carbon not only increases the conductivity of the electrodes but it also help in dispersing the Pt catalyst and ensuring the proper utilization of the catalyst [33].

Phosphoric acid is used as the electrolyte in the PAFC. The ionic conductivity of phosphoric acid is low at low temperatures, thus PAFC's are operated in temperature range of 150 - 200 ºC. In the beginning diluted PAFC was used to avoid the corrosion of the cell elements, but with the advent in technology and with development of better materials 100% concentrated acid is used. The higher the concentration of the acid,

higher is the conductivity of the electrolyte. Operating temperature and concentration of the acid have increased in order to achieve better performance.

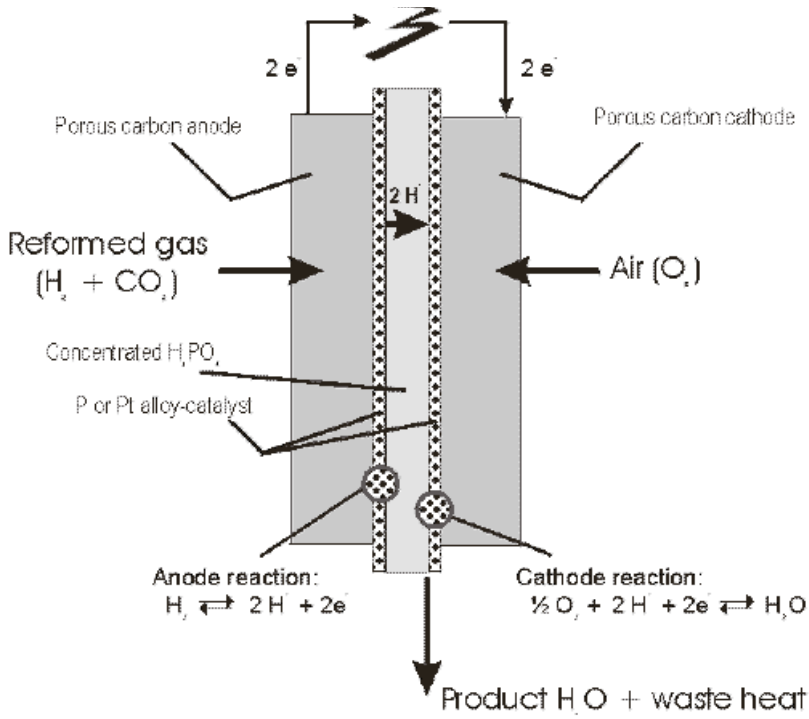

Figure 3: Phosphoric Acid Fuel Cell (http://corrosion-doctors.org/FuelCell/pafc.htm)

2.3.3 Molten carbonate fuel cell (MCFC)

In this section we discuss the Molten Carbonate fuel cell in detail. We start with a basic introduction of the fuel cell followed with the specifics of the electrodes and electrolyte used in a MCFC.

The *molten carbonate fuel cell* is a high temperature fuel cell having an operating temperature of about 600 - 700°C. The high temperatures are needed to improve the conductivity of its carbonate electrolyte and still work with low cost metal cell components. The high temperature also improves the oxidation - reduction processes at

the electrodes. The high temperature has two major disadvantages. It places a great demand on corrosion stability of the cell and it adversely affects the life span of the cell components. MCFCs have proven to attain an electrical efficiency of approximately 50%.

- Cell components for MCFC

Figure 4 below shows the working of a MCFC. Electrodes for a MCFC are usually made from Nickel. The cathode for MCFC is made of Nickel Oxide (NiO) and Ni-Al or Ni-Cr alloys [3, 10, 55]. The problem with nickel oxide cathodes is that particles of nickel oxide creep into the molten carbonate over a period of time which reduces its conductivity. Hence, lithium oxide material in combination with nickel oxide is used to avoid this problem. Nickel oxide is used because it is very active at high temperatures for oxygen reduction which eliminates the need for a Pt based catalyst.

The electrolyte used in the MCFC is alumina based and it is in the form of a stabilized matrix. Till the 1990's, the electrolyte was prepared by fabricating it into a tile using a hot pressing process. Nowadays tape casting methods are used for the preparation of the matrix. Ceria based electrolytes with better stability at higher temperatures are being used as electrolyte, but ceria-based materials are very expensive. Thus, mixtures of lithium and potassium carbonate salts that melt at high temperatures are also being considered [23].

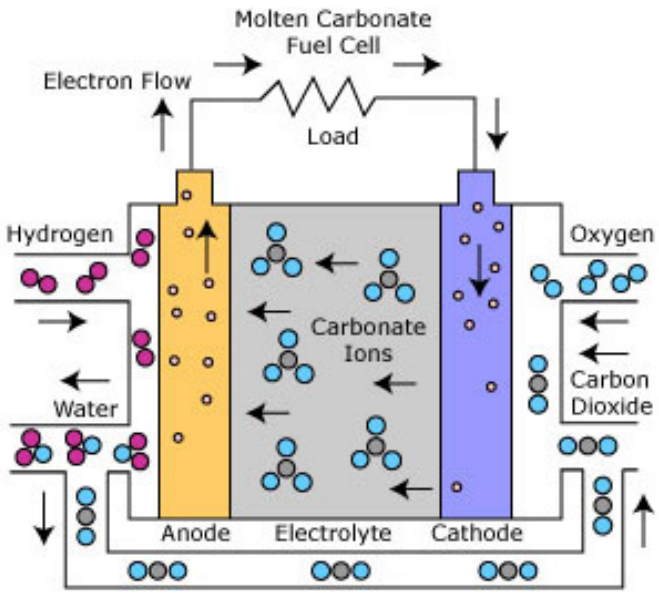

Figure 4: Molten Carbonate Fuel Cell (http://www.fctec.com/fctec_types_mcfc.asp)

2.3.4 Solid oxide fuel cell (SOFC)

In this section we discuss the Solid Oxide fuel cell. We start with a basic introduction of the fuel cell followed with the specifics of the electrodes and electrolyte used in a SOFC.

The SOFCs are the latest entry to the high temperature fuel cells with an operating temperature of 1000°C. SOFCs are a two-phase gas-solid system, which is a major advantage over other fuel cells i.e. the absence of a liquid electrolyte eliminates the need for elaborate systems for water management or flooding of the catalyst layer. SOFCs have demonstrated high power densities that help in the compact designing of its system. Due to the operating condition of the system, special materials are required to withstand the high operating temperature. Thus, the development of low cost ceramic structures (which would work efficiently under such high temperatures) is the key to commercialize SOFCs.

- Cell components for SOFC

Figure 7 below shows the basic working of a SOFC. The electrodes in the SOFCs have to perform under severe operating conditions. Thus, right from the beginning LSM (Lanthanum Strontium Manganite) cathodes have been used, since they are stable under SOFC operating temperatures and show high activity for oxygen reduction at high temperatures. The anodes of the SOFCs are Ni based usually Ni-Zr (nickel – zirconia cermet). Applying a thin layer of zirconia particles improves the conductivity and stability of the electrodes [3, 10].

The SOFCs use solid oxide ceramics, usually *perovskites*, as the electrolyte that operates at temperatures as high as 1000°C. Electrolytes supported with Zirconium oxide (ZrO_2) have proven to be highly conductive and stable [3]. Compared to other cell components, the electrolyte layer exhibits high ionic and low electronic conductivities.

The solid state character of the SOFCs, enable us to shape the cell according to the type of application. Also the solid electrolyte eliminates the need of a water management system (like in PEMFC) and helps in avoiding the corrosion of cell components. But due to the high temperature of the SOFCs, it is difficult to find suitable materials that would have the necessary thermal and stability properties. Thus, it is one of the major contributors to the cost of SOFC.

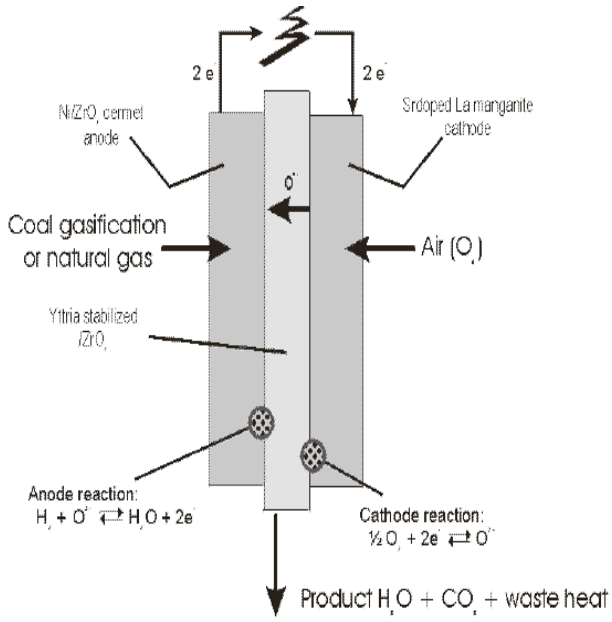

Figure 5: Solid Oxide Fuel Cell (http://corrosion-doctors.org/FuelCell/sofc.htm)

2.3.5 Other fuel cell technologies

In addition to the fuel cell technologies described above, there are other fuel cell technologies that had importance in the past, or are an important future option. In this section we briefly describe these fuel cell technologies and give some reasoning for not including them in our study.

Alkaline Fuel cell is a low temperature fuel cell that was amongst the first fuel cells to be used in the Apollo space missions that led to its application in the European Hermes Project [3, 4]. The AFC uses aqueous solution of potassium hydroxide as electrolyte and Pt-Co (Platinum-Cobalt) and Pt-Pd (Platinum Palladium) alloys electrodes. Major operating constraints for AFCs are that they work well only with pure gases and it requires for low carbon dioxide concentrations in the feed.

AFC's are known to have the highest electrical efficiency among fuel cells, but interest in these types of fuel cells has diminished over the years as they were considered too costly for commercial applications and also there are no significant advantages over PEMFCs.

Direct Methanol fuel cells are actually a subset of Polymer electrolyte membrane fuel cells, and are typically used for small portable applications having low operating temperature. Methanol is directly fed to the anode in these fuel cells. This eliminates the need for a fuel reformer to convert the fuel to hydrogen. This makes the DMFC a very promising candidate for portable power sources, electric vehicles and transportation application. The working of a DMFC is similar to that of the PEMFC and it also uses a selective membrane as its electrolyte.

The DMFCs are typically used for small portable applications having low operating temperatures. Thus, it is highly unlikely that these types of fuel cells could be used in a wind farm for storage purposes.

CHAPTER 3

BACKGROUND

3.1 Literature review

In this section we present a summary of reports and papers on which this study builds. An up to date review of several storage technologies for wind power applications is presented in [48, 49, 50]. The review includes the state of technology as well as issues related to installation and challenges of storage systems. They discuss the external factors like geographical limitations and mineral availability that may affect the widespread implementation of storage technologies. Although they do not focus on the economics of the system, their focus is on applicability of various storage technologies for large scale integration.

Reports published by the National Renewable Energy Laboratory ([34], [35], [36]) review in detail various technical scenarios and cost optimization for wind-hydrogen systems. The 2006 report [34] brings across the opportunities for renewable hydrogen i.e. production of hydrogen by renewable energy sources. The aim of this report was to study production of renewable hydrogen from wind so that it could become a viable production method for transportation fuel in the future. This included production of hydrogen at wind site and delivery to the point of use and also production of hydrogen at point of use using the wind energy transported through the electric grid from various wind farms. Both these analyses concluded that in order to optimize the hydrogen production from wind energy, the electricity and hydrogen production needed to be examined as an integrated system.

The 2008 report [35] was an electrolyzer study that focused on identifying the areas for improvement in the production of hydrogen at wind farms via electrolysis. The study provided a cost analysis of the state of the art electrolyzer technology that were already available or being developed. It focused on a single segment of the process for analysis so that a better picture of each stage of the process can be drawn. The 2011 report [36] is the latest cost study of wind to hydrogen systems that builds on earlier cost studies. In the analysis it considered the technical requirements of a large scale wind electrolysis system and optimized sizing of system components for a particular hydrogen output. The study inferred a correlation between the wind site capacity factor and the cost of hydrogen i.e. higher wind capacity factors correlate to lower hydrogen costs even at sites with lower average wind speeds.

Although all these studies were mainly focused on production of hydrogen at wind farms, they do present the option of wind to hydrogen based storage systems for improving the reliability of the grid and for maximum penetration of renewable sources of energy. Although the economics of the hydrogen storage system were not included in the scope of the research, they infer that the capital cost of the system is a significant factor that hinders the integration of the hydrogen storage system. According to the reports, combining energy storage and production of hydrogen at wind farms could present economic and environmental benefits that were not explored in these studies.

