Modeling and Analysis of Solar Photovoltaic Assisted Electrolyzer-Polymer Electrolyte Membrane Fuel Cell For Running a Hospital in Remote Area in Kolkata, India

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ABSTRACT. The present work consists of the modeling and analysis of solar photovoltaic panels integrated with electrolyzer bank and Polymer Electrolyte Membrane (PEM) fuel cell stacks for running different appliances of a hospital located in Kolkata for different climatic conditions. Electric power is generated by an array of solar photovoltaic modules. Excess energy after meeting the requirements of the hospital during peak sunshine hours is supplied to an electrolyzer bank to generate hydrogen gas, which is consumed by the PEM fuel cell stack to support the power requirement during the energy deficit hours. The study reveals that 875 solar photovoltaic modules in parallel each having 2 modules in series of Central Electronics Limited Make PM 150 with a 178.537 kW electrolyzer and 27 PEM fuel cell stacks, each of 382.372 W, can support the energy requirement of a 200 lights (100 W each), 4 pumps (2 kW each), 120 fans (65 W each) and 5 refrigerators (2 kW each) system operated for 16 hours, 2 hours, 15 hours and 24 hours respectively. 123 solar photovoltaic modules in parallel each having 2 modules in series of Central Electronics Limited Make PM 150 is needed to run the gas compressor for storing hydrogen in the cylinder during sunshine hours.

Keywords: Central Electronics Limited, Electrolyzer, PEM, PM 150, Solar photovoltaic.

Article History: Received Feb 5th 2017; Received in revised form June 2nd 2017; Accepted June 28th 2017; Available online


1. Introduction

Demand for electricity and the standard of living are increasing day by day. However, power in the form of electricity is not available in plenty of remote areas like villages. Many people have worked for providing power and useful technology to remote areas and areas where power is not easily available. Chow et al. (2006) developed hybrid PVT (photovoltaic-thermal) technology using water as the coolant in order to improve the energy performance of the photovoltaic system in residential areas. Nfah et al. (2008) simulated off-grid generation options for remote villages in Cameroon using a load of 110 kWh/day and 12 kWp. Chaurey & Kandpal (2010) used solar home systems for providing basic electricity services to rural households that are not connected to electricity grid. Elhadidy (2002) analysed hourly wind-speed and solar radiation measurements made at the solar radiation and meteorological monitoring station, Dharhan (26°32’N, 50°13’E), Saudi Arabia, to investigate the feasibility of using hybrid (wind+solar+diesel) energy conversion systems at Dharhan in order to meet the energy needs of 22-bedroom houses. Similarly authors in reference (Nfah et al. 2007; Wies et al. 2005; Al Suleimani & Nairb 2000; Manolakos et al. 2001; Zhai et al. 2009; Beck 2007; Saheb-Koussa et al. 2009; Nfah & Ngundam 2008) used different technologies and powering of appliances in different remote areas.

Hospital is very important for people since many villages do not have hospital. If the village has, it is not having proper facilities like electricity. So if
somehow electricity can be supplied to hospital in remote villages, village people could be cured without going to town or city. New technologies can be used for assisting the functioning of hospitals. Yoshida et al. (2007) used rational method to determine the system structure and operational strategies for the energy supply system for a hospital based on the optimization approach. Paksoy et al. (2000) designed a system using solar energy in combination with Aquifer Thermal Energy Storage (ATES) that conserved a major part of the oil and electricity used for heating or cooling the Cukurova University, Balcali Hospital in Adana, Turkey. Similarly, authors in references (Bizzarri & Morini 2004; Bizzarri & Morini 2006; Al-Karagholi & Kazmerski 2010) used different technologies for running and assisting hospitals.

The present work in this paper deals with the use of solar photovoltaic system assisted PEM electrolyzer fuel cell for powering a hospital. Many works on fuel cell application and solar hydrogen systems had been done. Wu et al. (2005) presented an integrated system framework for fuel cell-based distributed energy applications. Veziroglu & Macario (2011) highlighted some of the research and developmental work which had occurred in the past five years on fuel cell vehicle technology, with a focus on economic and environmental concerns. Similarly, authors in references (Kelly et al. 2011; Solis et al. 2010; Dorer et al. 2005; Hawkes et al. 2006; El-Shatter et al. 2002; Shapiro et al. 2005; Galli & Stefanoni 1997; Uzunoglu et al. 2009; Barbir 2005; Kelly et al. 2008; Zervas et al. 2008) used different technologies based on fuel cells for useful and beneficial purposes.

