Solar-PV & Fuel Cell Based Hybrid Power Solution for Remote Locations

Manish Kumar Singla, Parag Nijhawan, Amandeep Singh Oberoi

***Abstract:** Inherently variable nature of renewable sources of energy such as solar and wind, are incapable of meeting continuous supply demand. Combining solar photovoltaic (PV) and fuel cell could offer a feasible solution to the challenge of continuous power supply, particularly in those geographical locations where renewable resources are available in abundance. The present paper investigates a solar PV and fuel cell-based hybrid system in-context to a selected site in Indian sub-continent. The feasibility of harnessing renewable energy per sq. meter of land (i.e. energy density) from a combined solar PV-fuel cell based hybrid system employed in Jodhpur location in Rajasthan is reported. The solar irradiance data for the last three decades corresponding to the longitudinal and latitudinal coordinates of Jodhpur is collected using PVsyst software. A novel design of PV-fuel cell hybrid system is proposed to gauge the enhanced utilization of the existing space, productivity enhancement, and energy/m^2 harnessed from the utilized land. The obtained results of solar irradiance are analyzed for implementation in combination with a modified unitized regenerative fuel cell (URFC). The proposed system would outlay a path for the development of a more sustainable, effective and rugged hybrid renewable energy systems that could furnish the energy demands of the Indian sub-continent and similar geographical locations.*

***Keyword** - solar energy, solar irradiance, fuel cell, renewable energy harnessing, proton flow battery.*

I. INTRODUCTION

Most of the human activities are energy dependent and therefore, it is worthwhile mentioning that energy is an inherent and most essential part required for survival of mankind [Adejumobi, A., et. al. 2011]. Undoubtedly, ‘energy crisis’ is one of the most crucial challenges facing mankind. Moreover, for energy needs people are still relying on continuously depleting conventional fossil fuels which emit harmful green house gases, when burnt [Kumar, S., & Garg, V.K. 2013]. In lieu to this, the researchers are bound to explore alternate sources of energy that are capable of meeting the continuous power supply demand, are environmental friendly, and could contribute to a sustainable society. One of the solutions to the mentioned problem is shifting to renewable sources of energy [Shivrath, Y., et. al. 2012, Arjun, A.K., et. al. 2013, Subrahmanyam, J.B.V et. al. 2012].

Most of the renewable sources of energy are not available round-the-clock in nature and hence, are incapable of meeting the continuous power supply demand. Therefore, all renewable energy power generation/conversion systems are supported with energy storage devices such as batteries [Sawle, Y., et. al. 2016, Khisa, S., et. al. 2017]. Currently available batteries in market are lithium-based which are heavy, toxic, and expensive to recycle. One solution to all such problems is generation of hydrogen from renewable energy source (e.g. solar PVs), its storage and reuse in a fuel cell to give back electricity when renewable sources are not available. To investigate the feasibility of such a hybrid system a theoretical study is conducted for a selected site – Jodhpur located in north of India and simulation on solar irradiance is carried out in PVsyst software. The fixed input parameters of the selected site are inserted to obtain the results in terms of power generation and its variance through-out the year. The results were analyzed to develop a better understanding of the functioning and feasibility of a novel hybrid system before implementing in actual.

II. SYSTEM DESCRIPTION

The schematic of the proposed solar PV-fuel cell based hybrid system is shown in the Figure 1. The components used in the proposed system are PV array, a modified unitized regenerative fuel cell (URFC) system, dump load, inverter, electrical load and bus system. The output of solar PV array is fed to a DC bus in a day-light or when sun is available. When power from any of the systems is accessible, it runs the electronic load and any surplus power produce during peak hours could be used to drive a URFC in electrolyser mode to split water into oxygen and hydrogen. The generated hydrogen could be stored and reused to generate electricity through the same URFC but, running in fuel cell mode during night or when sun is not available. The converter circuit converts the DC power generated from solar PV cells module into AC to meet the load demand. The DC loads are directly fed from the DC bus. Although the proposed system runs similar to the conventional PV & fuel cell based hybrid systems however, the new design offers additional advantages discussed in the succeeding section.

