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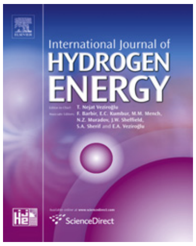

Hydrogen production probability distributions for a PV-electrolyser system

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ABSTRACT

In this study, we comprehensively analyze the probability distribution of the hydrogen production for PV assisted PEM electrolyser system. A case study is conducted using the experimental data taken from a recently installed system in Balikesir University, Turkey. A novel computational tool is developed in Matlab-Simulink for analyzing the data. The concept of probability density frequency is successfully applied in the analyses of the wind speed and the solar energy in literature. This study presents a method of applying this knowledge to solar energy assisted hydrogen production. The change in the probability distribution of the hydrogen production with the solar irradiation throughout a year is studied and illustrated. It is found that the maximum amount of hydrogen production occurs at between 600 and 650 W/m^2 of solar radiation. Annual hydrogen production is determined as 2.97 kg for per m^2 of PV system. Average hydrogen production efficiency of the studied PEM electrolyser is found to be 60.5% with 0.48 A/cm^2 of current density. The presented results of this study are expected to be valuable for the researchers working on renewable hydrogen production systems.

1. Introduction

Hydrogen is a sustainable option as a fuel and it is regarded as one of the potential solutions for the current energy and environmental problems present on Earth. Its eco-friendly production is one of the key features on the road for a better environment as well as for the success of sustainable development [1]. Implementing sustainable energy strategies for creating a sustainable living space is important for combating against climate change and global warming. Hydrogen energy and production of hydrogen from renewable energy sources is important for the solution of these problems.

Many scientists have focused on the feasibility and the system performance of hybrid renewable energy systems for the production of hydrogen, mainly concentrating on solar, wind, geothermal and the nuclear energy options [2–12]. Several methods have been and are being developed for the production of hydrogen from solar energy; the only one that is currently practical is through the electrolysis of water. The water electrolysis is considered a technology that has solid grounds and has been widely used for a long time [1]. In this regard, the performance of proton exchange membrane (PEM) electrolyser systems has been investigated from different perspectives by many researchers [13–19].

Knowledge of global solar radiation distribution is needed for design and analysis of solar energy systems. Many parameters affect the energy and exergy efficiencies or working conditions of PV arrays. One of the most important

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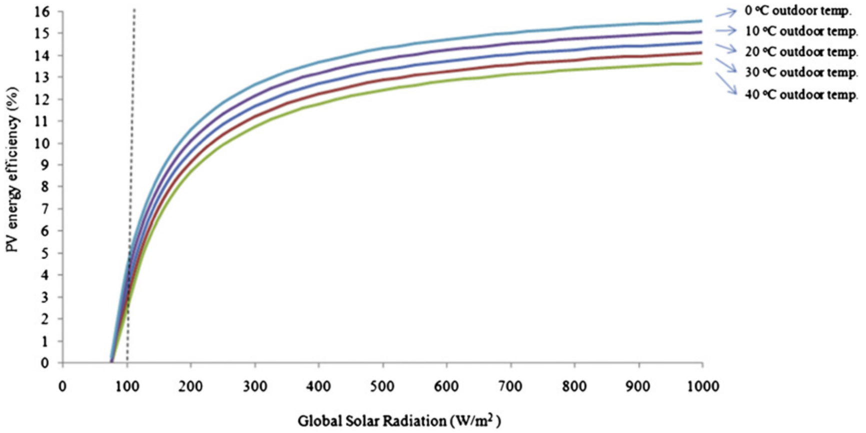

Fig. 1 – Change of PV energy efficiency with global radiation and ambient temperature.

parameters is the intensity of solar irradiance. It directly affects the PV collector efficiency which increases with the intensity of the solar irradiance. The average solar radiation and system efficiency are used in general calculations. However, it is clear that accurate results cannot be predicted by this method of calculation. Monthly distribution of global solar radiation should be predicted for accurate solar energy calculations. In this study, a new approach for calculating the production of hydrogen is proposed in terms of the solar irradiance intensity from actual data recorded during the year. The hydrogen production probability has not yet been defined based on the intensity of the solar radiation in any cited literature. In addition, the hydrogen production results are then compared with the literature data and simulation results for hybrid systems.