From the mentioned reviews a considerable work of powering remote areas, powering health clinics and on fuel cell has been done, yet no work on powering health clinic by using solar photovoltaic integrated with electrolyzer PEM fuel cell has been done.

Fig.1. Schematic view of proposed integrated configuration system.
2. Description of combined solar photovoltaic assisted electrolyser-PEM (polymer electrolyte membrane) fuel cell

The system configuration consists of solar photovoltaic modules, charge controller, PEM electrolyzer, gas storage cylinder, PEM fuel cell stacks and two inverters as shown in Fig.1. When enough sunlight is available, sun rays fall on solar photovoltaic modules and generate current $I_{PV}$. Some amount of current required for hospital ($I_h$) goes through an inverter to operate various appliances of the hospital. The excess current ($I_{PV}-I_h$) after meeting the requirements of the hospital goes to PEM electrolyzer. In electrolyzer water is present which gets dissociated into hydrogen and oxygen. The hydrogen gas generated in electrolyzer is stored in gas compressor. For pressurization of the hydrogen gas owing to low mass density, which requires a very large storage tank, the compressor derives its electrical energy ($I_L$) from solar photovoltaic modules and operates only when electrolyzer is in operation.

When enough sunshine is not available i.e. deficient current ($I_h-I_{PV}$) comes from the PEM fuel cell stack. The hydrogen required for running the fuel cell is obtained from gas storage cylinder which gets stored during sufficient solar radiation from the electrolyzer.

3. Modeling

3.1 Modeling of solar photovoltaic system

The electrical energy was generated by harnessing solar energy using photovoltaic modules. In the present work Central Electronics Limited Make PM-150 (Solar photovoltaic modules pm 150 2011) solar photovoltaic module has been used. The single cell terminal current is given by (Chenni et al 2007):

$$i_{PV} = i_L - i_D$$  

(1)

Where $i_L$ is the light current generated by a solar cell as a function of solar radiation (G) and $i_D$ is the diode current.

The light current generated from a photovoltaic module at any given intensity of solar radiation and temperature is given by (Chenni et al 2007):

$$i_L = \left( \frac{G}{G_{ref}} \right) i_{sat} \left( \mu_{isc} (T_{mod,ule} - T_{mod,uleref}) \right)$$  

(2)

Where $G$, $G_{ref}$ is the solar radiation at actual (Tiwari 2004) and reference condition (1000 W/m²) (Solar photovoltaic modules pm 150 2011) respectively, $i_{sat}$-short circuit current at reference condition(A)(Solar photovoltaic modules pm 150 2011), $\mu_{isc}$-manufacturer supplied temperature coefficient of short circuit current(A/K) (Solar photovoltaic modules pm 150 2011), $T_{mod,ule}$ and $T_{mod,uleref}$ module temperature at actual and at reference condition(K)(Solar photovoltaic modules pm 150 2011).

The module temperature is a function of ambient temperature ($T_{ambient}$), wind speed ($v_f$) and solar radiation(G) and given by (Chenni et al 2007):

$$T_{mod,ule}(K) = (0.943 \times T_{ambient} + 0.028 \times G - 1.528 \times v_f + 4.3) + 273.15$$  

(3)

Where, $T_{ambient}$ is in °C(Tiwari 2004), G in W/m² (Tiwari 2004), $v_f$-wind speed in m/s(Wind speed in Kolkata, West Bengal 700001, India 2014).

The diode current in equation (1) is a function of reverse saturation current and given by(Chenni et al.2007):

$$i_D = i_{sat} \left[ \exp \left( \frac{q(V + i_{PV} R_s)}{jK T_{mod,ule}} \right) - 1 \right]$$  

(4)

Where $i_{sat}$ - reverse saturation current(A), $q$-electron charge(1.6 x 10⁻¹⁹C), $V$-terminal voltage(V), $R_s$ - series resistance, $\gamma$-shape factor, $k$-Boltzamann constant(1.38 x 10⁻²³ J/K).

$$i_{sat} = i_{satref} \left\{ \left( \frac{T_{mod,ule}}{T_{mod,uleref}} \right)^{3/2} \exp \left[ \frac{qE_g}{kT_{mod,uleref} \left( \frac{1}{T_{mod,uleref}} - \frac{1}{T_{mod,ule}} \right)} \right] \right\}$$  

(5)

Where $A$-completion factor, $\varepsilon G$-material bandgap (1.12eV for Si), and

$$i_{satref} = \exp \left( \frac{-qV_{ocref}}{kT_{mod,uleref}} \right)$$  

(6)

Where $V_{ocref}$-open circuit voltage at reference condition (Solar photovoltaic modules pm 150 2011). $i_{sat}, i_{satref}$ is taken from Chenni et al (2007).