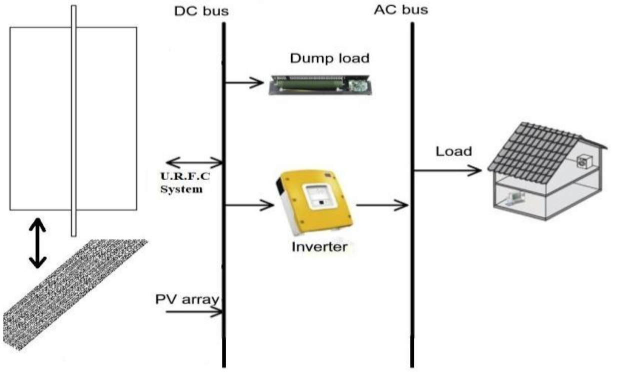

Figure 1. Schematic of the proposed solar PV-fuel cell based hybrid system

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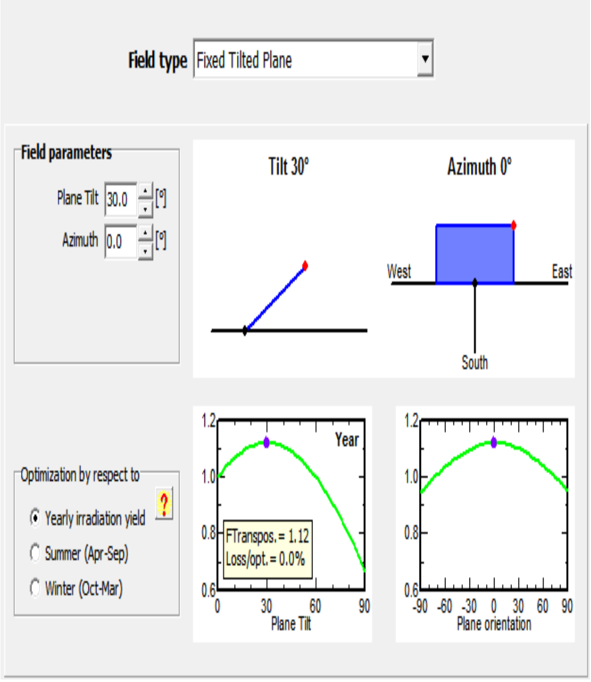
III. PROPOSED HYBRID SYSTEM

Generally, the concept of a solar-PV & fuel cell based hybrid system work as an independent unit connected to a DC bus which lowers the overall energy harness output per m^2 of the land occupied. Therefore, a novel design of PV & fuel cell based hybrid system could better utilize the existing space in terms of productivity enhancement and energy/m^2 harnessed from the utilized land.
Moreover, the tilted (angled) design of solar PV array would avoid shadow and hence, provide maximum time and intensity of sunlight exposure thereby generating more power.

IV. SITE ANALYSIS

It is viable to install the proposed hybrid system at particular sites where solar energy is available in abundance. One such site is Jodhpur in Rajasthan state of India located at 26.2389 latitude and 73.0243 longitudes. The Figure 2 shows the Snapshot of input parameters inserted in PVsyst for the site analysis. The generated curve helped in determining the maximum power point tracking of the projected PV system and is found to be equal to 98.7 kW at STC, KWdc at 60°C, and 126 kWac. Figure 3 shows the obtained MPP curve and inverter output distribution for the selected site i.e. Jodhpur.