2. Energy analysis

The energy efficiency of a PV system is dependent upon four parameters, namely; the global solar radiation (S_t), the PV area (A), the maximum voltage (V_m), and the maximum current (I_m). The energy of a PV system can be defined by following equation;

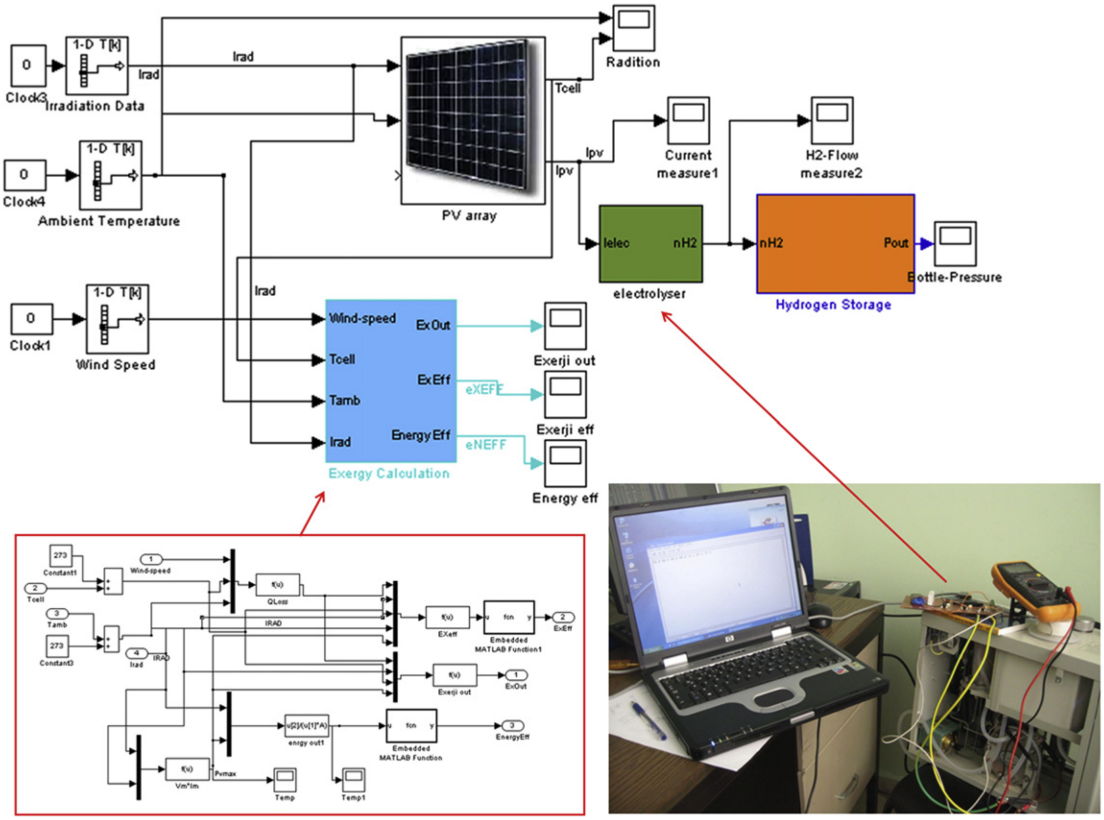

Fig. 2 – Matlab-Simulink Simulation of PV-electrolyser system and the experimental setup.

