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Annual Performance of a Photovoltaic Hydrogen Electrolyzer System in Egypt

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ABSTRACT

The photovoltaic (PV) hydrogen energy systems are considered one of the cleanest hydrogen production technologies, where the hydrogen is obtained from the sunlight by directly connecting the photovoltaic arrays to the hydrogen electrolyzer. This paper theoretically simulates the direct coupling of an alkaline electrolyte electrolyzer to a matched solar photovoltaic source for hydrogen generation. The performance of both monocrystalline silicon photovoltaic module and hydrogen electrolyzer have been investigated theoretically at Cairo, Egypt, latitude and facing south. The annual performance was predicted using a Fortran computer sub-program constructed based on the analysis and connected to TRNSYS simulation program. The monthly average incident solar energy on the PV module and the monthly average maximum output energy of PV module are calculated annually. Also, the annual hydrogen flow rate outlet from the electrolyzer as well as the hydrogen quantity are estimated. Finally, the electrolyzer and the overall system efficiencies are predicted. The theoretical results are compared with the practical results obtained from installing a small PV electrolyzer system under the weather conditions of Cairo, Egypt.

Key words: Photovoltaic module, Hydrogen production, Theoretical analysis and PV-H2 electrolyser.

Introduction

Hydrogen is considered to be as an ideal and clean fuel that can be used in mobile and stationary applications. Hydrogen, used as the principal energy carrier, could offer an answer to the threat of global climate change and help avoid the undesirable effects of the use of fossil fuels (Upendra et al., 2006). Although it is estimated that hydrogen is more expensive than fossil fuels, hydrogen from renewable energy resources is a virtually inexhaustible, environmentally benign, final energy carrier that could meet most of our future energy needs while avoiding the environmental costs and health problems associated with fossil fuels. Amongst the various techniques of producing hydrogen, photoelectrochemical splitting of water into hydrogen and oxygen using solar energy is a potentially clean and renewable source for hydrogen fuel (Ohmori et al., 2001).

Among the renewable energy systems, the photovoltaic cells, which generate direct current electric energy when exposed to solar radiant energy, can be considered the most important source of new and renewable energy. It generates electricity with a little impact on the environment, have no moving parts to wear out, modular, which means that they can be matched to a need for power at any scale, can be used as independent power source or in combination with others, and they are reliable with long live (Lasnier and Ang, 1990). The seasonal storage of solar energy in the form of hydrogen (H2) can provide the basis for a completely renewable energy system. One of the most promising applications is that of stationary stand-alone power systems, particularly those located in remote areas where the cost of transporting fuel is high. Photovoltaic (PV) in combination with electrolytically produced hydrogen, H2-storage, and fuel cells, is a design that has been investigated in various demonstration systems around the world over the last decade (Ulleberg, 2004).

Various experimental and theoretical references studied the production of the hydrogen by an electrolyzer using the PV modules (Lodhi, 1997), (Bilgen, 2001) and (Yamadaa, 2003). (Lehman et al., 1997) reported the performance, safety, and maintenance issues of photovoltaic power plant which used hydrogen energy storage and fuel cell regenerative technology. A mathematical model has been developed to determine and optimize the thermal and economical performance of large scale photovoltaic electrolyzer systems, either with fixed or sun tracking panels using hourly solar radiation data (Bilgen, 2001). The electrolysis of a synthetic alkaline was carried out at different temperatures varying between 10 °C and 80 °C and the effect of the electrolyte temperature on the rate of hydrogen production was studied (Yamadaa, 2003). (Bilgen, 2004) developed a simplified model to determine and optimize the thermal and economical performance of domestic photovoltaic-electrolyzer systems, either with fixed or sun tracking panels using annual total solar radiation on a horizontal surface and climatic data. The technical and economical feasibility for implementing a hypothetical electrolytic
hydrogen production plant, powered by electrical energy generated by alternative renewable power sources, wind and solar, and conventional hydroelectricity, was studied mainly through the analysis of the wind and solar energy potentials for the northeast of Brazil (Da Silva et al., 2005).