Field type: Fixed Tilted Plane

Field parameters

Plane Tilt 30.0 [°]

Azimuth 0.0 [°]

Optimization by respect to

● Yearly irradiation yield

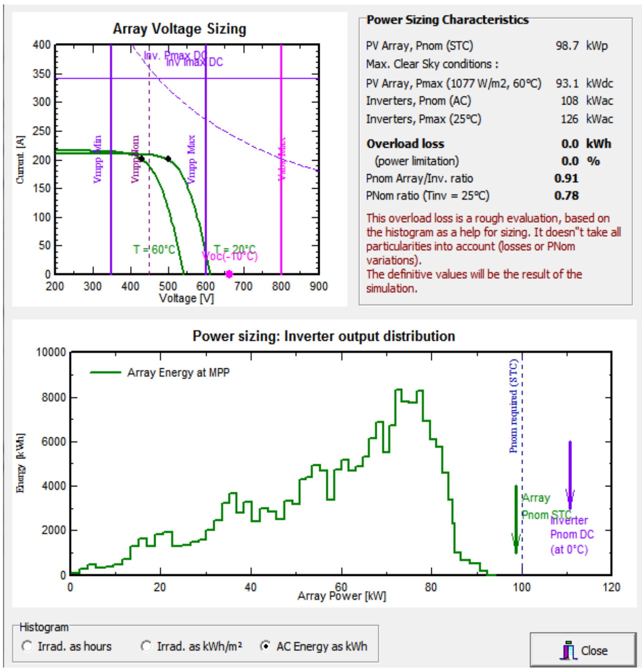
○ Summer (Apr-Sep)

○ Winter (Oct-Mar)

FTranspos. = 1.12

Loss/opt. = 0.0%

Figure 2. Snapshot of input parameters inserted in PVsyst for site analysis



Power Sizing Characteristics

PV Array, Pnom (STC) 98.7 kWp

Max. Clear Sky conditions :

PV Array, Pmax (1077 W/m2, 60°C) 93.1 kWdc

Inverters, Pnom (AC) 108 kWac

Inverters, Pmax (25°C) 126 kWac

Overload loss 0.0 kWh

(power limitation) 0.0 %

Pnom Array/Inv. ratio 0.91

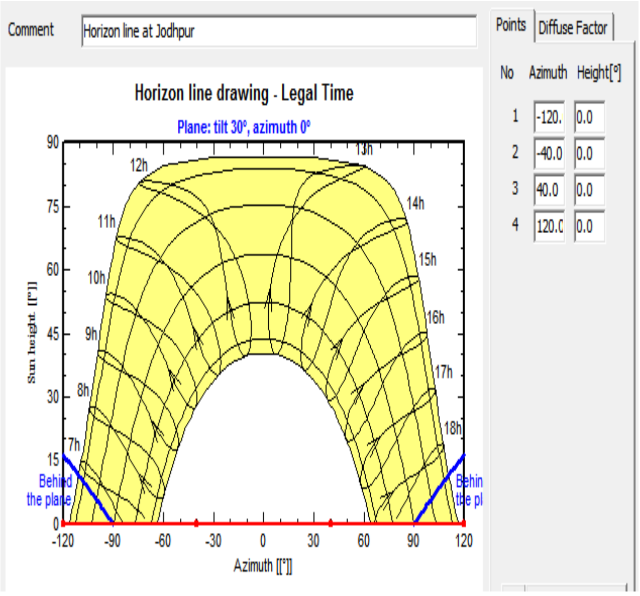
PNom ratio (Tinv = 25°C) 0.78

This overload loss is a rough evaluation, based on the histogram as a help for sizing. It doesn"t take all particularities into account (losses or PNom variations).
The definitive values will be the result of the simulation.