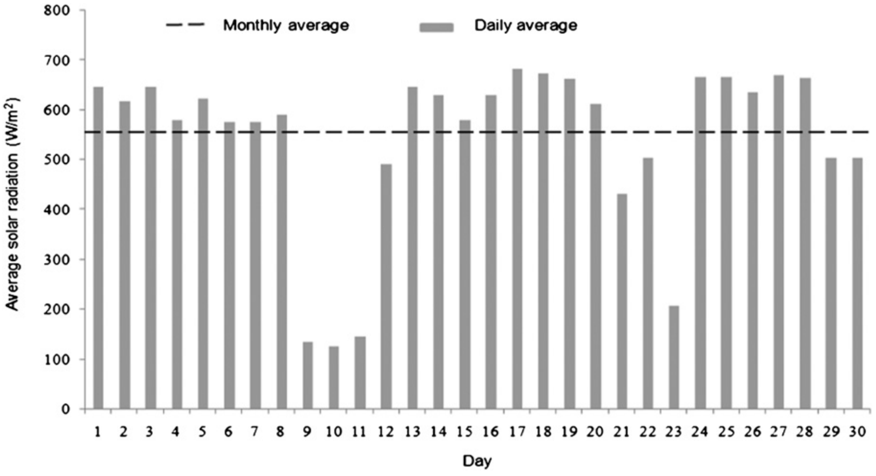

Fig. 3 – Change of daily average solar radiation for the month of June.

$$\eta_{pv} = \frac{V_m \cdot I_m}{S_t \cdot A} \tag{1}$$

The PV array voltage and the current vary proportionately with the intensity of the solar irradiance and the temperature of the cell. Considering the 'Power-Voltage curve', there is a point along the curve where the maximum power is generated. This point is called as the peak power point [20]. The peak power point function of the photovoltaic system is determined experimentally, and the equation is obtained as

$$Pm(S_t, T_a) = -11.017 + 0.34 \cdot S_t \cdot 2.73^{-0.003 \cdot T_a} \tag{2}$$

where T_a represents the ambient temperature in Kelvin. Eq. (2) is valid for $S_t > 75$ W/m^2 and $T_a > 273$ K. The change in the efficiency of the selected PV system with the solar radiation and the ambient temperature is given in Fig. 1. As it can be seen in Fig. 1, the PV system begins working efficiently at solar radiation levels above 100 W/m^2. In addition, the PV energy efficiency decreases with an increase in the ambient temperature.

3. Economic analysis

The life cycle cost (LCC) analysis is a useful tool for the comparison of the ultimate delivered costs of technologies using different cost structures. Rather than comparing only the initial capital costs or the operating costs, LCC analysis seeks to calculate the cost of delivering a service over the life of the project. The final cost per kg-H$_2$ is estimated to be independent of the technology that was used to produce hydrogen. The cost of hydrogen can be given in terms of its total present value (*TPV*), as follows [21,22]:

$$TPV = \text{Initial cost} + \sum \text{O \& M} + \sum \text{Replacement} \tag{3}$$

$$\text{Cost } (\$/kg\ H_2) = \frac{TPV \cdot CRF}{\text{Annual } H_2 \text{ production}} \tag{4}$$

where *CRF* is the capital recovery factor and defined as

$$CRF = \frac{(1+R)^N \cdot R}{(1+R)^N - 1} \tag{5}$$

The major guidelines for the economic assumptions in determining the costs are as follows:

- The net discount rate (R) is 8%. The economic evaluation (N) period is 25 years for the photovoltaic panels, the MPPT, the DC–DC converter, the storage systems and 15 years for the electrolyser.
- The cost of installation, operation and maintenance are not included;
- The total system cost per W_p of the photovoltaic panels, the MPPT and the DC–DC converter are about 6$.

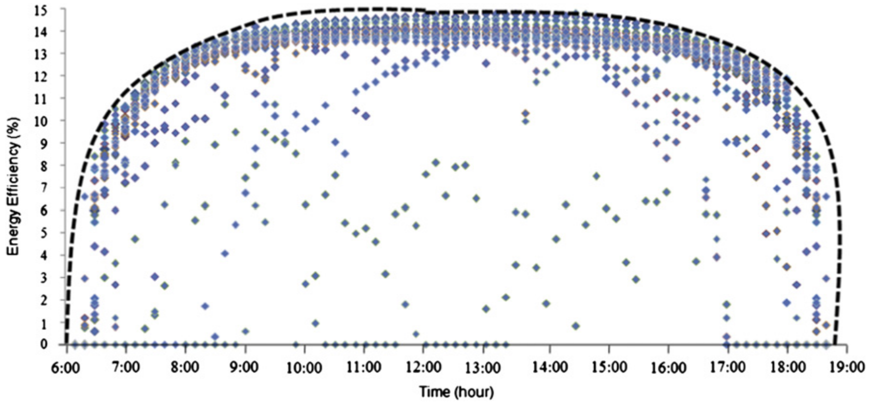

Fig. 4 – Change of PV energy efficiency during the month of June.