Shape factor($\gamma$) which is a measure of cell imperfection is given by Chenni et al (2007):

$$\gamma = A \times NCS \times N_s$$  

(7)
Where \( A, A_{NCS}, N_S \) is completion factor, number of cells connected in series in a single module (specified by manufacturer of the module) and number of modules connected in series of the entire photovoltaic array respectively.

\[
N_S = \frac{V_{\text{system}}}{V_{\text{module}}}
\]

(8)

Where \( V_{\text{system}} \) is the system voltage of the photovoltaic array (considered 48 V in present study) and \( V_{\text{module}} \) is the voltage obtained from single module.

Table 1 shows the specification of various equipment used in the hospital.

<table>
<thead>
<tr>
<th>Equipment(s)</th>
<th>No. of items(n)</th>
<th>Wattage(P)(in W)</th>
<th>Operating hours(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lights</td>
<td>200</td>
<td>100</td>
<td>16</td>
</tr>
<tr>
<td>Pump</td>
<td>4</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td>Fans</td>
<td>120</td>
<td>65</td>
<td>15</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>5</td>
<td>2000</td>
<td>24</td>
</tr>
</tbody>
</table>

The total daily electrical load (Ah) \((i_o)\) due to operation of equipments mentioned in table 1 is given by:

\[
i_o = \frac{n \times P_O \times t}{V_{\text{system}} \times PF}
\]

(9)

Where \( i_o \)- electrical load of an equipment, \( P_O \)-power rating of an equipment, \( t \)-operating hours of an equipment and \( n \)-number of items, \( PF \)-power factor (considered 0.85).

The total daily electrical load (Ah) \((i_{\text{total}})\) consisting of lights, pumps, fans and refrigerator can be given as:

\[
i_{\text{total}} = \sum \frac{i_o}{\eta_{\text{inverter}}}
\]

(10)

Where \( \eta_{\text{inverter}} \)-inverter efficiency (0.85)

The design current required from photovoltaic array \((i_{\text{spv}})\) is given by (Ganguly et al. 2010):\[
i_{\text{spv}} = \frac{i_{\text{total}} \times DF}{\text{peak sunshine hours} \times \eta_{\text{charge controller}}}
\]

(11)

Where \( DF \) is the de-rating factor of photovoltaic module (Telecommunication Engineering Centre (TEC), New Delhi 2011) is 1.25, \( \eta_{\text{charge controller}} \) is charge controller efficiency (Telecommunication Engineering Centre (TEC), New Delhi 2011) is 0.85, peak sunshine hours is considered 7 hours per day (Patra & Datta 2009).

Number of PV modules connected in parallel (\( N_p \)) is given by:

\[
N_p = \frac{i_{\text{spv}}}{i_{\text{mp}}}
\]

(12)

Where \( i_{\text{mp}} \) is the maximum current available from single module under peak power condition (Solar photovoltaic modules pm 150 2011)

Net current from solar PV array is:

\[
i_{\text{array}} = i_{\text{mp}} \times N_p
\]

(13)

3.2 Modelling of PEM fuel cell

Table 2 shows the input parameters used for modelling fuel cell.

