International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 06 Issue: 05 | May 2019 www.irjet.net p-ISSN: 2395-0072

Analysis and study of Hydrogen Fuel Cell Systems Used as an Electricity Storage Technology

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Abstract - *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.*

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. 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.

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 4 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.

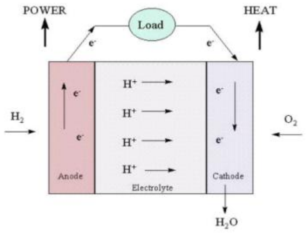

Fig 1 : Working of a fuel cell

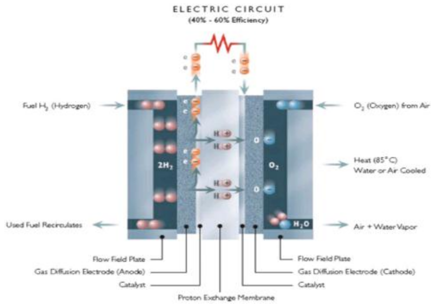

Figure 2: Polymer Electrolyte Membrane Fuel Cell*

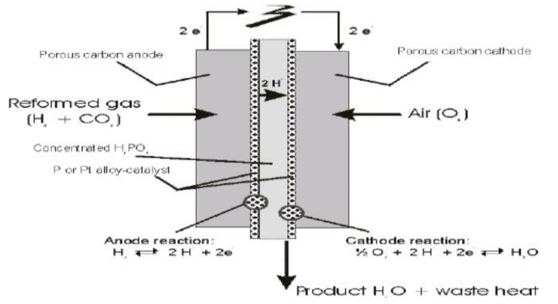

Figure 3: Phosphoric Acid Fuel Cell (http://corrosion-doctors.org/FuelCell/pafc.htm)

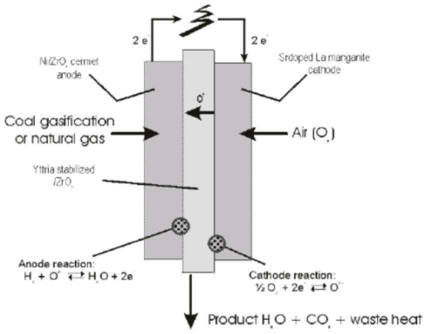

Figure 5: Solid Oxide Fuel Cell (http://corrosion-doctors.org/FuelCell/sofc.htm)

FUEL CELL AS AN ELECTRICITY STORAGE DEVICE

Introduction

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

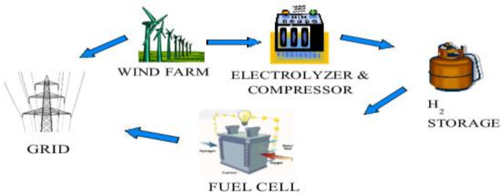

Figure 6: Hydrogen fuel cell storage system concept

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.

PRODUCTION AND STORAGE OF HYDROGEN IN A WIND FARM

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:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

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.

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 Wst which is always more than the actual amount of energy retrieved Wut. 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.

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.

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:

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

τ – Discharge Time (hour)

W_{st} – Total energy stored (W-h)

P_{max} - Maximum power or charge (W)

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 $_{st}$. Therefore, the efficiency of the storage can be stated as:

$$\eta = W_{ut} \,/\, W_{st}$$

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.

ECONOMICS

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 1/10th 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.

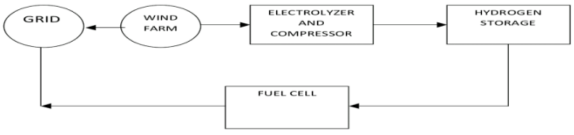

Figure 7: Hydrogen fuel cell storage system and its components

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

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

$$\text{Cost}_{\text{H2 total}} = \text{Cost}_{\text{FC}} + \text{Cost}_{\text{storage}} + \text{Cost}_{\text{electrolyzer}}$$

Where,

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

Cost_{FC} = Cost of fuel cells.

$\text{Cost}_{\text{storage}}$ = Cost of hydrogen storage

$\text{Cost}_{\text{electrolyzer}}$ = 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,

$$\text{Cost}_{\text{FC}} = \text{Unit cost}_{\text{gen}}\ (¥ / \text{kw}) * P_{\text{discharge}}\ (\text{kw}).$$

Where,

$\text{Unit cost}_{\text{gen}}$= Cost of Hydrogen Fuel Cell

$P_{\text{discharge}}$ = Rated power of fuel cell system

Cost of storage:

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

$$\text{Cost}_{\text{storage}} = \text{Unit cost}_{\text{storage}}\ (¥/\text{kwh}) * E(\text{kwh})/\eta_{\text{h2 discharge}}$$

Where,

$\text{Unit cost}_{\text{storage}}$ =Cost of hydrogen storage

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

$\eta_{\text{h2 discharge}}$ = 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 td each day at a power level Pdischarge. Thus, the electrolyzer would have to recharge over the remaining time

$$t_{ch} = 24\ \text{hr} - t_d\ (\text{hr}) \text{ and be rated at}$$

Power rating of electrolyzer

$$P_{\text{charge}} = \frac{\text{Pdischarge} * \text{td}}{\text{tch} * \eta\text{h2 elec}}$$

Wherer,

P_{charge} = Rated power of electrolyzer.