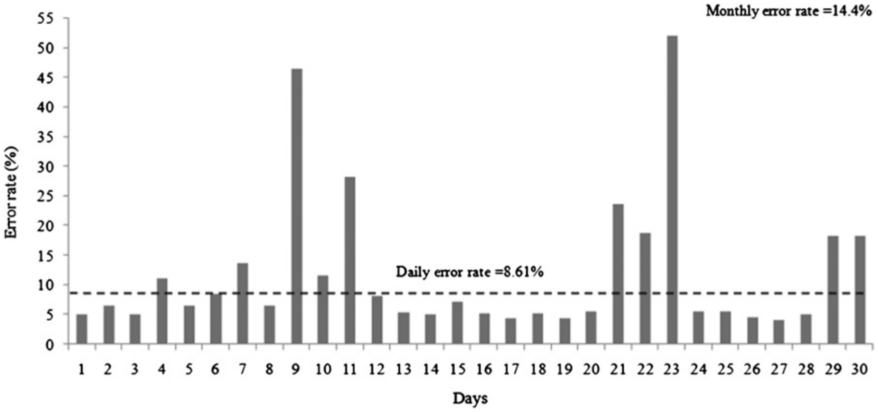

Fig. 5 – Error rates for daily and monthly based energy efficiency of PV system for the month of June.

4. System description

The PV-Electrolyser system and the meteorological measurement system were installed in the campus of Balikesir University at the end of the year 2008. The amount of global solar irradiation, wind speed, ambient temperature, cell temperature, voltage, current and hydrogen production were collected hourly by the Campbell Scientific dataloggers system (CR800) and were employed in further modeling analysis. Matlab-Simulink was used as the platform for running the simulations of the system. The photovoltaic-electrolyser system under study consists of the following major components: the photovoltaic array, the maximum power point tracker (MPPT), the DC–DC converter, and the PEM electrolyser system. The schematic representation of the system under investigation is given in Fig. 2.

4.1. *PV system*

The photovoltaic array, maximum power point tracker (MPPT) and DC–DC converter are considered as the PV system components. 0.90 m^2 of PV panel are utilized in the installed system. The MPPT and the DC– DC converter systems are used to operate the system at its maximum power at all times and to supply the DC current to the electrolyser.

In order to illustrate the change in energy efficiency, the peak power and the monthly solar radiation, the experimental data taken from the installed PV system in Balikesir University is captured daily during June as the baseline values for comparison. The average daily solar radiation is determined for each day of June and given in Fig. 3. The monthly average solar radiation was calculated as 547 W/m^2. The energy efficiency of the actual PV system was determined from Fig. 4. As it can be seen in Fig. 4, the maximum energy efficiency for PV array used in the analysis was found to be 15%.

The energy efficiency function of the PV arrays depends on global solar irradiation and temperature and does not have a linear trend. At this point, it is noticed that using the average daily and monthly data instead of hourly data leads to fluctuations. The error rate between the actual and the daily or the monthly based average values is given in Fig. 5. The panel voltage and the current are recorded and the peak power of the PV is determined for June. The change in the peak power in time is demonstrated for the selected month in Fig. 6. The maximum peak power occurred between 12:00 and 13:00.

4.2. *PEM electrolyser system*

The commercial PEM electrolyser system is used for the production of hydrogen. The electrolyser consisting of one cell, the water treatment unit, the hydrogen generator at