Table 2
Input parameters of fuel cell

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cell</td>
<td>Exchange current density ((H_d))</td>
<td>(10^{-4}\text{Acm}^2) (Hayre et al. 2006)</td>
</tr>
<tr>
<td></td>
<td>Charge transfer coefficient of reaction</td>
<td>0.5 (Hayre et al. 2006)</td>
</tr>
<tr>
<td></td>
<td>Cell effective area</td>
<td>100 cm(^2) (Pal 2004)</td>
</tr>
<tr>
<td></td>
<td>Operating current density</td>
<td>0.1 A/cm(^2) (Pal 2004)</td>
</tr>
</tbody>
</table>

The net voltage \((V_{fc})\) of a PEM fuel cell is given by (Ganguly et al. 2010):

\[
V_{fc} = V_{\text{nernst}} - V_{\text{activation}} - V_{\text{ohmic}} - V_{\text{concentration}}
\]

(14)
Nerst potential \( V_{\text{nerst}} \) of PEM fuel cell is given by Ganguly et al (2010):

\[
V_{\text{nerst}} = V_{\text{rev}}^o + \frac{RT}{nF} \ln \left( \frac{p_{H_2}P_{O_2}^{0.5}}{p_{H_2}O} \right)
\]  \hspace{1cm} (15)

Where \( V_{\text{rev}}^o \) is the reference reversible potential, \( T \) is fuel cell operating temperature (60°C in the present study), \( F \) is Faraday constant (96500 C/mole), \( p \) is the partial pressure of the gases(Pa), \( R \)-universal gas constant (8.314J/mole. K).

Activation voltage \( V_{\text{activation}} \) is given by Tafel equation (Hayre et al. 2006):

\[
V_{\text{activation}} = \left( \frac{\tilde{R}}{a_nF} \right) \ln \left( \frac{j_c}{j_o} \right)
\]  \hspace{1cm} (16)

Where \( a \) is the charge transfer coefficient of the reaction (Hayre et al. 2006), \( j_c \) and \( j_o \) being operating current density of fuel cell stack and exchange current density respectively.

Ohmic voltage \( V_{\text{ohmic}} \) is given by (Gangly et al. 2010):

\[
V_{\text{ohmic}} = R \times j_c
\]  \hspace{1cm} (17)

Where \( R \) is the resistance of the polymer membrane (Nafion 117 type) which is given by (Ganguly et al. 2010):

\[
R = \frac{u_{fc}}{f_{fc}}
\]  \hspace{1cm} (18)

Where \( u_{fc} \) is the thickness of Nafion 117 membrane (Nafion membranes-Fuel cell Etc. 2016), \( f_{fc} \) is the conductivity of Nafion 117 membrane depending on water content (\( \lambda \)) and fuel cell operating temperature \( T \) given by (Kandlikar & Lu 2009):

\[
f_{fc} = (0.5139\lambda - 0.326) \exp \left[ \frac{1268}{303} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right]
\]  \hspace{1cm} (19)

And \( \lambda = 8.38 \times 0.138 \times (T - 273.15) \) \hspace{1cm} (20)

Concentration voltage \( V_{\text{concentration}} \) is given by Ganguly et al. (2010):

\[
V_{\text{concentration}} = \left( \frac{RT}{nF} \right) \ln \left[ \frac{j_l - j_c}{j_l} \right]
\]  \hspace{1cm} (21)

Where \( j_l \) is limiting current density of fuel cell and given by (Ganguly et al. 2010):

\[
j_l = \frac{nFDC_B}{\delta}
\]  \hspace{1cm} (22)

Where \( D \) is the effective reactant diffusivity within catalyst layer having typical value \( 10^{-2} \text{ cm}^2/\text{s} \) (Hayre et al. 2006), \( \delta \) is the electrode(diffusion layer) thickness whose value ranges from 100-300µm (Hayre et al. 2006).

\( C_B \) is the bulk (flow channel) concentration of the reactant given by (Bhagat & Dhoble 2007):

\[
C_B = \frac{p_{H_2}}{R \times T \times m_{H_2}}
\]  \hspace{1cm} (23)

Where \( m_{H_2} \) is the mass of hydrogen.

Peak hourly current requirement from fuel cell stack (\( i_{\text{fuelcell}} \)) is given by:

\[
i_{\text{fuelcell}} = \frac{\text{peakloadcurrent}}{\eta_{\text{chargecontroller}}}
\]  \hspace{1cm} (24)

In Equation 24 peak load current means the maximum current requirement at any hour during non sunshine hours i.e from 1:00 am to 5:00 am and 7:00pm to 1:00 am.