The present paper studies theoretically the integration between a solar photovoltaic module and water electrolysis unit for hydrogen production. Water electrolysis is a mature technology, and it is being used for hydrogen production capacities ranging from few cm³/min to thousands m³/h. Water electrolysis is a particular electrochemical process (decomposing electrochemical process, also known as electrolytic process) in which water is split into its basic components, hydrogen and oxygen, through the use of continuous electric current. In order to assure that water electrolysis occurs through an ideal adiabatic process, the minimum potential difference between the cathode, where hydrogen is released (reduction), and the anode, where oxygen is released (oxidation), should be 1.482 V, which is called thermo-neutral potential. The electrolytes more commonly utilized are liquid solutions, which may be acidic or alkaline, the latter being more usual. Among the possible alkaline solutions, potassium hydroxide (KOH) is preferred since its ionic conductivity, together with its low power consumption, is maximized at the concentration rates of 28–30 wt.% (Da Silva et al., 2005).

Typically the operation voltage of an electrolytic cell is higher than the thermo-neutral potential (1.482 V) and the use of catalytic surfaces is made necessary so that the over potential caused by the receptivity to electric and ionic conduction is reduced. The objectives of the present study can be summarized as follows: a) analyze theoretically the annual performance of the PV module with 30° tilt angle and facing south, in Cairo, Egypt, b) predict the annual hydrogen production, the annual hydrogen flow rates and the hydrogen electrolyzer and overall system efficiencies and c) compare the theoretical results with the practical obtained from the installed small PV electrolyzer unit.

2. Theoretical analysis:

To analyze the performance of PV module as a power source for hydrogen production, its main parameters such as short circuit current, open circuit voltage, maximum output power and instantaneous efficiency should be determined. For simplicity, the analysis of the PV module is based on the following assumptions (Rauschenbach, 1980):

1. The shunt resistance of PV module is infinite, so the current in the shunt resistance can be neglected. The shunt resistance of the PV module is defined as the total leakage paths exist in the cell P-N junction (recombination current) and along the outer cell edges (surface leakage). These leakage paths are neither uniformly distributed across the cell area nor uniform from one cell to the next (Ahmad, 1996).
2. The short circuit current of PV module is equal to light generated current.
3. The series resistance of the PV module is independent of neither incident solar radiation nor the module surface temperature. The internal series resistance of the PV module is the sum of the following components: resistance with the back contact of the P-type silicon, the P-type base material resistance, resistance due to the sheet material of the N-type layer, contact resistance between the grid contact and the N-type layer, the resistance along the metallic finger and the resistance along the grid collector (Lasnier and Ang, 1990).

As a result of the above assumptions, the output current of PV cells connected in series-parallel combinations in the module can be calculated as follows (Rauschenbach, 1980):

\[ I = I_l - I_o \left[ \exp \left( \frac{(V + IR_s)}{V_T} \right) - 1 \right] \]  

(1)

The light generated current, \(I_l\), of the PV module can be calculated according to the following equation:

\[ I_l = N_p \left( \frac{G}{G_r} \right) I_{l_l} + \mu \left( T_{PV} - T_{PVR} \right) \]  

(2)

The reference parameters are obtained from the data sheet of the PV module at reference operating conditions (solar radiation intensity 1000 W/m² and ambient temperature 298 K).

For mono-crystalline silicon PV modules, the surface temperature, \(T_{PV}\), can be calculated as function of the meteorological conditions by the following empirical correlation (Ahmad, 1992):

\[ T_{PV} = (27.433 G + 1.1225 (T_a - 273.15) - 2.555 W) + 273.15 \]  

(3)

The reverse saturation current of the PV module is the current of minority carriers created by thermal excitation and accelerated within the built in field of the P-N junction. It can be calculated as follows (Lasnier and Ang, 1990):
The thermal voltage of the PV module can be calculated as follows (Green, 1982):

\[
V_t = N_c N_s K T_{pv} / q
\]  
(5)

Based on the third assumption, the series resistance of the PV module can be calculated as follows:

\[
R_s = \left(\frac{N_s}{N_p}\right) V_{Ir} \ln\left(1 - \frac{I_{mpr}}{I_{Ir}}\right) - V_{mpr} + V_{ocr} / I_{mpr}
\]  
(6)

The open circuit voltage of the PV module can be calculated as follows (Lasnier and Ang, 1990):

\[
V_{oc} = V_t \ln\left(\frac{I_1}{I_0}\right) + 1
\]  
(7)