There have been studies ([38], [43], [44], [46], [47], [66]) that have reviewed the viability of renewable hydrogen. WindHyGen was developed in [38]. It is a computer tool to conduct economical assessment of hybrid wind hydrogen system. The model was

guided by a management policy to derive maximum profits from energy sales i.e. sell as much energy as possible when the prices were higher and to store energy, in the form of hydrogen, when prices were lower. Wind energy and hydrogen storage power system is proposed for Corvo Island in Azores in [46]. The aim of the study was to decarbonize the power supply system of the island in order to reduce the harmful emissions and to reduce the cost incurred in transporting fuels as it is a small island that is exclusively dependent on imported fuel. The study introduced hydrogen as a storage medium and wind energy as an additional electricity production source. Future competitiveness of renewable hydrogen in environmental and economic aspects is discussed in [43, 44]. In these studies, the analysis was aimed at identifying the best energy policy for maximum penetration of hydrogen in the competitive fuel market. Integrated hydrogen production and utilization strategy of a PEMFC power plant is studied in [47]. The economic model was developed as a cost optimization problem subject to system and operational constraints. The model was used to determine the optimal operational strategy that would yield the minimum operating costs. The possibility of production of hydrogen by wind power for maximum wind energy penetration is investigated in [66]. There were two objectives of the research, the first one was to study the economics of an electrolysis unit in a wind farm to see if hydrogen could be technically and economically produced by wind energy and the second objective was to thermodynamically analyze the hydrogen and electricity production cycle for the same unit.

Almost all the studies mentioned above consider hydrogen fuel cells as a single technology and do not explore their individual types. They focus more on cost of produced hydrogen and electricity and do not focus on the capital costs and the

annualized costs incurred for hydrogen based storage system in a wind farm. The aim of this thesis is to explore 4 hydrogen fuel cell technologies (PEMFC, PAFC, MAFC and SOFC) that could be used in the storage system in a wind farm. We bring together a range of estimates for each of the fuel cell systems for the economic analysis that is targeted towards the total capital costs and the total annualized costs for the storage system for individual applications like rapid reserve and load shifting. We also perform sensitivity analysis to determine the effect of varying the rate of interest and cost of fuel cell on the total annualized cost of the storage system. Finally, we compare the costs of hydrogen storage system with other storage technologies like flywheel, pumped hydro, CAES and batteries for the individual application cases.

CHAPTER 4

FUEL CELL AS AN ELECTRICITY STORAGE DEVICE

4.1 Introduction

In this section, we answer two questions 'how can fuel cells be used as a storage technology?' followed by 'why is storage necessary?'

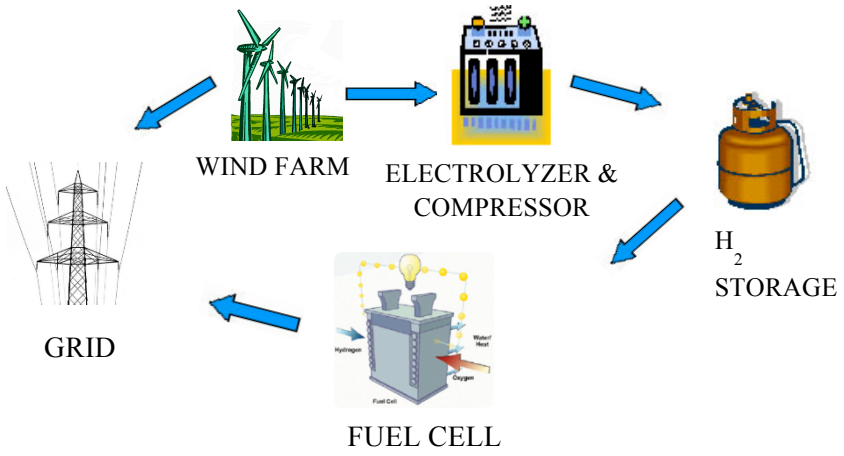

Figure 6: Hydrogen fuel cell storage system concept

Figure 6 above presents the concept of a storage system based on hydrogen fuel cell technology. The main idea of integrating a storage system with a wind farm is that the combined output supply of the entire system would be more constant. Thus not only does it supplement the grid but it also helps in the widespread deployment of wind and other renewable sources of energy. The reason for using hydrogen fuel cells as an electricity storage technology in a wind farm is the possibility of using the *off peak electricity* produced in the wind farm to produce hydrogen. This hydrogen can be stored and later be used to produce electricity on demand. For a fuel cell to be used as a storage device it has to be combined with an *electrolyzer*. This system is termed as a *regenerative*

fuel cell system. An electrolyzer is a device that uses electricity to perform electrolysis of water to produce hydrogen (and oxygen) gas that can be stored. This stored hydrogen fuel will be used to produce electricity when required by using the fuel cell. This system can provide full back up power for an extended time period depending on the hydrogen storage capacity of the system, unlike storage of electricity in batteries.

4.2 Why is storage necessary?

Electricity storage plays a pivotal role in the power market. Although there are no economical methods of storing electricity directly, it can be stored in other forms and can be converted back to electricity as the need arises. Storage not only improves the reliability of electricity supply but it also increases the efficiency of existing power plants and transmission facilities and reduces the investment required in these facilities.

Storage systems based on fuel cell technology permit the separation of the electricity storage and power conversion functions of the system. Thus, each of these functions may be optimized individually for performance, cost or other installation factors. The separation of each of the functions, for optimization, enables the storage system to provide significant benefits for its applications [7]. Storage systems have found application in the entire chain of the electrical system, from supporting the generation of electricity to transmission and distribution of electricity and to support the end customer applications. These multiple roles at times coincide with the area of the grid they will support.

The following section is synthesized from Energy Storage systems papers published by Ibrahim et al. [16] the Sandia report [15], Piyasak et al. [18], Makansi et al

[31] and Rastler et al [32].

4.2.1 Support for renewables

One of the greatest challenges faced by the world today is to harness and deliver the almost limitless amounts of renewable energy resources available to us. Development of these sources not only helps the environment but also improves energy security. However, these renewable sources of energy have two major problems.

Firstly, the potential power generation sites are far from the load centers. Although generating facilities for harnessing wind energy can be constructed in less than a year, new transmission facilities take longer (upwards of 7 years) to build these transmission assets. The second problem is that most of the power that is generated at these generating units is produced when there is low demand for it so that it can be supplied later. Thus, storage technologies would make the development of renewable sources far more cost effective, by increasing the value of electricity generated using renewable energy sources. Storage of electricity would reduce the fluctuations in the output of wind power thereby making it more reliable and readily available in times of peak demand [16].

Figure 9 below describes the electricity production in a wind farm in 24 hours. It is evident that there is significant fluctuation in instantaneous power available during the day cycle. Thus, if electricity is stored during off peak hours and used during peak demand, renewable energy sources can be supported.

Figure9: Power generation on March 16, 2004 at Cap-Chat wind farm (Canada) [16]

CHAPTER 5

PRODUCTION AND STORAGE OF HYDROGEN IN A WIND FARM

5.1 Production of hydrogen from electrolysis

In this section we discuss the production of hydrogen by electrolysis in a wind farm. The electrolyzer, similar to a fuel cell, is an electrochemical cell which produces hydrogen and oxygen from water when supplied with sufficient amount of electricity. Electrolysis was amongst the most popular techniques for hydrogen production before steam reforming processes were introduced [21]. We will focus on electrolysis because the electricity produced by wind is efficient and emission free.

The electrolyzer consists of water, which is the electrolyte, sandwiched between two oppositely charged electrodes, made of chemically inert conductors such as platinum. The electrodes are made from chemically inert conductors, to avoid unwanted reactions with the hydrogen or oxygen ions. When current is passed through water, the positively charged hydrogen ions gets attracted to the negatively charged cathode and similarly, the positively charged oxygen ions migrate towards the anode. The reaction at the anode is:

$$2H_2 0 \rightarrow O_2 + 4H^+ + 4e^-$$

The reaction at the cathode is:

$$4H^+ + 4e^- \rightarrow 2H_2$$

Therefore, the overall reaction is:

$$2H_2O \rightarrow 2H_2 + O_2$$

Under ideal circumstances the electrolysis process requires 39.4kWh of and 8.9 liters of water at normal conditions to produce 1kg of hydrogen. This is known as the higher heating value. This represents the higher heating value of hydrogen which includes the total amount of energy to dissociate water at normal conditions. In some cases, the lower heating value (LHV) of hydrogen is considered for efficiency comparison that is equivalent to 33.3kWh/kg of hydrogen. The system efficiency is calculated by dividing the heating value (LHV or HHV) by the actual energy input in kWh/kg [35].

Only 4% of total hydrogen produced in the world is produced from electrolysis [21]. In the production of hydrogen using electrolysis we realize that the driving cost of the process is the cost of electricity. Thus, using off peak electricity would help in lowering the cost of produced hydrogen.

5.2 Bulk storage of hydrogen gas on a wind farm

In this section we discuss bulk storage of hydrogen gas followed by the methods of storage. The storage technology used for hydrogen storage is determined based on storage capacity and the length of time the hydrogen is stored for. Thus, the cost of hydrogen storage depends on the technology used. Compressed gas, liquefied hydrogen, metal hydride and carbon based systems are major methods for hydrogen storage [21, 23]. Underground storage in depleted oil or gas fields (or aquifers and evacuated rock caverns) can also be considered, although it is only a special case of compressed gas storage. Each of the methods have advantages and disadvantages. For example, if we need the hydrogen to have the highest energy density we store it as liquid hydrogen, but

this also requires an insulated storage container and an energy intensive liquefaction process.

5.2.1 Compressed gas storage

Storage of hydrogen in compressed gas form is the simplest storage solution. The only equipment it requires is a compressor and a pressure vessel [30]. The main problem with gaseous hydrogen is that it has poor energy density by volume and therefore it needs larger tank for storage. The capital and operating costs are directly proportional to the storage pressure. Thus, higher the storage pressure, higher is the capital and operational costs. Also, one of the major concerns with large storage vessels is the cushion gas that remains in the empty vessel at the end of the discharge cycle. A large variety of vessels are in operation today. The size of these vessels is limited by its materialistic characteristic to withstand high pressure as the thickness of the walls increases with increase in volume of the vessel. Cylindrical steel vessels with about 5 to 7 MPa are the most commonly used industrial storage method of hydrogen gas. About 6-7% of the stored energy is used up in compressing hydrogen. Technical lifetime of these vessels is approximated to be around 22 years [23].

5.2.1.1 Underground storage of gaseous hydrogen

Storage of hydrogen underground is possible depending upon the geology of the area [30]. In general, caverns must provide containment of the gas. This is usually achieved by lining the cavern with steel or by using hydraulic pressure in the surrounding rock. Gas can be stored underground under pressure in formations like

- Depleted oil fields

- Aquifers
- Excavated rock caverns
- Solution mined salt caverns.

Underground storage of natural gas is very common. Helium, which diffuses faster than hydrogen has been stored underground successfully in Texas [30]. For underground storage of hydrogen gas, a large cavern or a porous rock with an impermeable caprock above is needed to contain the gas. This method is also vastly affected by the cushion gas, as mentioned for compressed gas storage, which occupies the underground storage volume at the end of the discharge cycle.

Although underground storage has considerable economical advantages over storage in pressure vessels, there are a few issues that need to be addressed. These include subsidence, shrinkage of approximately 0.25% per year and deformation/breakage causing equipment damage. Hydrogen stored in caverns also requires a purification process before it can be used in fuel cells [29]. Thus, further research is required to ensure purity of the gas, hydrogen mobility in different rock types, hydrogen embrittlement, mixing of gases and the effect of hydrogen on rock properties.

CHAPTER 6

CHARACTERISTICS OF FUEL CELL SYSTEMS

6.1 Introduction

Fuel cell systems have certain generic characteristics that make them favorable for electricity storage compared to other technologies. The purpose of this study is to critically analyze the fundamental characteristics of fuel cell systems and to check for their viability as an effective electricity storage technology. The key characteristics that we will consider are storage capacity, power transmission rate, discharge time, efficiency, durability, cost of the system, modularity, reliability and the siting flexibility of the plant.

Storage capacity and duration are the major criteria that classify energy storage technologies For example, for a pumped hydro storage system, mass and height of waterfall determine the storage capacity, whereas the size of conduit and power of the turbine determine the maximum power available. The characteristics explained in this section have been classified into two groups, the ones that affect the performance of the whole system and the ones that don't affect the performance of the system but still are very important characteristic of hydrogen fuel cell system when used as an electricity storage technology. The following characteristics are synthesized from [15, 16, 17].

