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Fuel Cell Application To Mitigate Load Ramping Impacts Of Rooftop PV System Installation.

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Abstract

This paper is based on a hybrid PV and fuel cell system designed to meet energy requirements of 100000 customers of Southern California in a sustainable way. Solar roof-top PV system is turning out to be a boon to the mankind with its positive effects of reducing Green House Gas (GHG) emission, lowering stress on conventional coal-fired or natural gas generators and even reducing costs associated with electricity pricing for consumers. However, with increased penetration from the grid tied PV systems, there is an inevitable rise in stress faced by conventional generators in terms of meeting and balancing the energy requirements during early morning and late afternoon hours which requires precise switching and control mechanisms. This paper addresses the ramping issues and offers an integrated solution in the form of fuel cells that can complement the existing PV system during intermittent times of energy production and even by reducing the ramp up and ramp down slopes of power production by conventional generators, in a promising way.

Keywords: Solar Photovoltaic;Fuel Cell Technology;System Sizing; Project Planning and Costing;Procurement and Financing; Open DSS Simulations;Battery Storage Systems;PAFC plant;SOFC/GT systems

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1. Introduction

Our major goal here is to design and develop a sustainable distributed energy generation system that can meet the energy requirements of 100000 customers based in the Southern California region. California has been heavily blessed with ample amount of solar irradiation all throughout the year, high enough to ensure a stable photovoltaic generation. Even though solar irradiation levels are quite high as 5 to 7.5 kWhrs/m^2-day, there is an inherent problem of intermittency associated with solar PV generation with causes attributable to cloudy days that can affect the energy generation and efficiency of the installed solar PV arrays.

Fuel cells have a promising future in terms of confronting the challenge of reversing the adverse effects of fossil-fuel fired power plants on climate change. Fuel cells rely on the supply of hydrogen for power generation. There are majorly two sources of hydrogen namely natural gas and biogas, and the source imparts and characterizes the renewable nature of the entire system. With the usage of biogas, we can ensure minimum (almost zero) amount of GHG emission from the fuel cells and can maintain the integrity of the renewable system.

The presence of solar PV systems in the electrical distribution system makes it difficult for the power system operators to control and optimize power production from conventional generators as these systems do not provide real-time generation information to the system operators as in the case of transmission-level solar power plants. To add to this, the variable nature of PV production combined with a dynamic nature of the load curve results in the famous "Duck" curve altogether giving rise to increased ramping needs during sunrise and sunset events. All these can result in increased damage to boiler in coal plants [1-2].

The structure and content of the paper is divided into various sections. Section II details down the specification and basic design of the PV system. Section III focuses on fuel cell technology and a comprehensive study on its sizing, arrangement of biogas as a source, costing etc. Section IV provides simulation results of the entire hybrid system scaled down to the IEEE 34 bus distribution system using Open DSS. Section V highlights some of the shortcomings of the fuel cell system and states alternate ways to complement the system. The entire discussion ends in Section VI with the conclusion and important remarks and observations.

2. Project Details

For our project, we are required to supply power for 100,000 customers in Greater Los Angeles area, which has an optimal irradiance all-round the year. Our main reason behind proposing a solar rooftop project instead of executing the same in an isolated location is that the loads connected to the system are nearby and further there is no additional cost of installation of transmission lines. This criterion of site selection is not only beneficial financially but shall also almost nullify the transmission line losses involved.

Table 1. System Size Calculation

Load	**Value**
Average kW demand per custom er (per hr.)	0.73 kWh
Average kW for 100,000 customer (per hr.)	73000 kWh
Energy required in a day	1752000 kWh
Generation	**Value**
Solar panel rating (Watts)	320 W
PV system size per house (kW)	4.8 kW
Generation in a day	21 kWh
Houses on which PV to be installed	84515 Nos.
Total PV System size	405673 kW
Connected load (houses)	100000 Nos.
Connected load (kW)	73000 kW

The solar panel rating of 320 W is under STC as given by standard manufacturers. As seen in the above table, we have considered 21 kWh generation per day. We are quite aware that generation is a variable parameter that depends on solar irradiance which is not constant throughout the year. The value 21 kWh has been arrived by considering generation curves in households having solar panels as mentioned in [3] that comes to about 4.3 hours of peak solar power production per day, which is quite reasonable taking into account the weather conditions all throughout the year. In line with the above table, we need to install rooftop solar of 405.6 MW over 84,515 houses.