Histogram

○ Irrad. as hours ○ Irrad. as kWh/m² ● AC Energy as kWh

Figure 3. The obtained MPP curve and inverter output distribution for the selected site



Comment: Horizon line at Jodhpur

No	Azimuth	Height[°]
1	-120.	0.0
2	-40.0	0.0
3	40.0	0.0
4	120.0	0.0

Figure 4. Solar azimuth angle

The obtained results for the selected site throw light on the annual variation behavior of the total received energy, global incidence, ambient temperature, effective global incidence, energy generated, grid-transfer, PV array efficiency and overall system efficiency. Table I below shows that annual global irradiance at Jodhpur, Rajasthan which is seen to have varied from 123.7 – 218.3 kWh/m^2.
The Table II shows the annual system losses and in Table III inverter losses are given for the proposed hybrid system. The various incurred PV losses are:

1. Inverter loss
2. Module mismatch loss
3. Ohmic loss
4. Module quality loss

The simulation also informs about the improvement in energy harnessing integrating PV array with the URFC. The annual energy need enhancement is projected in Table IV.

Table I. Annual meteorological and incident data

Month	Global diffusion in horizontal direction (kWh/m^2)	Global diffusion of irradiance (kWh/m^2)	Ambient temperature (°C)	Global incident in collateral plane (kWh/m^2)	Global energy efficiency (kWh/m^2)	Effective energy at the output of the array (kWh)	Energy injected into the grid (kWh)	Performance Ratio
January	129.2	34.0	17.26	185.5	181.6	15732	15382	0.840
February	144.3	36.4	20.59	188.6	184.7	15674	15325	0.824
March	187.2	56.2	26.81	213.5	208.4	17257	16861	0.800
April	201.9	70.8	31.23	203.8	198.2	16221	15842	0.788
May	218.3	84.8	34.79	198.8	192.5	15716	15346	0.782
June	189.9	98.5	33.58	168.3	162.8	13535	13210	0.795
July	169.9	102.4	31.18	152.9	147.7	12510	12199	0.808
August	160.7	84.8	29.72	154.4	149.5	12610	12290	0.807
September	169.6	68.9	30.18	181.3	176.4	14633	14294	0.799
October	163.5	49.1	28.77	201.8	197.2	16236	15871	0.797
November	127.1	40.2	23.08	174.4	170.6	14440	14105	0.820
December	123.7	28.9	19.20	185.2	181.6	15591	15239	0.834
Year	1985.3	754.8	27.23	2208.7	2151.3	180155	175964	0.807

Table II. Annual system losses

Month	ModQual (kWh)	MisLoss (kWh)	OhmLoss (kWh)	Array virtual energy at MPP (kWh)	Global inverter loss (kWh)
January	245.2	177.1	192.3	15732	350.5
February	244.5	176.6	206.8	15674	349.0
March	269.3	194.5	231.4	17257	396.1
April	253.0	182.7	208.6	16221	378.5
May	244.8	176.9	185.8	15716	369.8
June	210.5	152.1	139.0	13535	324.6
July	194.4	140.4	114.2	12510	310.9
August	196.2	141.7	128.9	12610	320.2
September	228.0	164.7	177.0	14633	338.6
October	253.3	183.0	213.5	16236	364.9
November	225.1	162.6	176.8	14440	335.0
December	243.1	175.6	194.5	15591	352.5
Year	2807.4	2027.9	2168.9	180155	4190.6

Table III. Annual inverter losses

Month	Available energy at inverter output (kWh)	Inverter efficiency (%)	Inverter Loss (kWh)	Inverter loss during operation (kWh)	Inverter loss due to power threshold (kWh)	Inverter loss due to nominal inverter power (kWh)	Inverter loss due to voltage threshold (kWh)	Inverter loss due to nominal inverter voltage (kWh)	Inverter loss due to maximum input current (kWh)
January	15382	97.8	350.5	350.5	0.000	0.000	0.000	0.000	0.000
February	15325	97.8	349.0	347.6	1.431	0.000	0.000	0.000	0.000
March	16861	97.7	396.1	393.0	3.119	0.000	0.000	0.000	0.000
April	15842	97.7	378.5	376.3	2.255	0.000	0.000	0.000	0.000
May	15346	97.6	369.8	369.8	0.000	0.000	0.000	0.000	0.000
June	13210	97.6	324.6	323.5	1.058	0.000	0.000	0.000	0.000
July	12199	97.5	310.9	310.7	0.230	0.000	0.000	0.000	0.000
August	12290	97.5	320.2	317.1	3.049	0.000	0.000	0.000	0.000
September	14294	97.7	338.6	335.6	3.026	0.000	0.000	0.000	0.000
October	15871	97.8	364.9	364.9	0.000	0.000	0.000	0.000	0.000
November	14105	97.7	335.0	331.5	3.473	0.000	0.000	0.000	0.000
December	15239	97.7	352.5	345.7	6.757	0.000	0.000	0.000	0.000
Year	175964	97.7	4190.6	4166.2	24.397	0.000	0.000	0.000	0.000