The characteristics that affect the performance of the fuel cell storage systems listed below:

6.2 Storage capacity

Storage capacity can be defined as the total energy that is available in the storage system once it is fully charged. It is the quantity of energy available after a complete

charging cycle. The units of storage capacity are Watt-hour (W-h). The discharge cycle of a storage system is usually incomplete. Thus, the storage capacity is usually defined on the basis of the total energy stored W_{st} which is always more than the actual amount of energy retrieved W_{ut}. The usable energy would be restricted to the minimum charge state, the state at which the system would need charging to continue operation. In times of quick discharge, the efficiency of the system deteriorates and the retrievable energy is much lower than the storage capacity. Thus, the storage capacity of a hydrogen fuel cell system depends upon the time of discharge. The aim is to design a system with storage capacity of 10MW-hr so that the storage system can supply 1MW power for 15 hours and upto 10MW power for an hour and a half depending on the need and application.

6.3 Power transmission rate

An important aspect of storing energy is to supplement the supply in case of peak demand. The power transmission rate may be defined as the delivery rate that determines the time required to extract the stored energy. Fuel cell systems have demonstrated fast response to demand which make them an alternative to shunt reactors and capacitors when connected to the grid [28]. The power transmission rate can be a limiting factor in deciding and designing the storage system. Power transmission rate depends upon the rate of reactions in the fuel cell, which in turn depend upon conditions like atmospheric pressure and temperature. Power transmission rate is proportional to discharge time.

6.4 Discharge time

Discharge time may be defined as time taken by the system for maximum energy discharge. The discharge time is dependent on the power transmission rate and the

minimum charge state, the state at which the system would cease to operate without recharging. It is expressed in units of time and can be calculated by the formula stated below:

$$\tau = \frac{W_{st}}{P_{max}}$$

τ – Discharge Time (hour)

W_{st} – Total energy stored (W-h)

P_{max} – Maximum power or charge (W)

6.5 Efficiency

Efficiency in general is the ratio of work output to work input. Thus, in a storage system it may be defined as the ratio between the released energy to the stored energy. The energy stored in the system is represented as W_{st} whereas the energy retrieved in the discharge cycle is expressed as W_{ut}. Therefore, the efficiency of the storage can be stated as

$$\square = \frac{W_{ut}}{W_{st}}$$

The losses in a fuel cell can be divided into fuel crossover and internal currents, activation losses, ohmic losses and mass transport losses.

Fuel crossover and internal current losses result from the flow of fuel and electric current in the electrolyte. The electrolyte should only transport ions, however a certain fuel and electron flow will always occur. Although the fuel loss and internal currents are

small, they are the main reason for the real open circuit voltage (OCV) being lower than the theoretical one.

Activation losses are caused by the slowness of the reactions taking place on the electrode surface. The voltage decreases somewhat due to the electrochemical reaction kinetics.

The ohmic losses result from resistance to the flow of ions in the electrolyte and electrons through the cell hardware and various interconnections. The corresponding voltage drop is essentially proportional to current density, hence the term "ohmic losses".

Mass transport losses result from the decrease in reactant concentration at the surface of the electrodes as fuel is used. At maximum (limiting) current, the concentration at the catalyst surface is practically zero, as the reactants are consumed as soon as they are supplied to the surface.

The overall efficiency is an important characteristic for a competitive storage system. For a fuel cell system to achieve maximum efficiency, it should be designed to use pure reactants, with the removal of the product in a pure form, in order to tap the maximum free energy available.

6.6 Durability

Durability is the ability of the fuel cell system to resist a permanent change in its performance over time. This change does not lead to failure of the system but it is simply the decrease in performance that is not recoverable or reversible. These losses could be due to loss of electrochemical surface area, carbon corrosion etc. Durability at times is also referred to as the cycling capacity of the system. One cycle corresponds to one charge and one discharge cycle. Thus durability can be defined as the number of times

the system can supply the maximum energy it has been designed for. It is expressed in maximum number of cycles N or hours depending on the application.

Durability at times is also referred to as ageing of the system. Thus, while designing storage systems ageing is considered and it becomes of utmost importance when choosing a system. Not a lot of testing has been done to quantify the durability or the decay of the system in a lifetime. The reason being that for 40000 hours of testing the system has to run uninterrupted for almost 4.5 years. Normal degradation targets are set upto 10% loss in efficiency of the fuel cell system at the end of lifespan, and a degradation rate of 2 – 10 μVh^{-1} is accepted for all applications [26, 27]. The small voltage drop signifies that over a number of cycles, the performance of the system decreases minimally as it is subjected to wear by usage due to constant charging and discharging cycles. This makes the system reliable.

The characteristics explained below are the ones that do not affect the performance of the system but are equally important. These are the characteristics of fuel cells that make this technology favorable for energy storage applications.

6.7 Modularity and reliability

Modularity may be defined as the degree to which the systems components may be dismantled and assembled again. In engineering terms, it may also be defined as the technique of building a larger system using smaller sub-systems or modules. Thus, we can say that fuel cell systems are certainly modular. Like batteries, fuel cell systems can be designed depending on the application it is meant to be used for. Due to the modular

nature of fuel cell systems, the lead time for the construction of a fuel cell system would be short.

The high reliability of the fuel cells is mainly attributed to the modularity of stacks and stack components and also due to the absence of highly stressed moving parts operating under extreme conditions. This also makes their maintenance easy. Fuel cell systems have improved the use of construction capital, as system capacity can be added in small increments based on the growth in actual demand. This ability to add capacity minimizes the risks involved from inaccurate load forecasting and provides flexibility to the planner.

6.7.1 Siting flexibility

The modular nature of a fuel cell system allows installation of a single unit in relatively smaller area. These characteristics, along with it being environmentally safe, permit fuel cell systems to be located in remote relatively inaccessible sites. Fuel cell systems may also be sited close to the point of use where the heat (product of the fuel cell reaction) may be used for cogeneration applications.

6.8 Cost

The total cost of the storage system is an important aspect that determines the value of the investment. Like any other transaction, the total gain from the system should exceed the total expense incurred in putting the system together. Thus, it is extremely important to analyze the overall costs over the entire life of the system, including materials, energy and other environmental costs from fabrication to recycling. Detailed explanation as to how the costs can be calculated has been presented in section 6 of the report.

CHAPTER 7

ECONOMICS

7.1 Introduction

In this section, we present the economic assessment of fuel cells when used as a storage technology. For the current analysis, the storage will be used in a hypothetical wind farm with a nameplate power capacity of 100MW and we assume that $1/10^{th}$ of the nameplate capacity will be provided by the storage system. Thus, for a 100 MW wind farm, we would like to have a storage system with rated power capacity of 10 MW. The storage system would help in increasing the reliability of the grid, as it would supplement the grid in times of peak demand.

Figure 7 shows the system diagram for a hydrogen fuel cell storage system. Unlike other storage technologies, fuel cell systems have different charging and discharging interfaces. The electrolyzer provides hydrogen fuel for the fuel cell to generate electricity. Although it is possible to use a reversible fuel cell to perform both operations, having separate interfaces makes the system more cost effective.

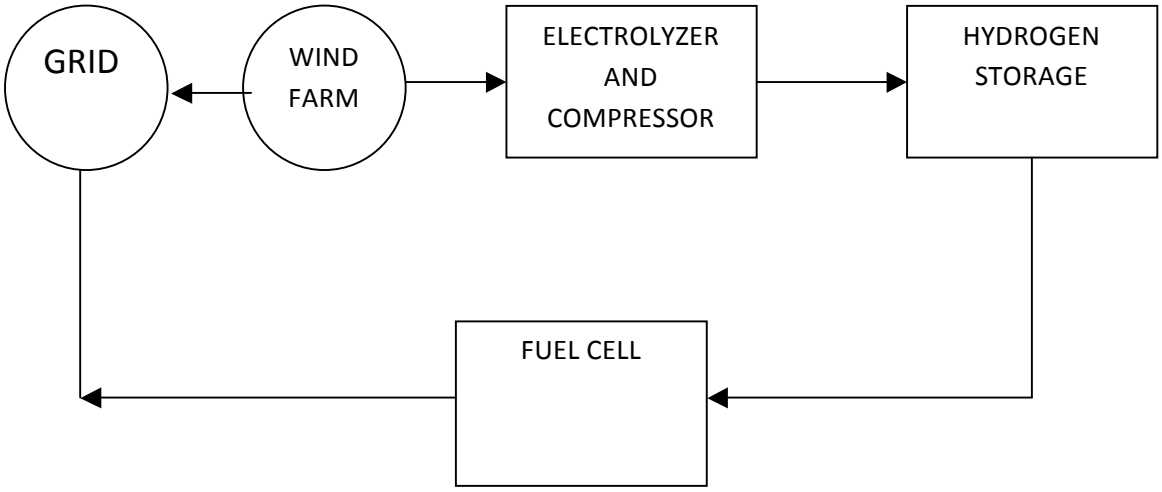

Figure 7: Hydrogen fuel cell storage system and its components

The following approach has been adopted from [13, 15, 18].

7.2 Total capital cost of the storage system

In this section, we present our approach for calculating the total capital cost incurred in a hydrogen fuel cell storage system.

The total cost of a system consists of: the cost of the fuel cells, the cost of the electrolyzer and the cost of storing hydrogen. Unlike other storage systems, hydrogen fuel cell systems have a separate charging component, the electrolyzer. A compressor is also necessary in order to pressurize the hydrogen for storage. These components add to the overall cost of the system.

There is no reliable data available for the Balance of Plant (i.e. housing, land etc.) cost for a fuel cell system. Thus, in this thesis we have not accounted for that.

The total system cost for a hydrogen fuel cell storage system may be given as:

Equation 1: Total Capital Cost of the Storage system

$$Cost_{H2\,total}(\$) = COST_{FC} + COST_{storage} + COST_{electrolyzer}$$

Where,

$Cost_{H2\,total}$= Total Capital Cost of the Hydrogen fuel cell storage system.

$COST_{FC}$ = Cost of fuel cells.

$COST_{storage}$ = Cost of hydrogen storage.

$COST_{electrolyzer}$ = Cost of Electrolyzer.

Cost of fuel cells:

The cost of the fuel cell system will be dependent on the rated power of the fuel cell system. Therefore,

Equation 2: Cost of Fuel Cells

$$COST_{FC} = UnitCost_{gen}\left(\frac{\$}{kW}\right) * P_{discharge}(kW).$$

Where,

$UnitCost_{gen}$ = Cost of Hydrogen Fuel Cell in $/kW

$P_{discharge}$ = Rated power of the fuel cell system in kW

Cost of storage:

The cost of the storage system is directly proportional to the amount of energy stored. Therefore,

Equation 3: Cost of Storage

$$COST_{storage} = UnitCost_{storage}\left(\frac{\$}{kWH}\right) * \frac{E\ (kWH)}{\eta_{H2\ dis}}$$

Where,

UnitCost $_{storage}$ = Cost of hydrogen storage in $/kWh

E = Stored energy capacity in kWh = $P_{discharge}$ * t_d

$\eta_{H2\ dis}$ = discharge efficiency or generating efficiency of the hydrogen system.

Cost of electrolyzer:

To estimate the cost of the electrolyzer, its power rating must be determined.

Electrolyzer rating

The power rating of an electrolyzer depends on the time available for charging and the rated power of the fuel system. It is very important to note that the electrolyzer would only operate when the fuel cell is not operating. Thus, the power rating of the electrolyzer can be lower than the power rating of the fuel cell system at discharge.

To calculate the rating of the electrolyzer, assume the fuel cell system is discharging for time t_d each day at a power level $P_{discharge}$. Thus, the electrolyzer would have to recharge over the remaining time t_{ch} = 24 hr – t_d (hr) and be rated at

Equation 4: Power rating of electrolyzer

$$P_{charge} = \frac{P_{discharge} * t_d}{t_{ch} * \eta_{H2elec}}$$

Where,

P_{charge} = Rated power of electrolyzer.

$P_{discharge}$= Rated power of the fuel cell system.

t_d = Time to discharge.

t_{ch} = Time to charge.

$\eta_{H2\ elec}$ = electrolyzer efficiency.

The cost of the electrolyzer is dependent on the power rating of the electrolyzer i.e. P_{charge}.

Equation 5: Cost of Electrolyzer

$$COST_{electrolyzer} = UnitCost_{electrolyzer}\left(\frac{\$}{kW}\right) * P_{charge}(kW)$$

Where,

UnitCost $_{electrolyzer}$ = Cost of electrolyzer in $/kW.

7.2.1 Application areas

In this sub section we discuss the key application areas that would be of major concern for the integration of wind farms to the grid. These applications can be divided into two categories based on their function. These categories are energy management applications and power management applications. Energy management applications involve long duration discharge i.e. discharge durations upto hours or more. Examples of energy management applications are load shifting, load following and transmission curtailment. Power management applications involve short duration discharge i.e. discharge duration from a few fractions of a second up to fifteen minutes depending on the application. Rapid reserve, power quality and frequency regulation are examples of power management applications.