2.1 Construction Process

The construction process of any project takes the most time. We propose to carry out two projects simultaneously, solar rooftop being in priority. The construction process of solar rooftop can be broadly classified into assembly and installation of structures, installation of modules, installation of panels and inverters, cabling works and testing & Commissioning to be done by the service engineer and checked and authorized by the local approving agency officer before final integration to the grid.

The construction process of fuel cells will mainly comprise of site investigation, foundation works: RCC (Reinforced Concrete Cement) work after marking and excavation works, building works (MEP): Installation of bracings and pre-fabricated structures after RCC works and beam work, installation of Fuel Cells: Use tele-handlers to move the equipment and cranes for proper accurate installation and cabling works: Laying out cables, then dressing and termination works.

2.2 Project Planning and Management

Project management constitutes of preparing the Work Breakdown Structure (WBS), which is a list of activities to be carried out in a sequential order. The major activities to be carried out in the planning and management processes are Resource Allocation, Schedule Summarization, Risk Assessment, Performance Measurement, Responsibility Assignment, Estimating Direct and Indirect Cost, Preparing Staff details and manpower list, invoicing details, material list and delivery schedule and liquidation plan that is Cash Flow.

2.3 Construction Schedule

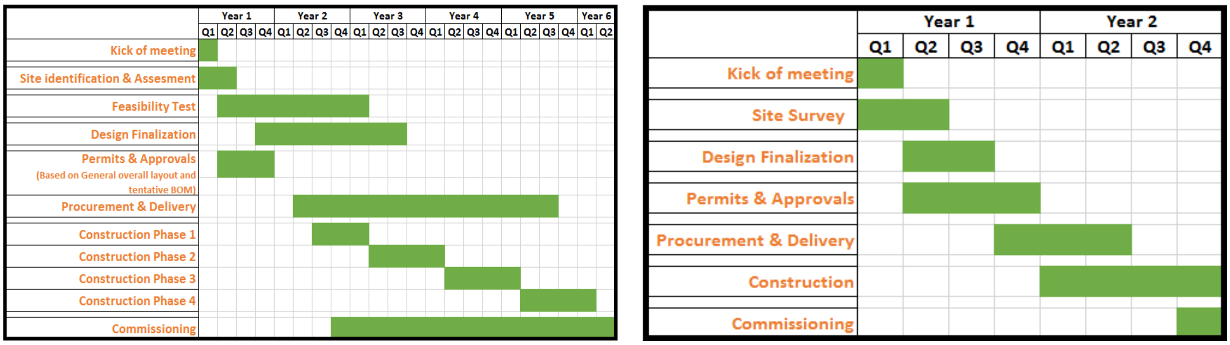

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Fig. 1. (a) Construction Schedule – Rooftop Solar, (b) Construction Schedule – Fuel Cells Plant

Figures 1 (a) and (b) shown above highlight the construction schedule for the rooftop solar and the fuel cell plant respectively specifying important milestones. Other important aspect includes procurement and sub-contracting.

3. Fuel Cell Technology

Fuel cell technology is much cleaner than conventional power generation methods. Water is an important requirement in the process of power generation in conventional power plants. A coal power plant requires 35,000 gallons to generate 1 MWh of electricity whereas; Bloom Energy's bloom box requires no water.

The average CO_2 emission from Bloom Energy's fuel cells is comparatively much less than that from conventional generators. Also, the power factor ranges in which these cells operate expand from 0.7 lagging to 0.7 leading. This makes fuel cells more suitable for reactive compensation purposes during peak load demand [4-6].