Table IV. Annual energy needs

Month	E_Grid (kWh)	PR
January	15382	0.840
February	15325	0.824
March	16861	0.800
April	15842	0.788
May	15346	0.782
June	13210	0.795
July	12199	0.808
August	12290	0.807
September	14294	0.799
October	15871	0.797
November	14105	0.820
December	15239	0.834
Year	175964	0.807

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V. FUEL CELL

The first demonstration of a basic fuel cell was given by Sir William Grove in 1839. Fuel cell is not only the most efficient method for generating electricity compared to conventional methods but, it is also one of the cleanest methods. “Fuel cell is an electrochemical device that produces electricity without combustion by combining hydrogen and oxygen to produce water and heat”. A typical single fuel cell is shown in Figure 5. Fuel cell has wide variety of applications including marine, aircraft, households and commercial transportation etc. According to the basis of electrolyte and operating temperature, there are different types of fuel cell. These includes proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC), alkaline fuel cell (AFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC) and direct methanol fuel cell (DMFC). Some of the different types of fuel cell are given in table V [Gautam, D., & Ikram, S. 2010].

Table V: Classification of Fuel Cells [Gautam, D., & Ikram, S. 2010]

Fuel Cell	Electrolyte	Operating Temperature	Efficiency	Commercial/Research
Proton exchange membrane fuel cell	Polymer membrane	50-100°C	50-60%	Both
Phosphoric acid fuel cell	Molten phosphoric acid	150-220°C	55%`	Both
Alkaline fuel cell	Aqueous alkaline solution	50-200°C	50-60%	Research
Molten carbonate fuel cell	Molten alkaline carbonate	600-700°C	55-65%	Both
Solid Oxide fuel cell	Solid non-porous metal oxide	700-1000°C	55-65%	Research
Direct methanol fuel cell	Polymer membrane	90-120°C	30-40%	Research
Reversible fuel cell	Polymer membrane	<50°C	-	Both
Planar solid oxide fuel cell	Conducting ceramic oxide	850-1100°C	60-65%	Both
Direct formic acid fuel cell	Polymer membrane	25-40°C	-	Both
Microbial fuel cell	Humic acid	<40°C	-	Research
Tubular solid oxide fuel cell	Conducting ceramic oxide	850-1100°C	60-65%	Both