For the current analysis, the storage system will be used in a hypothetical wind farm with a nameplate power capacity of 100MW. We assume that $1/10^{th}$ of the nameplate capacity will be provided by the storage system. Thus, for a 100 MW wind farm, we would like to have a storage system with rated power capacity of 10 MW. The applications considered for this study are mentioned below:

1. Load Shifting

Load shifting is the technique aimed to move demand from peak hours to off peak hours of the day. This is important for wind integrated grids because wind energy production is often unable to satisfy the peak demand periods, as wind is not uniform all the time. The fuel cell storage system produces hydrogen using the electricity provided by the wind farms during off peak hours and stores it for producing electricity during peak hours. This application would be beneficial for the wind farms. They can store

electricity at off peak times, when the cost of electricity is lower, and sell it in peak demand period when the cost of electricity is higher. It is a very energy intensive application in which energy may have to be supplied for a period of 3 to 5 hours at a low power rating of 2 to 3 MW [14, 19]. In order compare the results with the load shifting application in [14] we consider the power as 3MW and discharge duration as 5hours.

2. Rapid reserve

Rapid reserve is the reserved system capacity available to the operator within a short interval of time to meet the demand in case there is disruption in power supply. Energy Storage systems based on batteries, hydrogen fuel cells, flywheels, SMES, CAES and pumped hydro prove useful in providing reserve energy [3]. By providing energy at the time of need, stored energy can be utilized when generation units fail or during the intermediate periods when utilities are trying to fix the power failure.

This application was originally known as spinning energy as reserve was supplied within few minutes by hot-spinning generators. Due to the advancements in storage technologies, energy can be supplied without necessarily 'spinning' the generator. Thus, now it is termed as rapid reserve instead of spinning reserve. In case of disruption of power supply the storage system is required to provide high power for a period upto 30 mins [49]. DOE in 2010 identified the time for cold start up to 90% of rated power to be less than 30 seconds for PAFC and less than 15 seconds for PEMFCs. In order compare the results with the frequency regulation application in [14] we consider the power as 10MW and discharge duration as 15mins.

Although each application is unique, an ideal storage system would help a user to resolve both the issues at once. We introduce an additional application and call it ***combined application***. For this application we consider a storage system that could discharge at different power rating for varied discharge duration depending on the need of the application. It would benefit the user by satisfying high power requirements for the rapid reserve application and by also providing enough energy for longer duration application of load shifting. We design the system for maximum energy storage capacity requirement of 15MW-hr (for load shifting application) and capable of providing maximum power capacity of 10MW (for rapid reserve application). This storage system could provide 10MW for 30mins for rapid reserve application and could also provide 3MW for 5 hours for load shifting application.

Table 3: Application areas

Application	Power capacity (kW)	Discharge duration (hr)	Energy storage capacity (kW-hr)
Load Shifting	3000	5	15000
Rapid reserve	10000	0.25 (=15mins)	2500
Combined Application	10000	1.5	15000

7.2.2 Cost Data

In this sub section, we present estimates of the costs that we consider for this study.

- **Fuel cell cost data**

In this section we present the estimates of fuel cell cost for each of the hydrogen fuel cell technology. We present lower, baseline and higher cost estimates of fuel cells (CostFC) that we have used in the study for calculating the total cost of the storage system ($Cost_{H2total}$). A Whisker plot is used to present the range of the estimates across different fuel cell technologies. The lower and higher cost estimates are used for sensitivity analysis.

The cost of a 5kW PEM fuel cell in 2002 was estimated to $55,000 implying per unit cost of $11,000/kW [51]. The Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan has estimated the present cost of PEMFC system to be close $2500 - $4000 /kW and a target cost of $1000/kW [52]. The Oakridge National laboratory in their cost assessment of PEM systems present an estimate of PEMFC systems costing between $3000/kW – $6000/kW [53]. Reports published by EPRI in 2000 have estimated the price for producing 100,000 units of PEMFC to be around $1800/kW [54]. Thus, for PEMFC we take $750/kW as the lower end estimate, $2500/kW as the baseline estimate, and $4000/kW as the higher end estimate.

The installed cost of PC25, a 200 kW PAFC system by UTC is approximately $850,000 implying per unit cost of $4250/kW. Their stated target is to reduce the cost to $2000/kW [55]. The installed cost for a PAFC system is estimated to be $3000 –

$4000/kW [56, 57]. Thus, for this study we consider $2000/kW as the lower end estimate, $3000/kW as our baseline estimate and $4250/kW as the higher end estimate for the PAFC system.

The cost of MCFC systems declined from $ 8000/kW in 2004 to $6000/kW in 2005 and it was expected to decline to $ 4800/kW by 2006[58]. The installed cost of MCFC systems is in the range of $4200/kW – $5600 /kW [59]. The estimated costs for MCFC system is around $3000/kW [60] and is expected to be around $2700/kW [55]. Long-term goal for the MCFC system is $1250 /kW. Thus, for this study, we consider $1250 /kW as the lower estimate, $2700/kW as our baseline estimate and $4200/kW for the higher estimate.

SOFC are estimated to cost around $2500/kW to $5000/kW [23, 52]. EPRI published a report which stated a price of approximately $3000/kW considering 10,000 units were produced each year [54]. The long term target cost for SOFC systems is around $750/kW [61]. Thus, for this study, we use $1000/kW as the lower end estimate, $2500/kW as the baseline estimate and $5000/kW as the higher end estimate for SOFC.

Table 4: Hydrogen Fuel Cell cost data

	Lower estimate ($/kW)	Baseline estimate ($/kW)	Upper estimate ($/kW)
PEMFC	1000	2500	4000
PAFC	2000	3000	4250
MCFC	1250	2700	4200
SOFC	750	2500	5000

Figure 8 represents the whisker plot for the fuel cell cost data. Whisker plots are generally used when a large range of data points have to be covered. The number placed at the bottom of the vertical line is the lowest cost estimate and the number placed at the top of the line is highest cost estimate. The baseline estimate is placed in-between these two on the left hand side.

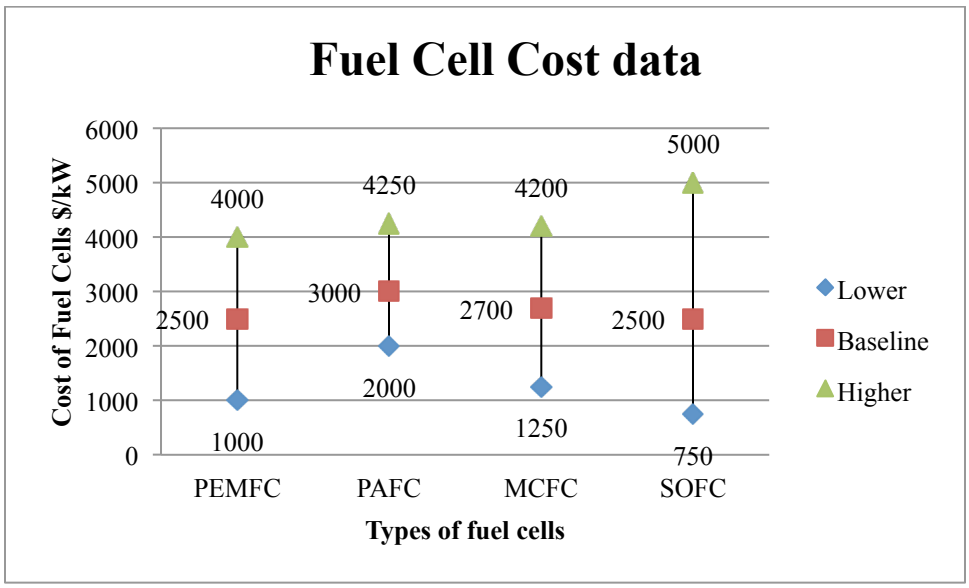

Figure 8: Whisker Plot depicting a range of fuel cell cost data

- **Hydrogen storage cost data**

In this section we present the estimates we use for the hydrogen storage cost data. The current cost estimate presented by for storage of hydrogen in tanks above ground is $19/ kWh [63]. In general, underground storage of hydrogen is anticipated to be significantly less expensive than storing hydrogen in steel tanks. However, development of underground storage is dependent on the characteristics of underground formations. Cost estimates for underground storage facilities for hydrogen were studied in [62]. Cost estimates were developed by studying the cost incurred in storing air for Compressed air energy storage (CAES) systems [62]. The storage volume required for storing hydrogen

is less than the volume required for equivalent energy capacity for a CAES reservoir because of the higher calorific value of hydrogen. Energy density for a typical hydrogen reservoir was estimated at 170kWh/m^3 compared to 2.4kWh/m^3 for a CAES system. They established estimates for storage of hydrogen in geological formations. The cost of underground storage for hydrogen ranges from 0.002$/kWh in naturally occurring porous rock formations, 0.02$/kWh in salt caverns and 0.2$/kWh in abandoned coal mines. In this study, we use 0.2$/kWh as the baseline estimate for geological storage of hydrogen.

Table 5: Hydrogen Storage Cost Data

Cost-storage ($/kWh)	
Above ground	Underground
19	0.2

- **Electrolyzer cost data**

In this section we present the estimates of electrolyzer costs that we have used in the study. The main drivers for the cost of production of hydrogen by electrolysis are the capital cost, electricity price and the efficiency of the electrolysis process. Significant technology advancements in reducing capital costs and improving efficiency have lead to substantially improved electrolysis production costs. The electrolyzer system is based on H2A central electrolysis cost assessment models by the DOE. The electrolyzer efficiency is 53% for the lower heating value (LHV) and 65% for the higher heating value (HHV) [35]. Thus, we use the average 59% as the baseline electrolyzer efficiency. NREL estimated the uninstalled capital cost of electrolyzer to be around $380/kW [36]. The DOE estimates current capital costs for central production systems and distributed

production system to be between $325 and $385/kW [64, 65]. Their stated target costs are between $215/kW and $270/kW. For this study, we assume $385/kW as the baseline estimate for electrolyzer capital cost.

7.2.3 Calculation of total capital cost

In this sub section we present a sample calculation for the total capital cost of the storage system. To calculate the total cost of the storage system we follow the approach mentioned in section 7.2. All calculations are based on the assumption that the excess off-peak electricity is used to electrolyze water to produce hydrogen, which is stored in compressed gas cylinders or underground geological formations. The hydrogen is reconverted into electricity using a fuel cell. Below we present sample calculations for the total cost of a PEM (polymer electrolyte membrane) fuel cell storage system with compressed tank storage for load shifting application. Our assumptions for load shifting are presented in Table 6. We can see that the electrolyzer rating is 1.34MW. As mentioned earlier, the wind farm nameplate capacity is 100MW. Thus, we assume that the excess off-peak electricity would be sufficient to charge the system.

Table 6: Assumptions for load shifting application

Storage Capacity E (kWh)	15000
Power rating of fuel cell system at discharge-$P_{discharge}$ (kW)	3000
Power rating of electrolyzer charge- P_{charge} (kW)	1338.5
Discharge time- td (hr)	5
Time to charge the electrolyzer- tch (hr)	19
Discharge or generating efficiency of the hydrogen system- nH2	0.59

We repeat equations (1) to (5) to calculate the capital cost of the fuel cell storage system. We use baseline estimates to calculate the cost of the fuel cells, storage of hydrogen in compressed steel tanks and the cost of the electrolyzer.

$$COST_{FC} = 2500\left(\frac{\$}{kW}\right) * 3000\ (kW) = \$7{,}500{,}000$$

$$COST_{storage} = 19\left(\frac{\$}{kWh}\right) * 15000\frac{(kWh)}{0.59} = \$483{,}050.84$$

$$COST_{electrolyzer} = 385\left(\frac{\$}{kW}\right) * 1338.5(kW) = \$515{,}165$$

$$Cost_{H2\ total}(\$) = COST_{FC} + COST_{storage} + COST_{electrolyzer}$$

$$Cost_{H2\ total}(\$) = 7{,}500{,}000 + 483{,}050 + 515{,}165 = \$8{,}498{,}215$$

We use the same approach to calculate the values for all the fuel cell systems. Table 7 presents the total capital cost calculations for four types of fuel cells with compressed tank storage for load shifting application.

Table 7: Total Capital Cost for storage system

Fuel Cell Type	Cost-Fuel Cell	Cost-Fuel Cell	Cost-storage	Cost-electrolyzer	Total Cost
	($/kW)	($)	Tank Storage ($)	($/kW)	($)
PEMFC	2500	7,500,000	483,050	515,165	8,498,215
PAFC	3000	9,000,000	483,050	515,165	9,998,215
MCFC	2700	8,100,000	483,050	515,165	9,098,215
SOFC	2500	7,500,000	483,050	515,165	8,498,215

For calculating the total capital cost of the storage system for rapid reserve application we use the power and discharge duration assumptions presented in Table3. Table 8 presents the values for the total capital cost of the fuel cell system for load shifting and rapid reserve application cases.