The voltage at maximum power point of the PV module can be estimated by trail and error from the following equation (Wenham et al., 1994):

\[
V_{mp} = V_{oc} - V_t \ln\left\{\left(\frac{V_{mp}}{V_t}\right) + 1\right\}
\]  
(8)

The current and the power of the PV module at maximum power point can be computed from the following equations (Ahmad, 1992):

\[
I_{mp} = I_t + V_t \ln\left(V_{mp}/V_t\right)
\]  
(9)

\[
P_{mp} = V_{mp} I_{mp}
\]  
(10)

The instantaneous efficiency of the PV module at maximum power point is calculated as follows:

\[
\eta_{mp} = \frac{P_{mp}}{GA_{pv}}
\]  
(11)

The annual production of hydrogen flow rate can be calculated as follows (Da Silva et al., 2005):

\[
Q = \frac{P t_s \eta_e}{E_{min}}
\]  
(12)

The hydrogen electrolyzer efficiency is calculated as follows:

\[
\eta_{electrolyzer} = \frac{Q \cdot E}{V \cdot I}
\]  
(13)

The overall system efficiency for the direct coupling between the PV module and the electrolyzer is calculated as follows:

\[
\eta_{overall} = \frac{Q \cdot E}{G \cdot A_m}
\]  
(14)

Based on the present mathematical model, a FORTRAN computer sub-program has been constructed and added to the standard TRNSYS library as TYPE 69 (Ahmad et al., 2003). An information flow diagram between the present sub-program (TYPE 69) and TRNSYS sub-programs has been constructed to compute the daily and yearly incident solar radiation and maximum output energy of the PV module at different tilt angles and orientations. The information flow diagram consists of a Data Reader (TYPE 9), a Radiation Processor (TYPE 16), a PV Module (TYPE 69), two Integrators (TYPE 24), and two Printers (TYPE 25). The Data Reader is used to read the meteorological conditions (solar intensity, ambient temperature and wind speed) of a typical year of Cairo, Egypt. TYPE 16 is used to compute the incident solar intensity at different tilt angles and orientations from the horizontal solar radiation of the meteorological conditions. The two Integrators are used to compute the daily and yearly incident solar energy and maximum output energy of PV module, while the two Printers print the outputs of the two Integrators.
3. Experimental Setup:

For comparison and verification of the obtained results from the theoretical model, a small PV hydrogen electrolyzer system is installed. Fig. 1 shows the overall photovoltaic–hydrogen electrolyzer system. The system consists of the photovoltaic module, the water electrolyzer and the measuring instruments for measuring the electrical and meteorological parameters and the hydrogen quantity and flow rate.

The used photovoltaic module is a monocrystalline silicon type with maximum power output of 53 W with an open circuit voltage of 21.7 V and short circuit current of 3.27 A at Standard Test Conditions, STC, (Ambient temperature 298 K, Solar radiation 1000 W/m²). The PV module generates the dc power that is transferred to the water electrolyzer directly. It is supported up on a tilted structure from steel frames. The tilt angle is fixed at 30° (latitude of Cairo, Egypt) with horizontal and the structure is mounted such that the module is facing south direction.

The electrolyzer is used for the water electrolysis and the hydrogen produced at the cathode is measured using a digital flow meter. As shown in Fig. 1, the electrolyzer consists of an acrylic box with the dimensions of 20x15x15 cm. The box is divided into two chambers by an acrylic separator. The electrodes that have a cross section area of 2 cm² are made of nickel and immersed in the electrolyte and were fitted on the chambers surface by a rubber stoppers. The electrodes were connected to the photovoltaic module directly. The electrolyte used is potassium hydroxide with a concentration of 27%, according to the highest conductivity with concentration (Da Silva et al., 2005).

The overall system parameters are measured accurately and recorded continuously for data storing. The PV module and the electrolyzer voltages and currents are measured using digital voltmeters and ammeters with accuracies of 0.01 V and 0.001 A, respectively. A thermopile pyranometer of type Kipp & Zonen (model CM5-774035) is used to measure the solar radiation intensity. The pyranometer is mounted at the PV module structure and parallel to the module surface. A type K thermocouple is used to measure the PV module surface and ambient temperatures. The hydrogen flow rate is measured with Wheaton Scientific Digital Flow meter with accuracy of 0.1 ml/min.