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

t_d = Time to discharge.

t_{ch} = time to charge

$\eta_{\text{h2 elec}}$ = electrolyzer efficiency.

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

Cost of Electrolyzer

$$Cost_{electrolyzer} = UnitCost_{electrolyzer} * P_{charge}$$

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 1/10th 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.

Application	Power capacity (kw)	Discharge duration (hr)	Energy storage capacity (kw-hr)
Load Shifting	3000	5	15000
Rapid reserve	10000	.25	2500
Combined Application	10000	1.5	15000

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 (CostH2total). 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.

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.

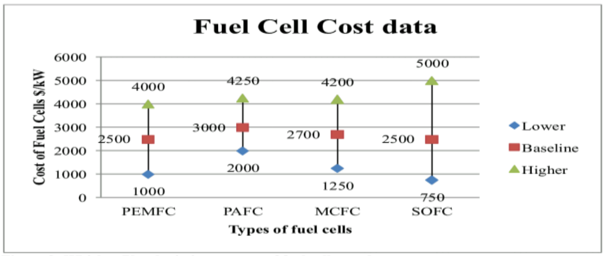

Figure 8: Whisker Plot depicting a range of fuel cell cost data

• 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 hydrogenis 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/m3 compared to 2.4kWh/m3 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.

Hydrogen Storage Cost Data

Cost-storage ($/kWh)	
Above ground	Underground
19	02

• 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 distributedproduction 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.

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--- t_{ch} (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.

$$\mathrm{COST}_{FC} = 2500 \times 3000 = \$7,500,000$$
$$\mathrm{COST}_{STORAGE} = 19 \times (15000/0.59) = \$483050.84$$
$$\mathrm{COST}_{ELECTROLYZER} = 385 \times 1338.5 = \$515165$$
$$\mathrm{COST}_{H2TOTAL} = \mathrm{COST}_{FC} + \mathrm{COST}_{STORAGE} + \mathrm{COST}_{ELECTROLYZER}$$
$$\mathrm{COST}_{H2TOTAL} = 7500000 + 483050.84 + 515165 = \$8,498,215.84=8498215$$

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

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	8,498,215
MCFC	2700	8,100,000	483,050	515,165	8,498,215
SOFC	2500	7,500,000	483,050	515,165	8,498,215

Total Capital Cost for assumed applications

	Total capital cost ($)	
Fuel cell type	Load shifting	Rapid reserve
PEMFC	8,498,215	25,149,197
PAFC	8,498,215	25,149,197
MCFC	8,498,215	25,149,197
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.

7.3 Total annualized cost of the storage system

The total annualized cost of the storage (TCstorage) is the sum of the annualized capital cost (AC) and the annualized operation and maintenance cost (O&Mc). It is measured in $.

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).

Annualized cost

$$AC = COST_{H2\ TOTAL} \times CRF$$

Capital Recovery Factor (CRF)

$$CRF = \frac{ir\ (1+ir)^{ny}}{(1+ir)^{ny} - 1}$$

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.

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.

$$\text{CRF} = \frac{ir\,(1+ir)^{ny}}{(1+ir)^{ny} - 1}$$

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

Therefore,

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

$$\text{O \& M}_{\text{CELL}} = 27 \times 3000 = \$81000/\text{Year}$$

$$\text{O\&M}_{\text{ELECTROLYZER}} = 0.02 \times 515165 = \$10{,}300/year$$

$$\text{O\&M}_{\text{C}} = 81000 + 10300 = \$91{,}300/year$$

$$\text{TC}_{\text{STORAGE}} = \text{AC} + \text{O\&M}_{\text{C}} = 1357687 + 91300 = \$1448987/\text{Year}$$

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

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.

Following tables 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$)

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

Fuel cell type	Load shifting	spinning reserve
PEMFC	1.448	4.289
PAFC	1.807	5.421
MCFC	2.138	6.588
SOFC	1.622	4.869

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

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

Levelized cost of electricity

$$\boldsymbol{L_C}\ \textbf{(\$/kwh)} = \textbf{COST}_{\textbf{H2 TOTAL}}\ /\ \textbf{AEP}$$

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:

$$\text{AEP (kw h)} = 3000\ \text{(kw)} \times 5000\ \text{(hr)} \times 365 = 5475000\ \text{(kw h / year)}$$

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

	$\text{COST}_{\text{H2 TOTAL}}$	AEP	L_{COE}
Fuel Cell	($/yr)	(kWh/yr)	($/kWh)
PEMFC	1448990.765	5475000	0.264656

PAFC	1807597.288	5475000	0.330155
MCFC	2138847.647	5475000	0.39065
SOFC	1622990.765	5475000	0.29643

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.

3. CONCLUSION

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 .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.

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