Table 8: Total Capital Cost for assumed applications

	Total capital cost ($)	
Fuel Cell Type	Load Shifting	Rapid reserve
PEMFC	8,498,215	25,149,197
PAFC	9,998,215	30,149,197
MCFC	9,098,215	27,149,197
SOFC	8,498,215	25,149,197

Figure 9 presents the cost components of the initial capital cost for each of the fuel cell system for the above mentioned applications. It is evident from the figure that the fuel cell cost is the major cost component in each of the application. The cost of the fuel cell system is dependent on the power requirement of the application. The power requirement for the load shifting application is 3MW and it less compared to the power requirement for the rapid reserve application case which is 10MW. Therefore, there are such vast differences in the initial capital cost requirement.

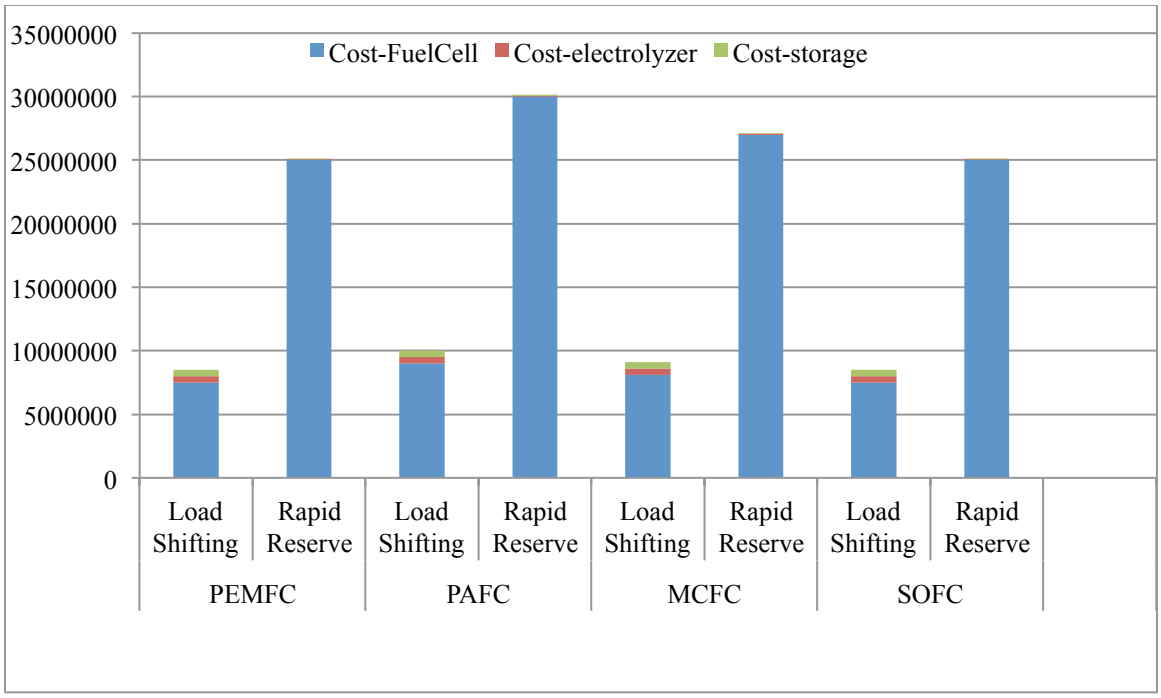

Figure 9: Initial capital cost components of fuel cell storage system

7.3 Total annualized cost of the storage system

The total annualized cost of the storage ($TC_{storage}$) is the sum of the annualized capital cost (AC) and the annualized operation and maintenance cost ($O\&M_c$). It is measured in $.

Equation 6: Total annualized cost

$$TC_{storage} = AC + O\&M_c$$

The annualized capital cost includes the initial capital cost and the replacement costs associated with the proper functioning and maintenance of the storage medium. It can be calculated by multiplying the total capital cost and the capital recovery factor (CRF).

Equation 7: Annualized cost

$$AC = Cost_{H2\ total}(\$) * CRF$$

Equation 8: Capital Recovery Factor

$$CRF = \frac{i_r(1+i_r)^{n_y}}{(1+i_r)^{n_y}-1}$$

Where,

Cost $_{H2\ total}$- cost for a hydrogen fuel cell storage system.

i_r - the annual interest rate in %

n_y – system lifetime in years.

Assumptions

The interest rate is an important aspect that determines the value of the investment. Like any other transaction, the total gain from the system should exceed the total expense incurred in putting the system together. The interest rates typically used by firms for investment are in the range of 10% to 15%. We have assumed 15% as our baseline estimate in all calculations.

7.3.1 Calculation of total annualized cost of storage system

In this sub-section we present a sample calculation for the total annualized cost of the storage system. To calculate the total annualized cost of the storage system we follow the approach mentioned in section 7.3. We repeat equations (6) to (8) for each of the fuel cell storage systems for load shifting and rapid reserve application cases. For calculating the capital recovery factor (CRF) we use an interest rate of 15% and system lifespan of 20 years. We obtained the O&M costs for PEM, PAFC MCFC and SOFC from [8, 11, 55, 54] respectively. For annualized O&M costs we multiply these costs with the power capacity. The annualized O&M cost for electrolyzer has been obtained from [36] to be

2% of the electrolyzer system cost. Below we present sample calculations for the total annualized cost of the PEM (polymer electrolyte membrane) fuel cell storage system with compressed tank storage for load shifting application.

$$CRF = \frac{i_r(1+i_r)^{n_y}}{(1+i_r)^{n_y}-1} = \frac{15(1+15)^{20}}{(1+15)^{20}-1} = 0.159761$$

Therefore,

$$AC = \$8{,}498{,}216 * 0.159761 = \$1{,}357{,}687/year$$

$$O\&M_{cell} = 27\left(\frac{\$}{kW-yr}\right) * 3000\ (kW) = \$81{,}000/year$$

$$O\&M_{electrolyzer} = 0.02 * \ 515165 = \$10{,}300/year$$

$$O\&M_c = \$81{,}000/year + \$10300/year = \$91{,}300/year$$

$$TC_{storage} \ = \ AC \ + \ O\&M_c = \$1357687 + \$91300 = \$1{,}448{,}987/year$$

Table 9 presents the calculations for each type of fuel cell storage system for load shifting application

Table 9: Total Annualized Cost of Storage

Fuel Cell Type	Total Capital Cost ($)	Annualized Cost($/yr))	O&M ($/yr)	Total Annualized Cost($/yr)
PEMFC	8,498,215	1,357,687	91,300	1,448,987
PAFC	9,998,215	1,597,329	210,264	1,807,593
MCFC	9,098,215	1,453,544	685,300	2,138,844
SOFC	8,498,215	1,357,687	265,300	1,622,987

We use the same approach for calculating the total annualized cost for each type of fuel cell storage system for load shaving and rapid reserve application cases.

Table 10 and Table 11 present values for the total annualized cost of the storage system for each of above mentioned application with compressed tank and underground storage of hydrogen respectively. These values have been plotted in Figure 10 and Figure 11 respectively. (All values in million$)

Table 10: Total Annualized cost of storage system with compressed tank storage (in millions of $)

Fuel Cell	Load Shifting	Spinning Reserve
PEMFC	1.448	4.289
PAFC	1.807	5.421
MCFC	2.138	6.588
SOFC	1.622	4.869

Table 11: Total Annualized cost of storage system with underground storage (in millions of $)

Fuel Cell	Load Shifting	Rapid Reserve
PEMFC	1.372	4.276
PAFC	1.731	5.408
MCFC	2.062	6.576
SOFC	1.546	4.856

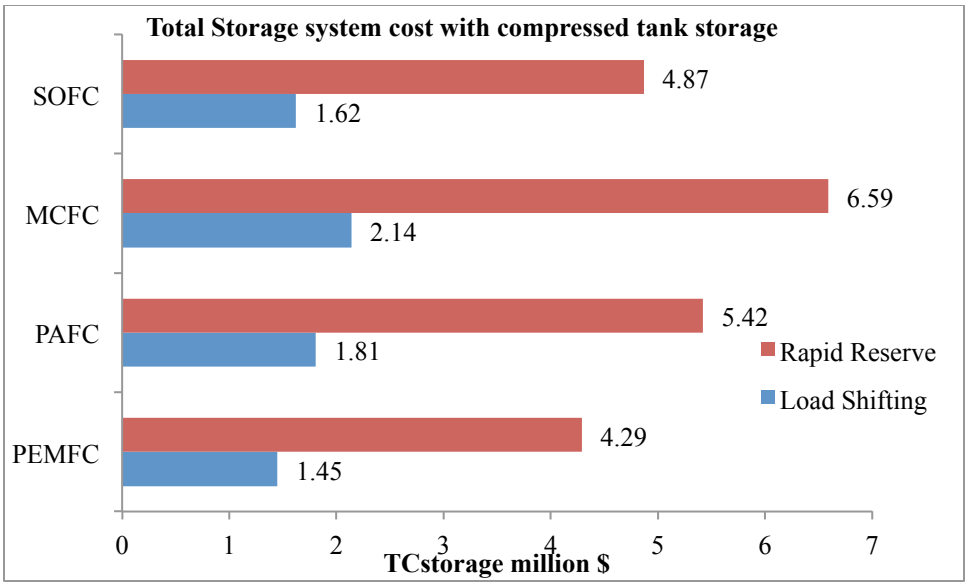

Figure 10: Total Annualized cost of storage system with compressed tank storage

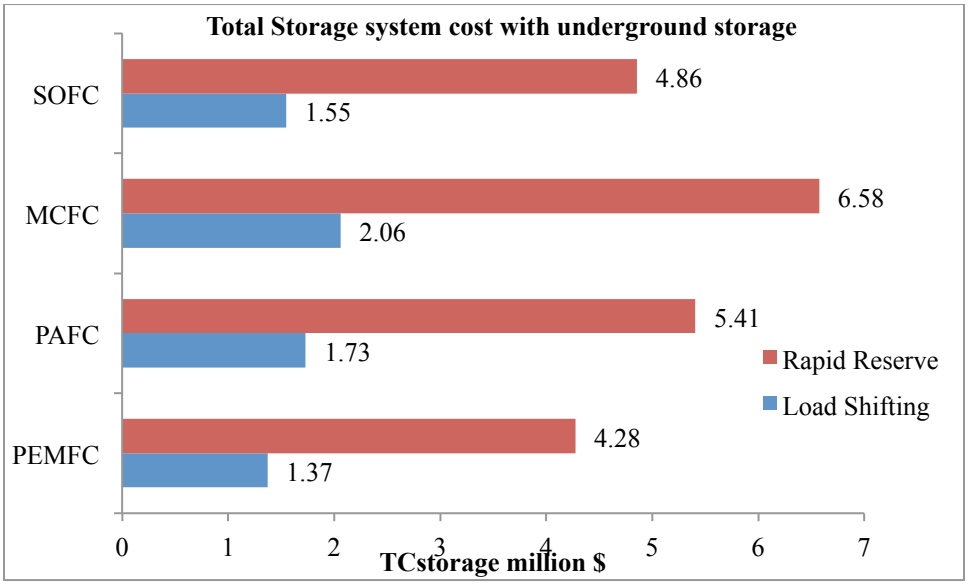

Figure 11: Total Annualized cost of storage system with underground storage

Figure 12 represents the components of the total annualized cost of storage. As mentioned earlier, it is the sum of the annualized capital cost and the annualized operation maintenance costs of the system. For all the systems, the annualized capital cost is the major component of the cost.

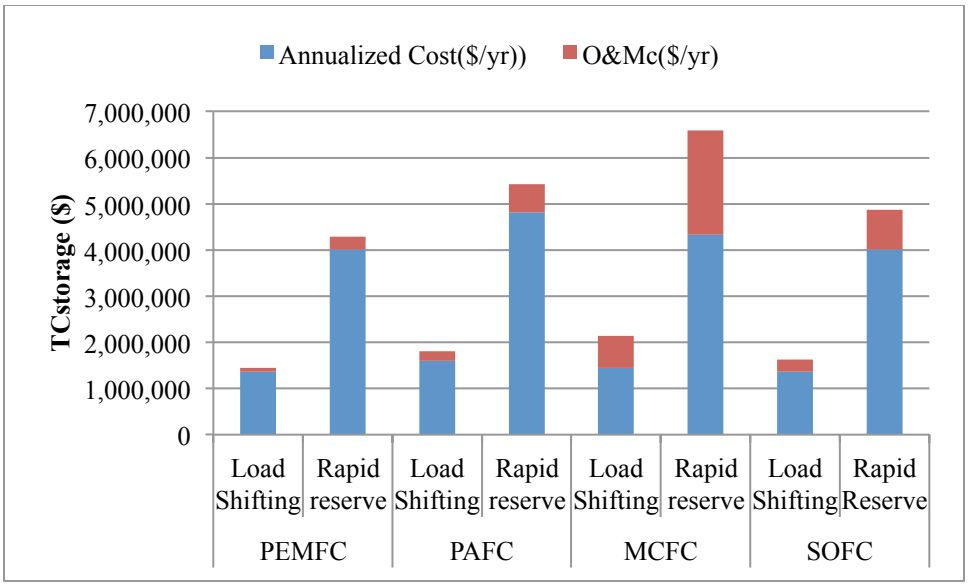

Figure 12: Total annualized cost of storage components

- **Discussion**

From figures 10 and 11, we can see that PEMFCs have the lowest cost for all the studied applications. The lowest cost of PEMFC system may be attributed to the lowest cost of fuel cells and low operation and maintenance costs. PEMFC operate at low temperatures and therefore have the ability to cycle on and off more readily than the other fuel cells that operate at higher temperatures. However the scenarios considered here require much larger fuel cells than the ones currently available. Thus, it is not clear if they can be scaled up.