Number of PEM fuel cell stacks in parallel \( (N_{\text{fparallel}}) \) can be obtained as shown:

\[
N_{\text{fparallel}} = \frac{i_{\text{fuelcell}}}{i_{\text{cell}}}
\]  \hspace{1cm} (25)

Where \( i_{\text{cell}} \) is the current generated by single fuel cell, which can be obtained from effective area of each cell, and fuel cell operating current density. \( N_{\text{fseries}} \) is the number of fuel cell connected in series and is given by:

\[
N_{\text{fseries}} = \frac{V_{\text{system}}}{V_{fc}}
\]  \hspace{1cm} (26)

The hourly hydrogen consumption of a fuel cell stack \( (m_{fc}) \) at design load is given by (Ganguly et al 2010):

\[
m_{fc} = \frac{i_{\text{fuelcell}} \times N_{\text{fseries}} \times 3600 \times 2}{2 \times F \times \eta_{\text{fuel}}}
\]  \hspace{1cm} (27)

Where \( \eta_{\text{fuel}} \)-fuel utilization factor in fuel cell (considered 0.9)
3.3 Modeling of PEM electrolyzer

In electrolyzer excess current after meeting the requirements of the hospital is used for dissociating water into hydrogen and oxygen gas. Table 3 shows the various input parameters used for modeling electrolyzer.

Table 3
List of input parameters of electrolyzer

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyzer</td>
<td>Number of cells in stack(in series)</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Cell area</td>
<td>86.4 cm² (Dale et al. 2008)</td>
</tr>
<tr>
<td></td>
<td>Maximum current density</td>
<td>1.6 A/cm² (Dale et al. 2008)</td>
</tr>
<tr>
<td></td>
<td>Dry thickness of membrane</td>
<td>178 µm (Dale et al. 2008)</td>
</tr>
</tbody>
</table>

The electrolyzer electrical efficiency ($\eta_{elec}$) is defined as the product of the current efficiency($\eta_i$) and voltage efficiency($\eta_{voltage}$) given as (Li et al. 2009):

$$\eta_{elec} = \eta_i \times \eta_{voltage} \tag{28}$$

Where current efficiency ($\eta_i$) varies with the current passing through the electrolyzer cells ($I_{pv}$-$I_{li}$) and given by (Li et al. 2009):

$$\eta_i = 96.5 \times \exp \left( \frac{0.09}{(I_{pv} - I_{li})} - \frac{75.5}{(I_{pv} - I_{li})^2} \right) \tag{29}$$

The voltage efficiency is assumed to be 74% (Li et al. 2009).

Amount of hydrogen produced (in gm mol) in electrolyzer with $N_{elec}$ (number of cell in series) in one hour is given by (Li et al. 2009):

$$M_{elec} = \frac{(I_{pv} - I_{li}) \times N_{elec} \times \eta_{elec} \times 3600}{2F} \tag{30}$$

3.4 Modelling of gas compressor

Hydrogen gas produced in electrolyzer needs to be compressed. For compressing the hydrogen gas energy i.e current is obtained from solar photovoltaic modules integrated with inverter as shown in fig.1. Table 4 shows the various input parameters used for modeling gas compressor.

The power required to run the gas compressor is given by (Li et al. 2009):

$$W_C = \frac{m_{H_2} \times C_p \times T_1}{\eta_C} \left[ \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \tag{31}$$

Where $m_{H_2}$ - mass flow rate of hydrogen gas in compressor, $C_p$ - specific heat of hydrogen at constant pressure, $T_1$ - gas temperature at compressor inlet, $P_1$ and $P_2$ - inlet and exit pressure of hydrogen gas at entry and exit of compressor respectively, $\eta_C$ - isentropic efficiency of compressor, $\gamma$ - isentropic exponent of hydrogen (1.4).

Current required for running the gas compressor ($i_{compressor}$) is given by:

$$i_{compressor} = \sum_{i=6}^{18} \frac{W_{C,i}}{V_{system} \times PF} \tag{32}$$

where $W_{C,i}$ - compressor power rating from 6 hours to 18:00 hours.

$$i_{compressor} = \frac{i_{compressor}}{\eta_{inverter}} \tag{33}$$

The design current required from photovoltaic array ($i_{pv}$) given by:

$$i_{pv} = \frac{i_{compressor} \times DF}{peaksunshinehours} \tag{34}$$

Number of photovoltaic modules needed for running the gas compressor ($N_{p,compressor}$) is given by:
\[ N_{\text{p, compressor}} = \frac{i_{\text{ispv}}}{i_{\text{imp}}} \]  

(35)

4. Results and Discussion

A numerical code in C was developed for simulating the required combination of solar photovoltaic assisted electrolyzer PEM fuel cell for running a hospital.