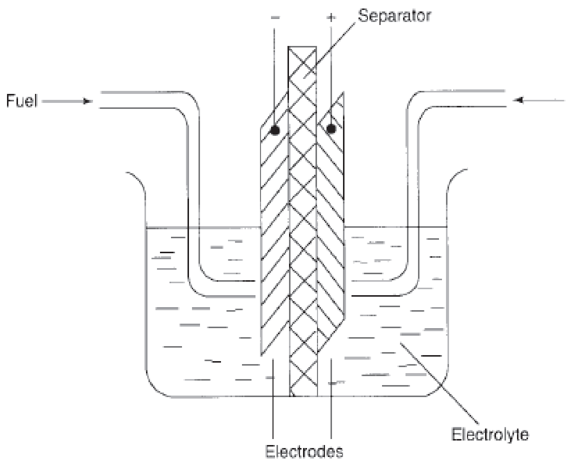

Figure 5. Schematic of Fuel Cell

Out of all commercially available fuel cells, PEM fuel cell is widely adopted because of quick start up and shut down time that makes it adaptive for mobile applications. Other advantages that a PEM fuel cell offers include its simplicity and viability. The operating temperature of the PEM fuel cells lies between the range of 50-100°C and efficiency between 40-60% [Singla, M.K., et. al. 2019]. PEMFC is divided into two categories based on the temperature i.e. low temperature and high temperature fuel cell. The operating temperature of low temperature fuel cell varies from 50-100°C whereas for high temperature fuel cells 100-200°C. The electrochemical reactions associated with a PEMFC are:

The chemical reaction of the anode is:

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

The chemical reaction of the cathode is:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

The overall chemical reaction of this fuel cell is:

$$H_2 + \frac{1}{2}\,O_2 \rightarrow\ H_2O$$

The overall maximum cell potential of high temperature PEMFC is equal to 1.18V and for the low temperature PEMFC cell it is 1.229V. But in practical the maximum cell potential varies from 0 to 1.0 Volts because there can be losses depending upon operating conditions [Feroldi, D., & Basualdo, M. 2012]. Activation losses, ohmic losses and mass transfer losses are three losses associated to the working of a PEMFC.

VI. CONVENTIONAL HYDROGEN SYSTEMS

The Figure 6 shows the representation of a conventional hydrogen system. In this system; excess solar energy is used to produce hydrogen through water electrolysis. Water is split into hydrogen and oxygen by means of an electrolyser operating on direct current from the photovoltaic cells. The hydrogen produced is stored in a separate storage, which is recovered later for use in a fuel is reported in [Paul, B., & Andrews, J. 2008]. Power supply to remote areas is a possible application for such systems [Paul, B., & Andrews, J. 2008]. Hydrogen production from the water section is a well-known and commercially developed method used in the industry [Ngoh, K.A., & Njomo, D. 2012].

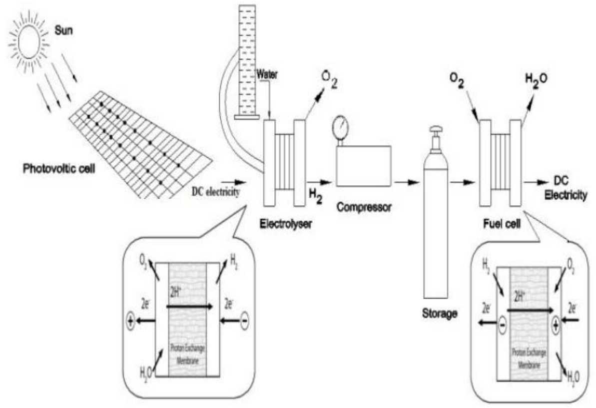

Figure 6. Schematic of a Conventional hydrogen system

The main advantage of traditional hydrogen systems are scalability, zero greenhouse gas emissions and quiet operation [Ngoh, K.A., & Njomo, D. 2012]. An important advantage of this system over commercial batteries is that, unlike ordinary batteries, the hydrogen storage system does not automatically discharge over time and neither does it emit any harmful fumes. It is therefore, known that ordinary batteries store energy for a short period of time and hydrogen energy can be stored until it is used. Conventional hydrogen systems also have many disadvantages like; the system contains more devices than batteries. When switching from electricity to power generation, the return efficiency of conventional hydrogen systems is only 40-45% compared to 70-80% to batteries [Gray. E., et. al. 2011].

VII. UNITIZED REGENERATIVE FUEL CELL

A unitized regenerative fuel cell or URFC is a single unit capable of operating in both electrolyser and fuel cell modes [Andrews, J., & Doddathimmaiah, A. 2008].