PAFC systems may not be the least expensive technology for the studied applications but they were amongst the first commercialized fuel cell systems as they were reliable and also very effective in co-generation of low temperature steam. PAFC systems have been installed worldwide with output capacity ranging from 5 – 20MW supplying towns and cities with electricity, heat and hot water [3]. The advantages of PAFC systems are its chemical, thermal and electrochemical stability and the low

volatility of the electrolyte at its operating temperature. Being a low temperature fuel cell system, they have the capability to cycle on and off faster than high temperature fuel cell systems like MCFC and SOFC. These factors assisted in deployment of PAFC systems faster than other fuel cell types.

We can see that MCFCs are the most expensive fuel cell system for the studied applications. This may be attributed to the highest operation and maintenance costs amongst all the fuel cell technologies as seen in Figure 12. The operation and maintenance cost of MCFC is so high because the operating conditions are so extreme that the stack has to be replaced every 5 years. Thus, this reduces its ability to compete with fuel cells with longer stack life. For MCFC systems to be economically acceptable, their stack life has to be improved to 10yrs as this would help in reducing the O&M costs. For SOFC systems, the cost is more than PEMFC, but less than MCFC systems. SOFC systems are known to have high power densities, thus compact designs are possible. The temperature of the exhaust gases are high and can be used in other power generation systems which can provide high overall electrical efficiency. SOFC technology is suited for stationary applications with longer discharge durations than for applications that have short discharge durations, as the operating temperature of the SOFC system is very high it takes time for the system for start up and shut off. Thus, SOFC systems would be better suited for load shifting operations as the discharge duration is longer.

7.4 Levelized cost of electricity (LCOE)

In this section we calculate the levelized cost of electricity. Levelized cost of electricity can be calculated by the following formula.

Equation 9 – Levelized cost of electricity

$$\boldsymbol{LCOE}\ (^{\$}/_{\boldsymbol{kWh}}) = \frac{\boldsymbol{Cost_{H2\ total}}(\$/\boldsymbol{yr})}{\boldsymbol{AEP}\ (\boldsymbol{kWh/yr})}$$

AEP is the annual energy production. Annual energy production (AEP) is the total energy discharged by a storage unit in a year. This is proportional to the energy storage capacity and number of operating days per year of the unit. It is measured in kWh. Therefore, for the load shifting application:

$$AEP\ (kWh) = 3000(kW) * 5(hr) * 365 = 5475000\ (\frac{kWh}{yr})$$

In this sub-section we present a sample calculation for the levelized cost of electricity for the storage system. We repeat equation (9) for each of the fuel cell storage systems for load shifting application case.

	Cost H2 Total	AEP	LCOE
Fuel Cell	($/yr)	(kWh/yr)	($/kWh)
PEMFC	1448990.765	5475000	0.264656
PAFC	1807597.288	5475000	0.330155
MCFC	2138847.647	5475000	0.390657
SOFC	1622990.765	5475000	0.296437

The daily peak price is in the range of 0.15 – 0.17 $/kWh. Thus, the cost of electricity produced by the storage system is almost twice the cost of the current cost.

7.4 Combined application case

In the previous sub section we calculated the total annualized cost of the storage system for individual application cases like load shifting and rapid reserve application. In this sub section, we calculate the total annualized storage system cost for the combined case application.

For this application we consider a storage system that could discharge at different power rating for varied discharge duration depending on the need of the application. It would satisfy high power requirements for the rapid reserve application and could also provide enough energy for longer duration for the load shifting application. We design the system for maximum energy storage capacity requirement of 15MW-hr (for load shifting application) and capable of providing maximum power capacity of 10MW (for rapid reserve application). This storage system could provide 10MW for 30mins for rapid reserve application and could also provide 3MW for 5 hours for load shifting application.

We use the same approach for the calculations for the combined case as we did for load shifting and rapid reserve in the previous section. Figure 13 and Figure 14 present the results for the total annualized cost of storage system and the cost components of the total annualized cost for combined application case respectively. As mentioned earlier, the cost of the fuel cell system is dependent on the power capacity of the system. Thus, the total annualized cost of storage is high due to the high capital investment in a 10MW fuel cell system. The pattern we see here is similar to the load shifting and rapid

reserve application cases where PEMFC have the lowest annualized cost of storage system. As noted above, this application requires much larger fuel cells than the ones currently available and it is not clear if they can be scaled up. Also as expected, the cost of the MCFC system is highest among all systems and this may be attributed to its highest operation and maintenance costs.

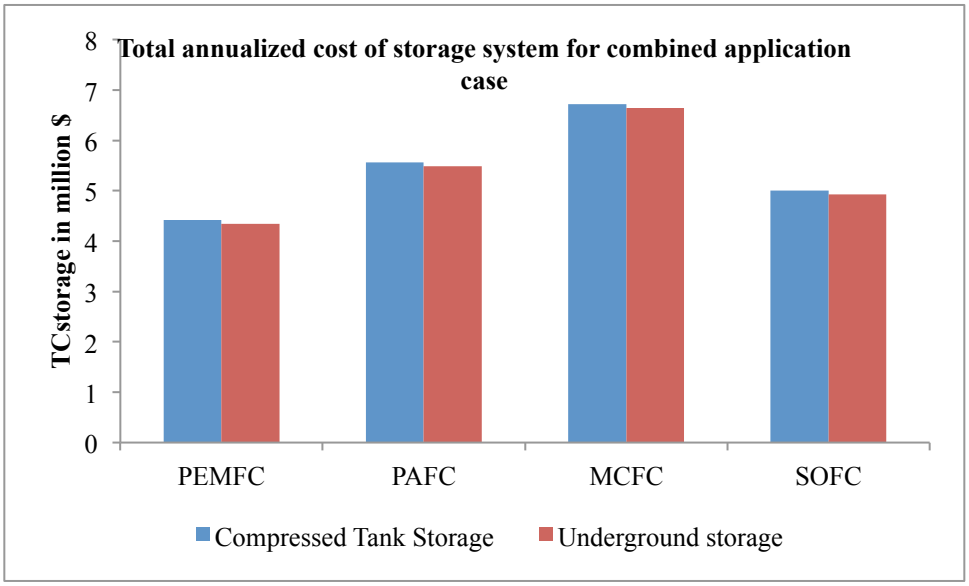

Figure 13: Total Annualized cost of storage system for combined case application

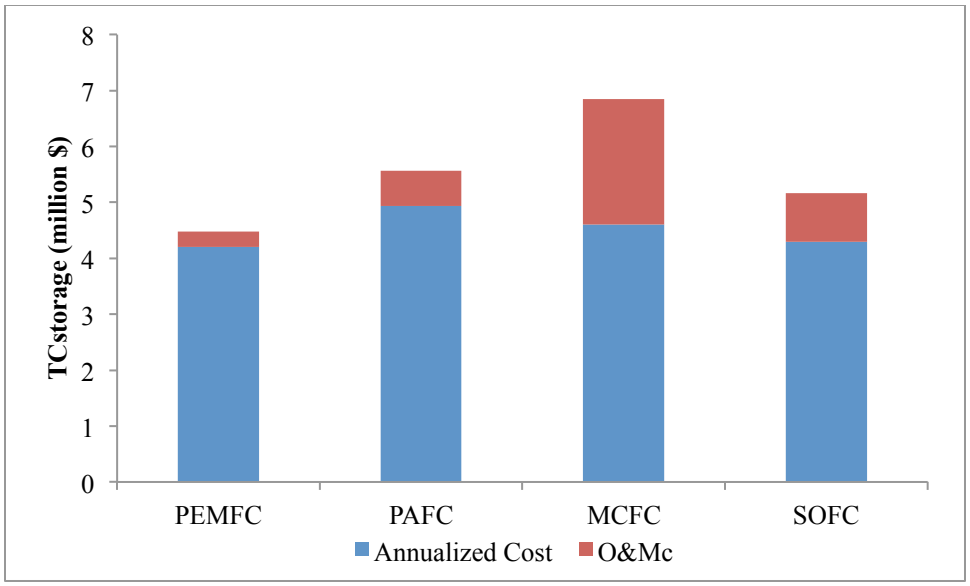

Figure 14: Cost components of Total annualized cost of storage system with compressed tank storage for combined application case

7.5 Sensitivity analysis

In this section, we will study the effect of varying the interest rate and the cost of the fuel cell system on the total annualized cost of the storage system ($TC_{storage}$). We consider the combined case application for the sensitivity analysis because it has the maximum energy storage capacity and power requirement of 15MW-hr and 10MW respectively. We have mentioned the lower, baseline and higher cost estimates of individual fuel cell systems in section 7.2.2 and as mentioned earlier, our baseline interest rate is 15%. In this sub-section we vary these factors within the deviation range presented in Table 12 to see the effect on $TC_{storage}$. We use tornado diagrams to study the sensitivity of each of the characteristics for all the fuel cell systems.

Table 12: Deviation range for fuel cell cost and interest rate for sensitivity analysis

Fuel Cell	Fuel Cell Cost (CostFC in $/kW)	Interest rate (i%)
PEMFC	1000 to 4000	3 to 25

PAFC	2000 to 4250	3 to 25
MCFC	1250 to 4200	3 to 25
SOFC	750 to 5000	3 to 25

In tornado diagram, the vertical axis lists the factors considered for the sensitivity analysis and the values on the horizontal axis represents the total annualized cost of the storage system. The factor at the top of the vertical axis is the most sensitive factor and the sensitivity decreases as we move downwards. The underlined value on the horizontal axis represents the total annualized cost of the storage system for baseline estimates of fuel cell cost (CostFC) and the interest rate (i). Figure 15 is the tornado diagrams, for the four types of fuel cells considered in this study, for the combined application case. The effect of varying the rate of interest (i %) and the cost of the fuel cells (CostFC) can be seen in Figure 15.

The results of varying the interest rate from 3% to 25% is shown in figure 16. The low interest rate represents the interest rate that may be available for renewable energy systems under some government policies for widespread deployment of these renewable energy systems. We observe that even a small change in the interest rate has a significant effect on the total annualized cost of the storage system. This may be attributed to the large initial capital investment for the storage system. In the case of a PEMFC system, if the interest is lowered from 15% to 14% we see that the total annualized cost of the storage system reduces by over $225,000. Similar is the case with PAFC, MCFC and SOFC where the total annualized cost of the storage system reduces by $275,000, $250,000 and $245,000 respectively.

The lowest estimate of fuel cell cost represents the long term target costs of the fuel cell systems. This would be the best case scenario for the widespread deployment of these technologies. This may be attributed to technological developments and multiple large scale installations. The higher estimate represents the high estimates of costs of installations that could be built at the time the referenced study was developed. These values have been obtained from existing studies as mentioned in section 7.2.2. From the sensitivity study we observed that variation in the cost of the fuel cell system has significant effect on the total annualized cost of the storage system. This could be attributed to the fact that the capital cost of the fuel cell system is the major component of the capital cost of the storage system. In case of a PEM fuel cell system, if the target costs of $1000/kW are achieved, we observe that the total annualized of the storage system would reduce from 4.44 million dollars to almost 2.04 million dollars.