Table 5 shows different appliances operated at different hours of a day for all the months i.e. March, May, September and December.

Table 5

<table>
<thead>
<tr>
<th>Time span of day</th>
<th>Nature of load</th>
</tr>
</thead>
<tbody>
<tr>
<td>12AM-7AM</td>
<td>200 lights+5 refrigerators</td>
</tr>
<tr>
<td>7AM-9AM</td>
<td>200 lights+4 pumps+120 fans+5 refrigerators</td>
</tr>
<tr>
<td>9AM-5PM</td>
<td>120 fans+5 refrigerators</td>
</tr>
<tr>
<td>5PM-10PM</td>
<td>200 lights+120 fans+5 refrigerators</td>
</tr>
<tr>
<td>10PM-12AM</td>
<td>200 lights+5 refrigerators</td>
</tr>
</tbody>
</table>

The ratings of different power system components are given in Table 6. In Table 6 it is seen that number of photovoltaic modules in parallel is 875 which is obtained from equation 2 where \( I_{\text{pv}} \) total is 4198.033 and \( I_{\text{mp}} \) is 4.8 A. Number of modules in series is given by equation 8 where \( V_{\text{system}} \) is 48V and \( V_{\text{module}} \) is the maximum voltage from a given module being 34 V. Electrolyzer input at 48 V is 178.537 kW which is taken at 12:00 hours (maximum radiation in a day) for the month of May because month May has the highest solar radiation and electrolyzer input will be maximum due to greater production of hydrogen by electrolyzer, hence electrolyzer which works well in May will work well throughout the year. The number of fuel cells in a stack in series is 47 given by equation no.26 where \( V_{fc} \) is given by equation no.14 is 1.028 V. The number of fuel cell in stacks in parallel is given by equation no.24 and 25. In equation no.24 peak load current during non-sunshine hours is 228.984 A which is between 17:00 hours to 22:00 hours. icell is the current obtained from parameters given in Table no. 2.

The maximum output of each fuel cells stack in series is 7.966 A and power of each fuel cell stack is given by product of 48 V and 7.966 A which is 382.372 W. Gas compressor rating at 48V (14.234kW) is given by equation 31 and is taken from the month of May at 12:00 hours because at this time the hydrogen production is maximum (1189.084 gm.mol) and consumption of power by gas compressor to compress large hydrogen generated by electrolyzer is maximum. Hence gas compressor if it works well in this time and it can work well also throughout the year. The number of photovoltaic modules in parallel for operating the gas compressor is given by equation 35. The total ispv current for the gas compressor is 588.235 Ah and number of photovoltaic modules in parallel needed is obtained by dividing 588.235 Ah by \( I_{\text{mp}} \). Current ispv for the gas compressor is taken for the month of May due to the fact that month May has highest solar radiation, hence it will need a more current and more number of photovoltaic modules for generating current to compress a large amount of hydrogen generated by electrolyzer in the month of May. The number of modules in series is obtained by the same method as equation 8.

Fig. 2, 4, 6, and 8 shows the hourly current consumption (load current Ah) throughout the day for running the appliances of the hospital by using equation 11. In all the figures it is seen that current consumed in Ah from 10 PM to 7 AM is 181.733 Ah per hour. Similarly, current consumed from 7 AM to 9 AM is 277.446 Ah per hour, 9 AM to 5 PM is 107.828 Ah per hour, 5 PM to 10 PM is 228.984 Ah per hour. The current consumption will be same for all the months due to the operation of the same number of equipments for the same number of hours shown in Table 5 for all the different months i.e. March, May, September, and December.

Solar photovoltaic (SPV) current generated during sunshine hours (6:00hours to 18:00hours) in Figures 2, 4, 6, and 8 from the photovoltaic array for the months i.e. March, May, September, and December is obtained from equation 13. It was observed that the trend of SPV current generated increases from 6:00 hours to 12:00 hours and again decreases to 18:00 hours because solar radiation increases from 6:00 hours to 12:00 hours and again decreases to 18:00 hours.