3.1 Theory

Fuel cell technology is at par with renewable technology and has the advantage of both renewable and conventional sources. The difference in fuel source causes it to swing between conventional air polluting power plants and renewable power harnessing plants like solar and wind. With biogas, fuel cells give out 0g of CO_2. On the other hand with natural gas as fuel, few grams of carbon dioxide are given out during the combustion process, however, it is still negligible as compared to emissions from conventional sources. Another important factor in favor of fuel cell technology is that they do not require any water, instead, they produce water as a by-product of the chemical reaction.

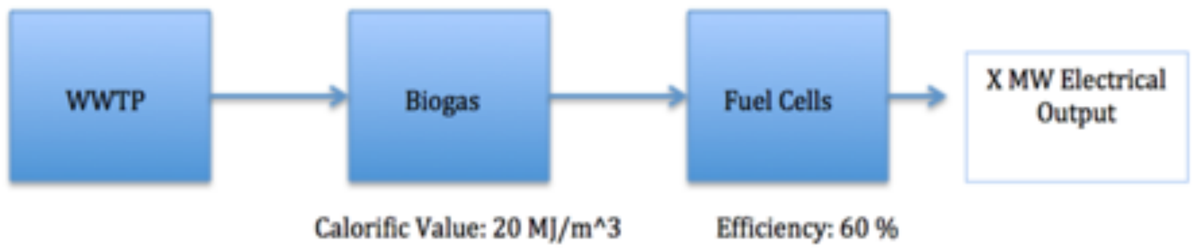

Fig. 2. Fuel Cell System Flowchart

3.2 Working

There are different types of fuel cells, but in general terms, hydrogen atoms enter the cell from anode where it is stripped off of its electrons and is converted into its ionic form. The electrons travel through the electrolyte to complete the circuit resulting in an electric current (DC). If AC output is needed, the DC power should be routed through an inverter. Oxygen atoms enter the fuel cells at the cathode where it combines with the returning electrons and hydrogen ions resulting in the formation of water. The electrolyte plays an important role here, as it must permit only appropriate ions to pass between the electrodes. Solid Oxide Fuel cells (SOFC) use ceramic compound metal oxides like calcium or zirconium oxide as an electrolyte. They have an efficiency of about 60 percent and operating temperatures of up to 1000 degree Celsius. They are resistant to leak, however, can develop cracks. Fuel cells require continuous supply of hydrogen and oxygen to produce power.

3.3 Sizing

California ranks #1 among the U.S. states for its methane production potential from biogas sources. Currently, the state has 276 operational biogas systems and there is enormous potential for more than 1187 new projects to be developed based on the estimated amount of available organic material. Some of the important sources of biogas are food waste, agricultural farms, wastewater treatment plants (WWTPs) and landfill gas systems. There are numerous biogas companies located in California (http://americanbiogascouncil.org/membership_list.asp). Anaerobic digestion, a process that uses microorganisms in the absence of oxygen to convert organic material into biogas, is used by WWTPs as a means of production of alternative energy source. California has the highest number of municipal facilities using anaerobic digestion, about 102, of which 25 do not use their biogas [7-11].

To arrive at the MW size of the fuel cell plant, we use a conservative reverse engineering approach. As shall be seen in Section IV, operating fuel cells from 17:00 hrs. to 08:00 hrs. i.e. 15 hours per day shall give us the most desired benefits. We assume operating the fuel cells at its full capacity all throughout this time as this will give us safe optimal values of the system size. The calorific value of biogas is 20 MJ/m^3 and it primarily contains 55-65% methane, 35-45% carbon dioxide, 0.5-1% hydrogen sulphide and traces of water vapor. Also, assuming 60 percent efficiency of fuel cells, the calculations is as follows.