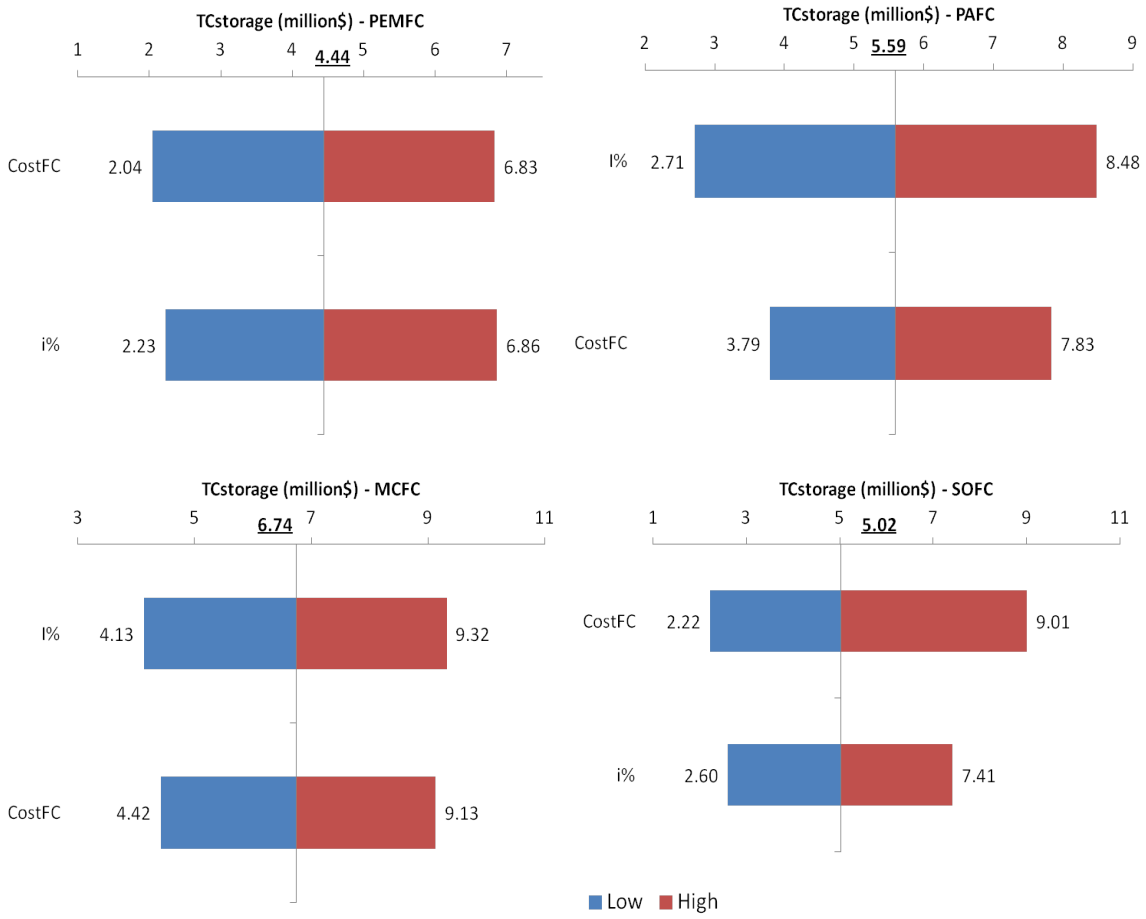

Figure 15: Sensitivity analysis for PEMFC, PAFC, MCFC and SOFC storage system with compressed tank storage.

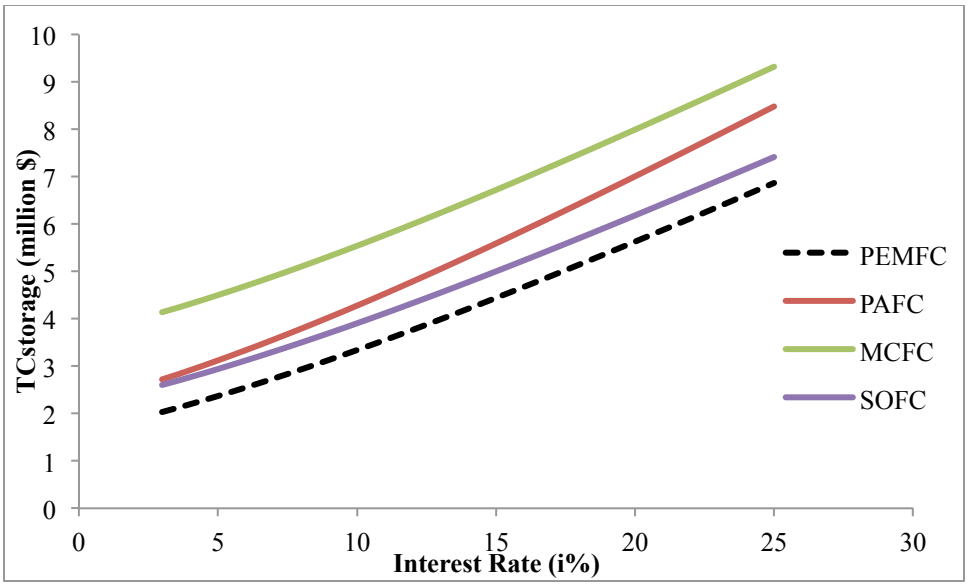

Figure 16: Impact of varying the interest rate from 3% to 25% on total annualized cost of storage system

7.6 Comparison with other existing technologies

In this section we compare hydrogen fuel cell storage system to other storage systems already available. The values for these technologies have been obtained from [14]. The technologies considered in the comparison are listed below:

- Compressed air energy storage (CAES).
- Pumped hydro storage (PHS).
- Flywheel.
- Zinc Bromide battery (Zn-Br)
- Lithium ion battery (Li-ion)
- Lead acid battery (Pb-acid).
- Sodium – sulphur battery (NaS).
- Nickel cadmium battery (Ni-Cd).

Figure 17 shows that a storage system based on hydrogen fuel cell technology is more economical for energy management applications (like load shifting) with longer discharge duration than for power management applications (like rapid reserve) for shorter discharge duration. This may be attributed to the fact that the capital cost of the fuel cell system is dependent on the rated power of the system. As mentioned earlier energy management applications are energy intensive where enough energy has to be supplied for longer discharge duration and the power requirement is much lesser compared to power management applications that require high power to be supplied for shorter discharge duration. Thus, we see such different costs for the two applications.

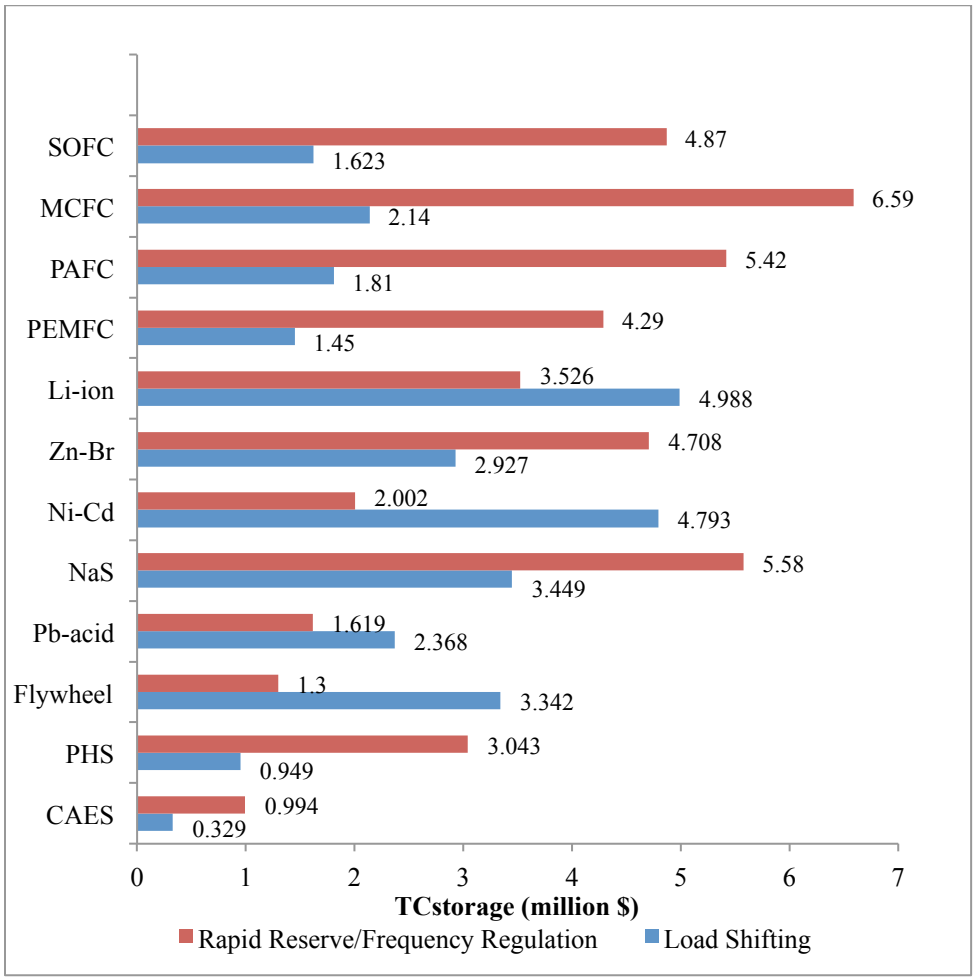

Figure 17: Comparison of total annualized cost of storage system for various technologies

From the figure we can see that for load shifting application, fuel cells are most economical after CAES and PHS. However technologies like CAES and PHS present a lot of limitations like site availability and development that limit their applications and deployment. Due to this reason the modularity of fuel cell storage system present significant advantages over CAES and PHS storage systems. Other than CAES and PHS, storage systems based on hydrogen fuel cell technology are economically better suited for

the load shifting application compared to flywheels and storage system based on batteries.

For power management application of rapid reserve, the fuel cell system is amongst the most expensive system compared to other storage technologies. Flywheels seem to be economically better suited compared to fuel cells. The issue with flywheels is that they very bulky and their size would grow proportionally to the energy requirement. Storage systems based on batteries for example Pb-acid batteries seem to be a cheaper option compared to fuel cells but due to the presence of toxic lead content they are being replaced by other storage technologies. Other batteries like Zn-Br and NaS are as expensive fuel cells but they are known to have better reliability and higher efficiency when compared to fuel cells.

CHAPTER 8

CONCLUSION AND FUTURE WORK

The aim of this research was to study the impact of integrating a hydrogen fuel cell storage system in a wind farm to improve the reliability of the grid and for allowing higher penetration of renewable energy sources in the power system. The installation of an energy storage system strongly depends on the economic viability of the system. Four types of hydrogen fuel cells were considered for this study. It is important to note that the cost estimates used for this study are lower bound as we have not included the balance of plant costs.

Although PEMFC storage systems were found to be the cheapest for the study applications, it is uncertain if they can be scaled up to perform the study applications, as the system requirements are much more than the system size currently available. PAFC systems might not be the least expensive option available, but these are amongst the most developed fuel cell technology with large installation capacities worldwide. PEMFC and PAFC systems are a type of low temperature fuel cell technology that cycle on and off quicker than the other fuel cell systems considered in the study. This makes these systems suitable even for applications with shorter discharge durations. It was found that MCFC systems were the most expensive systems for the studied applications. They have the highest operation and maintenance costs due to the high operating temperature of the system. This high temperatures place a great demand on corrosion stability of the components and it adversely affects the life span of the cell components. SOFC systems are the latest entry to the hydrogen fuel cell technology. SOFC storage systems are more

expensive than PEMFC systems but less expensive than MCFC systems. They are high temperature systems with high power densities that enable compact designing. SOFC and MCFC systems are high temperature systems that are more suitable for applications with longer discharge durations as they take longer to cycle on and cycle off. The current costs of these systems are very high and thus they are not a viable substitute for the load shifting application as we have seen in section 7.

In the sensitivity analysis it was found that even a small change in the interest rate has a significant effect on the total annualized cost of the storage system. Thus, favorable government policies with low interest rates may be helpful in the widespread deployment of renewable energy sources. Technological development and large scale installations will help in the reduction of fuel cell system costs making them more competitive in the energy storage market.

The results of this study enable cost comparison of storage systems based on hydrogen fuel cells and 8 other technologies. For energy management applications like load shifting, fuel cells are most economical storage system after CAES and PHS. On the other hand, for power management applications like spinning reserve, the total annualized cost of the hydrogen fuel cell storage system is more than the other technologies considered in the study. Hydrogen fuel cell storage systems have good potential for energy storage applications but they face uncertainty due to high system costs and low efficiency. This may be solved with the help technological developments and favorable government policies.

In future, we propose to explore the idea of integration of hydrogen fuel cells with other renewable energy sources like solar photovoltaic and biomass. R&D should be conducted to reduce the cost and to improve the efficiency of fuel cells systems as this would directly affect the total annualized cost of the storage system. Better operational practices to reduce the operation and maintenance costs of the fuel cell systems should be developed. In this thesis we studied the effects of varying interest rate and cost of fuel cell on the total annualized cost of the storage system. Studying the effect of varying efficiencies, storage costs of hydrogen and lifespan of the system would also be interesting.