Results and Discussion

The theoretical results obtained from the system simulation model and the experimental results obtained from the installed PV hydrogen electrolyzer system are discussed. Fig. 2 shows the simulated current-voltage and power-voltage characteristics (I-V and P-V curves) of the PV module at reference operating conditions. From the figure, it is clear that the PV simulation model can predict the module parameters (open circuit voltage, short circuit current and the maximum power) that confirm with the exact values of the PV module, previously described in section 3. Table 1 shows the theoretical and experimental parameters of the PV module. Fig. 2 and table 1 show that the theoretical model of the PV module can simulate its performance accurately.
Table 1: Theoretical and experimental parameters of the PV module.

<table>
<thead>
<tr>
<th>Value</th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit voltage, V</td>
<td>21.89</td>
<td>21.7</td>
</tr>
<tr>
<td>Short circuit current, A</td>
<td>3.38</td>
<td>3.27</td>
</tr>
<tr>
<td>Maximum power, W</td>
<td>53.95</td>
<td>53</td>
</tr>
</tbody>
</table>

A typical year of meteorological measured data of Cairo, Egypt (instantaneous solar radiation intensity, W/m², ambient temperature, °C, and wind speed, m/s) are shown in Fig. 3 and Fig. 4, respectively. Fig. 5 shows the calculated variation of monthly average solar energy incident in kW.h/m².day on the surfaces of the PV module mounted facing south with 30° tilt angle. From the figure, it is clear that the monthly average incident solar energy variation is according to the months of the year. It has a maximum value of 6.72 kW.h/m².day during summer months, while it has a minimum value of 4.49 kW.h/m².day during winter months. During spring and autumn months, it is found that it has an average value of 5.8 kW.h/m².day.

![I-V and P-V characteristics of PV module at reference conditions.](image1)

**Fig. 2:** Predicted I-V and P-V characteristics of PV module at reference conditions.

![Solar radiation intensity of a typical year for Cairo, Egypt.](image2)

**Fig. 3:** Solar radiation intensity of a typical year for Cairo, Egypt.
Fig. 4: Ambient temperature and wind speed of a typical year for Cairo, Egypt.

Fig. 5: Calculated variation of monthly average solar energy incident in kW.h/m².day on the surface of the PV module mounted facing south with 30° tilt angle.

The variation of the calculated monthly average maximum output of the PV module, W/m².day, is shown in Fig. 6, while the variation of the calculated monthly average efficiency of the PV module is shown in Fig. 7. From Fig. 6 and Fig. 7, although the PV module output energy increases in the summer months, the module efficiency is lower than that of the winter months. This is because the increase of incident solar energy increases the surface temperature of the PV module that leads to a decrease of module efficiency (Pyle et al., 1994). It is noticed that the monthly average efficiency in spring months is higher than that in autumn months. This is because the daily average ambient temperature of Cairo, Egypt, during autumn months is higher than that during spring months.

Figure 8 shows the measured solar radiation intensity and the ambient temperature for a sample day (August 18th), while the corresponding electrolyzer voltage and current were shown in Fig. 9. The corresponding calculated and measured hydrogen flow rate was shown in Fig. 10 for the same day. It is clear that the photovoltaic module current is directly affected by the solar radiation intensity as well as increasing the electrolyzer current increases the hydrogen production flow rate, as shown in Fig. 10. Also, the convergence between the calculated and the measured hydrogen flow rates is evidence. This indicates the capability of the PV hydrogen mathematical model of estimating the annual hydrogen production. By the same manner, the annual hydrogen production through the months of the year can be estimated. Fig. 11 shows the annual hydrogen production through the months of the year. From the figure, we can conclude that, with the proposed small scale system which has an electrolyzer box of 4500 cm³ containing 80% of its volume electrolyte solution with electrodes of 2 cm² cross section area gives an average 300 liters of hydrogen monthly. When the volume of electrolyte and electrodes increases the hydrogen productivity will be increased.
Figure 12 shows the electrolyzer and overall system efficiencies. From the figure, although the electrolyzer efficiency is almost (60-65%), the overall system efficiency is lower than it (1-2%), which is compatible with the previous work in these systems (Yamadaa et al., 2003) and (Ohmori, 2001). This is due to the small efficiency of the PV module. The following factors limit the efficiency of the photovoltaic solar energy conversion device; a) reflection losses at the top surface, which can be reduced using selective etching on the face of the cell material, b) shade due to the current collection grid at the top surface, c) incomplete absorption of photon energy if this energy is less than the energy gap (1.1 ev in case of silicon cells), which, will heat the material and increases the cell temperature, which will result in low efficiency, d) incomplete use of excess photons energy that have energies larger than the energy gap, this excess energy adds to the lattice vibrations resulting in heating the semiconductor and e) series and shunt resistance losses (Garg, 1987).