Table 2. Calculation of system size of fuel cell

Title	Value
Electrical Output of fuel cells:	X MW

Input Power required considering 60% efficiency:	1.66X MW
Hours of operation:	15 hrs.
Energy input required from biogas in MWhrs or MJ:	1.66X * 15 MJ = 25X MJ
Calorific Value of biogas:	20 MJ/m^3
Biogas required in m^3:	$25X \div 20m^3 = 1.25Xm^3$
Biogas output from a WWTP:	3774 gallons or 14.28 m^3
System size X in MW (considering biogas availability from a single WWTP):	11.424 MW

There are about 265 WWTPs in California that have a total output of 1 million gallons per day (MGD) or more flow of biogas. The availability of biogas actually places some restrictions on the system sizing. We assumed availability only from a single WWTP. However, we can safely increase our fuel cell system size to 20 MW with enough biogas supply margin available. As shall be seen in the simulations, 20 MW fuel cell system size can bring about significant improvements in the ramping issues faced by conventional generators. Now, we can calculate the daily amount of biogas required.

Table 3. Calculation of WWTPs required

Title	Value
Fuel Cells System Size in MW:	20 MW
Input required considering 60% efficiency:	20/0.6 = 33.33 MW
Energy input required from biogas in MWhrs for 15 hours:	33.33*15 MJ = 500 MJ
Bio gas required in gallons:	6604.3 gallons
WWTPs needed to meet this daily requirement:	1.75 ~ 2

4. Software Simulation

For simulation purposes, we have chosen a standard IEEE 34 bus system, which is an actual feeder located in Arizona, with a nominal voltage of 24.5 kV and also an in-line transformer for short 4.16 kV section [12]. Since, the actual load in the 34-bus system is 1769 kW, we have scaled down our PV system and fuel cell generation accordingly for simulation in Open DSS. Since, solar PV generation and system load are fluctuating all throughout the day, to take the variability into account we consider actual PV generation and system load curves with hourly data in [13] and [3]. Additionally, we know that most of the PV generation is from 0800 hrs. to 1700 hrs. and there is excess generation during this time that gets fed into the grid. To have the maximum benefit of system ramp improvements from fuel cell generation, we can operate the system from 1700 hrs. to 0800 hrs. with the exception at 1700 hrs., where we operate the fuel cell at 30 percent of its maximum capacity i.e. 6MW, at all other times we operate it at its rated system size of 20MW.

Referring figure 3, we vary the fuel cell system size from 5MW to 73 MW and observe the peak load size that has to be met by the conventional generator. We observe a considerable reduction in the size of the conventional system as we increase the fuel cell system rating. With PV itself, we observe an 8 MW reduction in system size. With 20 MW fuel cell system in addition to the base solar photovoltaic system, we observe a 30 MW reduction in conventional generator capacity. The saving of 30 MW of system capacity can be broken down into three parts: 20 MW fuel cell system, 8 MW attributable to the PV system and 2 MW due to a reduction in transmission losses as a result of placing the fuel cell system at its optimal location. We also observe that to completely offset the conventional generator system, we need a 73 MW fuel cell system i.e. an integrated 405.6 MW solar PV system with 73 MW fuel cell system will enable the 100000 customers to go off the grid.

Table 4. System Scale Down and comparison of power supplied

System scale Down			Comparison of power supplied			
IEEE 34 bus load	**Actual Load**	**Scale Down factor**	**Scenario**	**Load in MW**	**Scenario**	**Load in MW**
1769 kW	73000 kW	41.27	**Without PV**	**84.48**	**PV+20MW fuel cell**	**54.02**
	Actual Size in kW	**Scale down size in kW**	**With PV**	**76.18**	PV+60MW fuel cell	12.48
Connected Load	73000	1769	PV+5MW fuel cell	70.72	**PV+73MW fuel cell**	**-0.527**
PV generation	405673	9831	PV+10MW fuel cell	64.99		
Fuel Cells	20000	485	PV+15MW fuel cell	59.48		