BIBLIOGRAPHY

1. International Energy Agency, IEA Key statistics. http://www.iea.org/publications/freepublications/publication/name,26707,en.html accessed on October 2011
2. U.S. Department of Energy Hydrogen Program. Hydrogen Fuel Cells. http://www.hydrogen.energy.gov/ accessed on August 2011
3. Carrette, L.; Friedrich, K. A.; Stimming, U. Fuel Cells-fundamental and application. Fuel Cells, 2001, WILEY-VCH Verlag GmbH
4. Karl Kordesch, Viktor Hacker, Josef Gsellmann, Martin Cifrain, Gottfried Faleschini, Peter Enzinger, Robert Fankhauser, Markus Ortner, Michael Muhr, Robert R. Aronson, Alkaline fuel cells applications, Journal of Power Sources, Volume 86, Issues 1-2, March 2000.
5. Y. Kiros, Electrocatalytic properties of Co, Pt and Pt-Co on carbon for the reduction of oxygen in alkaline fuel cells, Journal of Electrochemical Society, Volume 143, July 1996.
6. Y. Kiros, S. Schwartz, Long-term hydrogen oxidation catalysts in alkaline fuel cells, Journal of Power Sources, Volume 87, Issues 1–2, April 2000.
7. W Smith, The role of fuel cells in energy storage, Journal of Power Sources, Volume 86, Issues 1–2, March 2000.
8. Lipman T.E, Edwards J.L, Kammen D.M, Fuel cell system economics: comparing the costs of generating power with stationary and motor vehicle PEM fuel cell systems, Energy Policy, Volume 32, Issue 1, January 2004.

9. Barbir F, PEM electrolysis for production of hydrogen from renewable energy sources, Solar Energy, Volume 78, Issue 5, May 2005.

10. Larminie, James; Dicks, Andrew (2003). Fuel Cell Systems Explained (2nd Edition). John Wiley & Sons.

11. UTC Power personal conversation, Michael Glynn, April 28th 2012.

12. Moldrik, P.; Sebesta, R.;, "Hydrogen fuel cells as a part of the system for accumulation of electric energy," *Electrical Power Quality and Utilisation,* September 2009

13. A Kazim, Economical and environmental assessments of proton exchange membrane fuel cells in public buildings, Energy Conversion and Management, Volume 42, Issue 6, April 2001.

14. Sandhya Sundararagavan, Erin Baker, Evaluating energy storage technologies for wind power integration, Solar Energy, Available online 13 July 2012

15. Schoenung, S. M. (March 2001). Characteristics and Technologies for Long vs-Short Term Energy Storage: A Study by the DOE Energy Storage Systems Program No. SAND2001-0765. Albuquerque, New Mexico 87185 and Livermore, California 94550: Sandia National Laboratories.

16. H. Ibrahim, A. Ilinca, J. Perron, Energy storage systems—Characteristics and comparisons, Renewable and Sustainable Energy Reviews, Volume 12, Issue 5, June 2008.

17. R.M Dell, D.A.J Rand, Energy storage — a key technology for global energy sustainability, Journal of Power Sources, Volume 100, Issues 1–2, 30 November 2001.

18. Poonpun, P.; Jewell, W.T.; , "Analysis of the Cost per Kilowatt Hour to Store Electricity," *Energy Conversion, IEEE Transactions on* , vol.23, no.2, June 2008.

19. EPRI (2003a). EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, Palo Alto, CA, and the U.S. Department of Energy, Washington, DC: 2003. 1001834.

20. EPRI (2003b). Comparison of Storage Technologies for Distributed Resource Applications. EPRI, Palo Alto, CA: 2003. 1007301.

21. Padró C.E.G., Putsche V. "Survey of the Economics of HydrogenTechnologies". NREL/TP-570-27079. Technical Report. National Renewable EnergyLaboratory. Golden, Colorado, September, 1999.

22. International Energy Agency (2005). "Prospects for Hydrogen and Fuel Cells", Prospects for Hydrogen and Fuel Cells [data file]. International Organizations, LexisNexis (10/18/2010).

23. Krewitt Wolfram, Schmid Stephan, Fuel Cell Technologies and Hydrogen Production/Distribution Options, September 2005, Cascade Mints. http://www.dlr.de/fk/Portaldata/40/Resources/dokumente/publikationen/2005-09-02_CASCADE_D1.1_fin.pdf

24. ESECS 2003: Fuel Cell Report to Congress (ESECS EE-1973). http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb2003.pdf

25. U.S Department of Energy, Fuel Cell Handbook, Seventh edition, 2004. http://www.osti.gov/bridge/servlets/purl/834188/834188.pdf

26. S. D. Knights, K. M. Colbow, J. St-Pierre, D. P. Wilkinson, "Aging Mechanisms and Lifetime, PEFC and DMFC", Journal of Power Sources (2004).

27. Jinfeng Wu, Xiao Zi Yuan, Jonathan J. Martin, Haijiang Wang, Jiujun Zhang, Jun Shen, Shaohong Wu, Walter Merida, A review of PEM fuel cell durability: Degradation mechanisms and mitigation strategies, Journal of Power Sources, Volume 184, Issue 1,September 2008.

28. Blomen, Leo, and Michael Mugerwa. *Fuel Cell Systems*. New York: Plenum Press, 1993.

29. Casey, E. (2009). "Salt Dome Hydrogen Storage." Fuel Pathways Integration Technical Team (FPITT) Meeting, Washington, DC, March 7, 2009.

30. Amos, W. "Costs of Storing and Transporting Hydrogen," National Renewable Energy Laboratory,NREL/TP-570-25106, May 1998.

31. J. Makansi, J. Abboud. Energy Storage, The Missing Link in the Electricity Value Chain," An ESC White Paper by the Energy Storage Council, May 2002.

http://www.smartgridnews.com/artman/uploads/1/sgnr_2008_0103.pdf

32. Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. EPRI, Palo Alto, CA, 2010. 1020676.

33. Larminie, James; Dicks, Andrew (2003). Fuel Cell Systems Explained (2nd Edition). John Wiley & Sons.

34. Levene J, Kroposki B, Sverdrup G. Wind energy and production of hydrogen and electricity—opportunities for renewable hydrogen. NREL/CP-560-39534, National Renewable Energy Laboratory, 2006

35. Saur G. "The Wind to Hydrogen Project: Electrolyzer Capital Cost Study", Report NREL/TP-550–44103; 2008.

36. Saur, G. and T. Ramsden. "*Wind Electrolysis: Hydrogen Cost Optimization"*. NREL/TP- 5600-50408. Golden, CO:NREL, 2011.

37. E.I. Zoulias, N. Lymberopoulos, Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems, Renewable Energy, Volume 32, Issue 4, April 2007.

38. Aguado M, Ayerbe E, Azcárate C, Blanco R, Garde R, Mallor F, Rivas D.M, Economical assessment of a wind–hydrogen energy system using WindHyGen® software, International Journal of Hydrogen Energy, Volume 34, Issue 7, April 2009.

39. Mantz R.J, Battista H, Hydrogen production from idle generation capacity of wind turbines, International Journal of Hydrogen Energy, Volume 33, Issue 16, August 2008.

40. Gökçek M, Hydrogen generation from small-scale wind-powered electrolysis system in different power matching modes, International Journal of Hydrogen Energy, Volume 35, Issue 19, October 2010.

41. Sánchez C, Abad B, Hübner S, Alfonso D, Segura I, Wind park reliable energy production based on a hydrogen compensation system. Part I: Technical viability, International Journal of Hydrogen Energy, Volume 36, Issue 24, December 2011.

42. Sánchez C, Abad B, Hübner S, Alfonso D, Segura I, Wind park reliable energy production based on a hydrogen compensation system. Part II: Economic study, International Journal of Hydrogen Energy, Volume 37, Issue 4, February 2012.

43. Lee J, Yoo M, Cha K, Lim T, Hur T, Life cycle cost analysis to examine the economical feasibility of hydrogen as an alternative fuel, International Journal of Hydrogen Energy, Volume 34, Issue 10, May 2009.

44. Lee J, An S, Cha K, Hur T, Life cycle environmental and economic analyses of a hydrogen station with wind energy, International Journal of Hydrogen Energy, Volume 35, Issue 6, March 2010.

45. Abbasi T, Abbasi S.A, 'Renewable' hydrogen: Prospects and challenges, Renewable and Sustainable Energy Reviews, Volume 15, Issue 6, August 2011.

46. Parissis O.S, Zoulias E, Stamatakis E, Sioulas K, Alves L, Martins R, Tsikalakis A, Hatziargyriou N, Caralis G, Zervos A, Integration of wind and hydrogen technologies in the power system of Corvo island, Azores: A cost-benefit

analysis, International Journal of Hydrogen Energy, Volume 36, Issue 13, July 2011.

47. El-Sharkh M.Y, Tanrioven M, Rahman A, Alam M.S, Economics of hydrogen production and utilization strategies for the optimal operation of a grid-parallel PEM fuel cell power plant, International Journal of Hydrogen Energy, Volume 35, Issue 16, August 2010.

48. Beaudin M, Zareipour H, Schellenberglabe A, Rosehart W, Energy storage for mitigating the variability of renewable electricity sources: An updated review, Energy for Sustainable Development, Volume 14, Issue 4, December 2010.

49. González F, Sumper A, Bellmunt O, Robles R, A review of energy storage technologies for wind power applications, Renewable and Sustainable Energy Reviews, Volume 16, Issue 4, May 2012.

50. Evans A, Strezov V, Evans T.J, Assessment of utility energy storage options for increased renewable energy penetration, Renewable and Sustainable Energy Reviews, Volume 16, Issue 6, August 2012.

51. Fuel Cell Today: The Industry Review 2002, May 2012 http://www.fuelcelltoday.com

52. The Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan, Chapter 3.4, Table 3.4.5 http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

53. Oak Ridge National Laboratory (2008). *Bootstrapping a Sustainable North American PEM Fuel Cell Industry: Could a Federal Acquisition Program Make a Difference?* ORNL/TM-2008/183. Oak Ridge, TN: Oak Ridge National Laboratory.

54. Fuel Cells: Identifying Promising Development Opportunities*,* EPRIsolutions, Palo Alto, CA: 2000. 1001243.

55. Remick R, Wheeler D, "Molten Carbonate and Phosphoric Acid Stationary Fuel Cells: Overview and Gap Analysis," Technical Report NREL/TP-560-49072, September 2010. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/49072.pdf

56. Giddey S., Badwal S.P.S., Kulkarni A., Munnings C., A comprehensive review of direct carbon fuel cell technology, Progress in Energy and Combustion Science, Volume 38, Issue 3, June 2012.

57. Staffell I., Green R., Kendall K., Cost targets for domestic fuel cell CHP, Journal of Power Sources, Volume 181, Issue 2, 1 July 2008.

58. Williams M.C, Maru H.C, Distributed generation—Molten carbonate fuel cells, Journal of Power Sources, Volume 160, Issue 2, 6 October 2006.

59. Hengeveld D.W, Revankar S.T, Economic analysis of a combined heat and power molten carbonate fuel cell system, Journal of Power Sources, Volume 165, Issue 1, 25 February 2007.

60. Dicks A, Siddle A, Assessment of commercial prospects of molten carbonate fuel cells, Journal of Power Sources, Volume 86, Issues 1–2, March 2000.

61. Bessette N, "Development of a Low-Cost 3-10 kW Tubular SOFC Power System," in: FY 2011 Progress Report for the DOE Hydrogen Program, U.S. Department of Energy, Washington, DC, 2011, http://www1.eere.energy.gov/hydrogenandfuelcells/annual_reports.html

62. Crotogino, F.; Huebner, S. (2008). "Energy Storage in Salt Caverns: Developments and Concrete Projects for Adiabatic Compressed Air and for Hydrogen Storage." Solution Mining Research Institute Spring 2008 Technical Conference, Porto, Portugal, April 28–29, 2008.

63. Ramsden, T.; Kroposki, B.; Levene, J. (2008). *Opportunities for Hydrogen-Based Energy Storage for Electric Utilities*. Golden, CO: National Renewable Energy Laboratory.

64. DOE (2012). Hydrogen Production Case Studies. Current Central Hydrogen Production from Grid Electrolysis version 3.0 and Future Central Hydrogen Production from Grid Electrolysis version 3.0.

http://www.hydrogen.energy.gov/h2a_prod_studies.html accessed on April 2012

65. DOE (2012). Hydrogen Production Case Studies. Current Forecourt Hydrogen Production from Grid Electrolysis version 3.0 and Future Forecourt Hydrogen Production from Grid Electrolysis version 3.0.

http://www.hydrogen.energy.gov/h2a_prod_studies.html accessed on April 2012

66. C. Koroneos, E. Katopodi, Maximization of wind energy penetration with the use of H2 production—An exergy approach, Renewable and Sustainable Energy Reviews, Volume 15, Issue 1, January 2011, Pages 648-656, ISSN 1364-0321, 10.1016/j.rser.2010.06.022.