From the simulated solar intensity on the surface of the PV module, and from the calculated output electrical energy from the module, and the corresponding daily hydrogen production quantity and flow rates, the annual hydrogen flow rates can be estimated. Fig. 13 shows the predicted annual hydrogen flow rates. It is found that the hydrogen flow rate is strongly affected by the climatic conditions of solar radiation and ambient temperature. The hydrogen flow rate ranges from 15 ml/min in winter months to about 30 ml/min as maximum value for summer months for the proposed electrolyzer dimensions.

![Graph](image1.png)

**Fig. 6:** The monthly average output energy variation of south facing PV modules.

![Graph](image2.png)

**Fig. 7:** The monthly average efficiency variation of south facing PV modules.
Fig. 8: Solar radiation and ambient temperature measured of a certain day in Aug. as a sample of measurement.

Fig. 9: Load voltage and load current measured for the direct coupling system during the same day of Fig. 8.

Fig. 10: Measured and calculated hydrogen flow rate for the direct coupling system during the same day of Fig. 8.
Fig. 11: Annual hydrogen production through the months of the year.

Fig. 12: Overall system and electrolyzer efficiencies for the proposed system.

Fig. 13: Annual hydrogen flow rates for a typical year for Cairo, Egypt
Conclusions:

A Theoretical study for the photovoltaic hydrogen electrolyzer system for hydrogen production by water electrolysis has been successfully demonstrated, for Cairo, Egypt climatic conditions. For comparison, a small PV hydrogen electrolyzer system was installed. It can be concluded that the monthly average incident solar energy has a maximum value of 6.72 kW.h/m².day during summer months, while it has a minimum value of 4.49 kW.h/m².day during winter months for a module facing south and tilted by an angle of 30°C. During spring and autumn months, it is found that the monthly average solar energy are in between, 5.8 kW.h/m².day. The photovoltaic module efficiency in summer months is lower than that in winter months due to higher ambient temperatures in summer. The proposed small scale system that has the electrolyzer box of 4500 cm³ containing 80% of its volume potassium hydroxide with a concentration of 27% electrolyte solution and electrodes of 2 cm² cross section area gives hydrogen flow rate ranges from 15 ml/min in winter months to about 30 ml/min as maximum value for summer months and an average 300 liters of hydrogen monthly. The obtained results showed the evidence convergence between the theoretical and practical results.

Nomenclatures:

A Surface area of PV array, m².
C Device specific constant of solar cell material.
E Calorific value for hydrogen, J/ml.
E_{\text{min}} Minimum theoretical energy necessary to produce 1 m³ of hydrogen, MWh/m³.
G Solar intensity, W/m².
I Current, A.
K Boltzmans Constant, 1.381 x 10^{-23} J/K.
N Number.
P the power of electrolysis plant, W.
q electronic charge, 1.602 x 10^{-19} Coulomb.
Q Hydrogen flow rate, ml/sec.
R Resistance, Ω.
t_{y} Annual plant availability, hours/yr.
T Temperature, K.
V Voltage, V.
W Wind speed, m/s.

Greek letters:

η_{E} Efficiency of the electrolyzer for hydrogen production.
η_{\text{electrolyzer}} Electrolyzer efficiency.
η_{\text{overall}} Overall system efficiency.
μ Temperature coefficient of PV module (A/K)

Subscripts:

a Ambient.
c Solar cells per module.
g Band gap for solar cell material.
l Light generated.
l_{r} Light generated of PV module at reference conditions.
mp Maximum power point.
mpr Maximum power point of PV module at reference.
o Reverse saturation.
oc Open circuit.
ocr Open circuit of PV module at reference conditions.
opt Optimum.
p Parallel.
pv PV module.
pvr PV module at reference conditions.
r Reference conditions, solar radiation intensity 1000 W/m² and ambient temperature 298 K.
s Series.
sc Short circuit.
scr Short circuit of PV module at reference conditions.

I Thermal.

References