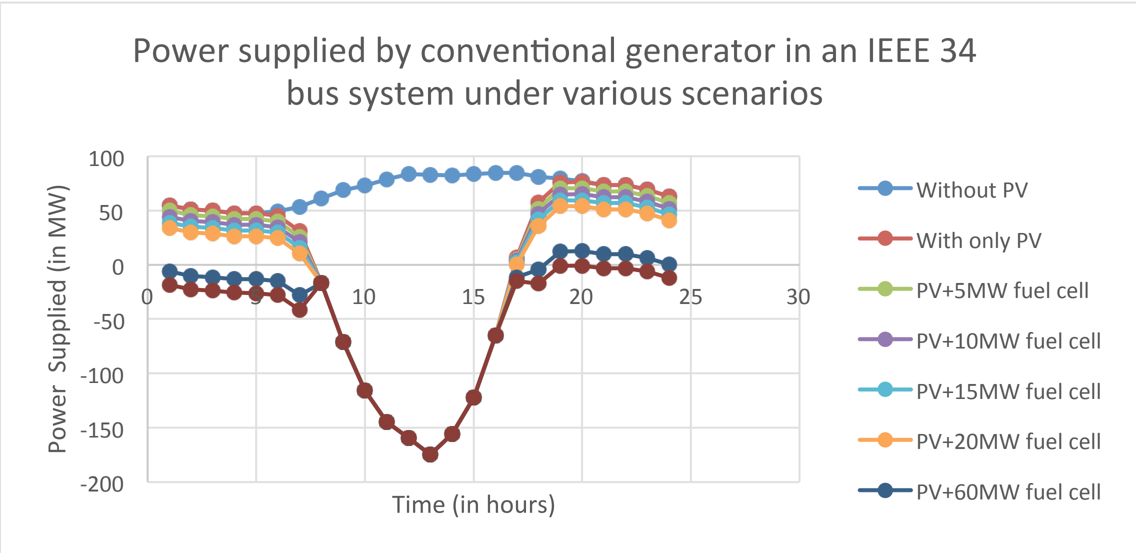

Fig. 3. Plot of power supplied by conventional generator under varying fuel cell system size

Now, we compare the power supplied by conventional system in the morning and evening hours under two scenarios, with PV system only and with integrated PV and 20W fuel cell system to have an in depth understanding of how fuel cell installation can help mitigate ramping issues. The table above compares the power supplied by the conventional generator in the morning and evening hours in the two different scenarios stated above. Upon comparison of power supplied by conventional generator in morning and evening hours under two scenarios, we observe a reduction in hourly differential power or in other words the slope of the curve. We can observe that there is a reduction of 20.42 MW of system ramp from 0700 hrs. to 0800 hrs. and 15.29 MW from 1700 hrs. to 1800 hrs. in the integrated fuel cell and PV system as compared to the PV system alone.

5. Shortcomings and Alternatives

For any distributed generation (DG) system, its load following and voltage regulation capability forms an important system requirement. Fuel cells have some technical challenges associated with themselves, the most important being its slow output power ramping, that can place some restrictions on its stand alone usage as a DG source. There are alternative technical solutions that can be sought like the combined use of fuel cell modules and a gas turbine (GT). The high operating temperatures of SOFC results in high temperature exhaust, that can be used to increase the overall system efficiency. Other options include the use of external energy storage such as batteries, flywheels, or superconducting magnetic energy storage devices or using a phosphoric acid fuel cell (PAFC) power plant [14].

6. Conclusion

In this paper, a sustainable distributed energy generation process comprising of a hybrid 405.6 MW solar rooftop PV system and a 20 MW fuel cell system is discussed. This includes a complete design review, planning methodology and project methodology of the solar PV system. Additionally, the theory, working and sizing criteria of the 20 MW fuel cell system is explored. Our discussion is further strengthened and supported by Open DSS simulation. The simulation results help us in gaining an understanding of how the fuel cells can complement the photovoltaic system by aiding them during turbulent times and by attenuating critical system ramping issues faced by conventional generators. We conclude this paper by a brief discussion on the limitations of using fuel cells in a DG system and suggest some remedies to overcome them.

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