This individual URFC unit replaces the separate fuel cell and electrolyser in a conventional hydrogen system. In this hydrogen system, URFC uses direct current while operating in electrolysis mode to split water into hydrogen and oxygen. The hydrogen produced in the electrolysis mode is pressurized and stored in a separate storage unit. While operating in fuel cell mode, the URFC combines hydrogen and oxygen to produce electricity and water. The hydrogen required for URFC is supplied from the storage unit. Figure 7 shows the schematic of this hydrogen system with URFC. This system has fewer components than a conventional hydrogen system that can reduce mass and volume.

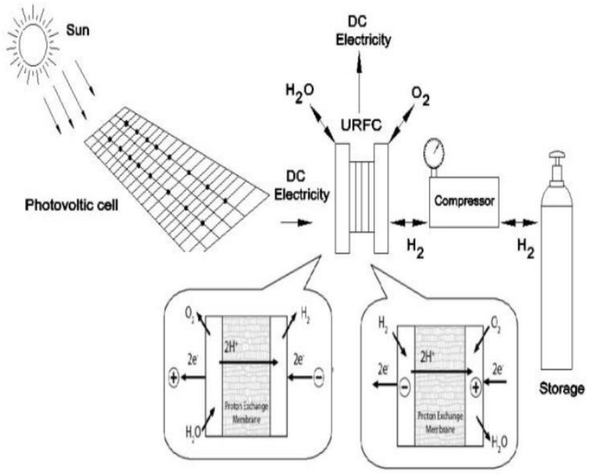

Figure 7. Schematic of a Hydrogen system with URFC

URFC used in the system must be comparable in terms of both efficiency and lifetime, compared to the commercially available electrolysers and fuel cells [Paul, B., & Andrews, J. 2008]. Purchasing a single URFC cell is economically advantageous because it reduces the cost of purchasing separate electrolysers and fuel cells [Doddathimmaiah, A.K., & Andrews, J. 2006]. Many researchers are trying to improve the efficiency of URFC [Petterson, J., et. al. 2006, Doddathimmaiah, A.K., & Andrews, J. 2009]. The performance of PEM URFC can be achieved in the vicinity of special electrolysers and fuel cells, but URFC has short term limitations that it will decline after several hundred cycles [Millet, P., et. al. 2011, Andrews, J., & Shabani, B. 2012].

A concern when using a hydrogen system with URFC is that an external hydrogen storage unit is required to store the generated hydrogen. However, the current research work is a maiden attempt to ascertain the technical feasibility of a solar PV and fuel cell-based (URFC in this case) hybrid system. The obtained results have shown that the average solar irradiation that incidents on the selected site is enough to generate electricity through photovoltaic cells and simultaneously run a URFC to produce hydrogen from water, when sun is available. There is enough excess DC current available during peak hours to be used to disassociate water in a URFC and store the produced hydrogen as well as oxygen for later use. During the times when sun is not available, the stored reactants (hydrogen and oxygen gases) could be fed back to the URFC to give out electricity and water. Compared to the conventional system of hydrogen generation through renewable, the proposed system offers more round-the-trip efficiency i.e. electricity in to electricity out; due to lesser number of components and associated losses.

VIII. CONCLUSIONS

The proposed solar PV & fuel cell based hybrid system utilizes third generation solar photovoltaic cells coupled with a unitized regenerative fuel cell (URFC). The system is proposed to be installed at site location of Jodhpur; Rajasthan, which is a feasible, fit due to availability of abundant solar irradiance in the area through-out the year. During daylight hours, the electrical load is met directly by solar PV system through a DC bus and inverter thereby simultaneously running a URFC in electrolyser mode to generate hydrogen from water. During off–light hours, the electrical load is met through URFC working in fuel cell mode by consuming the stored reactants to give out electricity and water. A simulation was conducted by inserting fixed variable inputs to assess the technical feasibility of the overall system. The simulation results as mentioned in the preceding sections were found to be within the acceptable limits. The conducted theoretical study has proved the feasibility of the system but, yet to be tested experimentally for gauging the actual losses and remedial actions.

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