Table 6

<table>
<thead>
<tr>
<th>Components of power system</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of photovoltaic modules in parallel((N_p))</td>
<td>875</td>
</tr>
<tr>
<td>No. of photovoltaic modules in series((N_s))</td>
<td>2</td>
</tr>
<tr>
<td>Electrolyzer input at 48V</td>
<td>178.537 kW</td>
</tr>
<tr>
<td>No. of fuel cell in a stack((N_{fcell}))</td>
<td>47</td>
</tr>
<tr>
<td>No. of fuel cells stacks((N_{parallel}))</td>
<td>27</td>
</tr>
<tr>
<td>Maximum output of each fuel cell stack</td>
<td>7.966A,382.372W</td>
</tr>
<tr>
<td>Gas compressor rating at 48V</td>
<td>14.234 kW</td>
</tr>
<tr>
<td>No. of photovoltaic modules in parallel for gas compressor((N_{p, compressor}))</td>
<td>123</td>
</tr>
<tr>
<td>No. of photovoltaic modules in series for gas compressor ((N_{s, compressor}))</td>
<td>2</td>
</tr>
</tbody>
</table>

Based on the analysis of Figures 2, 4, 6, and 8 it is seen that months March and September have the same pattern of SPV power generation due to the same amount of solar radiation values from 6:00 hours to 18:00 hours. Month May has highest SPV power generation due to the availability of maximum solar radiation in a year. Month December has lowest
SPV power generation due to the availability of lowest solar radiation in a year. The SPV power generated is almost same at 6:00 hours and 18:00 hours in figures 2, 4, 6, and 8 due to the same value of solar radiation at 6:00 hours and 18:00 hours. The solar radiation data is taken from Tiwari (2004).

Based on the analysis of figures 3, 5, 7, and 9 it is seen that months March and September have the same pattern of hydrogen generation due to the same reason mentioned earlier in Figs. 2, 4, 6, and 8 for SPV power generation. Month May has highest hydrogen generation and month December has lowest hydrogen generation due to the same reason mentioned in Figs.
2, 4, 6 and 8 for SPV power generation. It is also seen that hydrogen production is less at 18:00 hours compared to 6:00 hours due to the greater amount of current consumed from 17:00 hours to 22:00 hours which is 228.984 Ah per hour by the hospital as discussed earlier, hence less amount of current is available to electrolyzer for hydrogen production.

The cumulative daylong hydrogen generation in electrolyzer is summation of hydrogen generated from 6:00 hours to 18:00 hours and cumulative consumption of hydrogen in fuel cell stacks is the summation of hydrogen consumption during non-sunshine hours from 19:00 hours to 5:00 hours for different months representing different seasons of a year is shown in Table 7.

<table>
<thead>
<tr>
<th>Month</th>
<th>March</th>
<th>May</th>
<th>Sept</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative daylong H₂ generation(gm mol)</td>
<td>7920.714</td>
<td>9527.437</td>
<td>7952.121</td>
<td>5596.532</td>
</tr>
<tr>
<td>Cumulative daylong H₂ consumption(gm mol)</td>
<td>4977.61</td>
<td>4977.61</td>
<td>4977.613</td>
<td>4977.613</td>
</tr>
</tbody>
</table>

It can be seen that cumulative day long hydrogen consumption is same for all the four months due to operation of same number of equipments for same definite hours throughout the year.

5. Conclusion

In the present work appliances of a hospital located in a remote area in Kolkata is operated with the integrated system of solar photovoltaic and electrolyzer-polymer electrolyte membrane fuel cell. It is seen that cumulative hydrogen generation in electrolyzer is more than hydrogen consumption in PEM fuel cell stack of four different months of a year.

A total of 875 solar photovoltaic modules in parallel, 2 modules in series of Central Electronics Limited Make PM 150 with a 178.537 kW electrolyzer and 27 PEM fuel cell stacks, each of 382.372 W can support the energy requirement of a 200 lights (100 W each), 4 pumps (2 kW each), 120 fans (65 W each) and 5 refrigerators(2 kW each)system operated for 16 hours, 2 hours, 15 hours and 24 hours respectively. 123 solar photovoltaic modules in parallel each having 2 modules in series of Central Electronics Limited Make PM 150 is needed to run the gas compressor for storing hydrogen in the cylinder during sunshine hours. If the number of types of equipment and operating hours change, then the configuration of integrated solar photovoltaic and electrolyzer-PEM fuel cell will change

References


system consisting of photovoltaic arrays and fuel cells. 