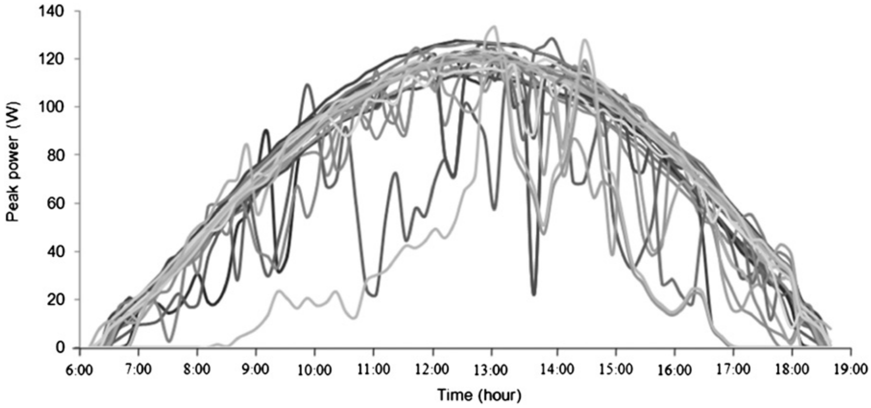

Fig. 6 – Change of peak power during the month of June.

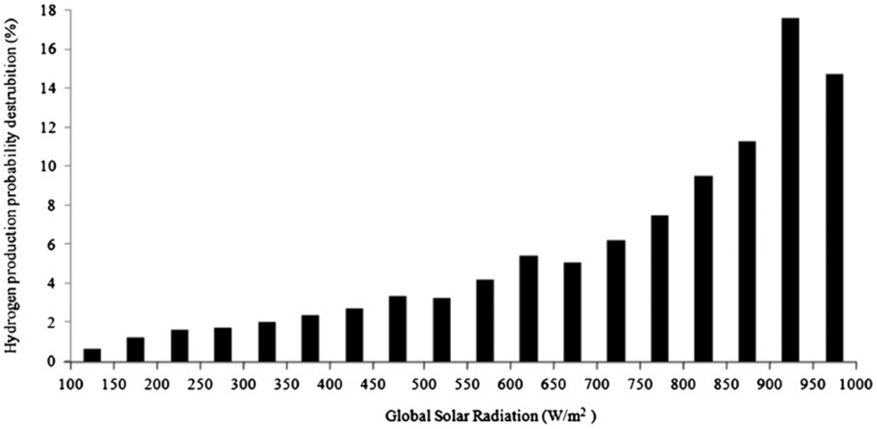

Fig. 7 – Chance of hydrogen production probability distribution with intensity of solar radiation for the month of June.

process pressure without a compressor. The PEM electrolyser considered has a capacity of 150 ml/min. H_2 production. The maximum power is 120 W. The output pressures chance from 0.02 MPa to 0.4 MPa. The water consumption is 10 g/h

In order to illustrate how the probability distribution for the hydrogen production changes with the intensity of solar radiation and time, the actual data obtained on each day of June (Figs. 7 and 8) is used. The highest hydrogen production is achieved between 12:00 and 13:00 during the day with a probability distribution of 13%.

5. Result and discussion

Various parameters, such as voltage, current, amount of hydrogen produced, PV cell temperature, solar radiation, ambient temperature and wind speed were recorded in 2009 via a data acquisition system. During the annual analysis, the entire solar irradiation and the hydrogen production data were clustered with respect to the intensity of the solar radiation and the time of the day in terms of hours. Then, the hydrogen production probability distribution based on the amount of solar radiation and the time was calculated. 50 Watt intensity intervals of solar irradiation were selected for the probability distribution of hydrogen production. The change in the hydrogen production probability distribution with respect to the solar irradiation throughout a year is studied and illustrated. It is deduced that the highest hydrogen production occurs in a range between 600 and 650 W/m^2 of solar radiation for the studied year (Fig. 9). Also, the amount of monthly hydrogen production is determined and given in Fig. 10. As it can be seen from Fig. 4, the highest amount of hydrogen is produced in July based on an annual investigation. The total amount of hydrogen produced in July equals 14.95% of the total amount of hydrogen production throughout the year. The annual amount of hydrogen production was calculated as 2.97 kg/yr for the Balikesir region.

Also in this study, general formulations for the production of hydrogen as a function of the daily fraction of the annual average solar radiation for the utilized system are proposed. Annual H_2 production in (kg H_2/m^2/year) and the cost of H_2 production are given as a function of the average daily total solar radiation in (kWh/m^{2}d) by Eq. (6) and (7). The correlation coefficient R^2 is found to be 0.9993 and 0.9931 for the functions of the annual production of H_2 and the cost of the production of H_2, respectively. As seen from Fig. 11, when the solar

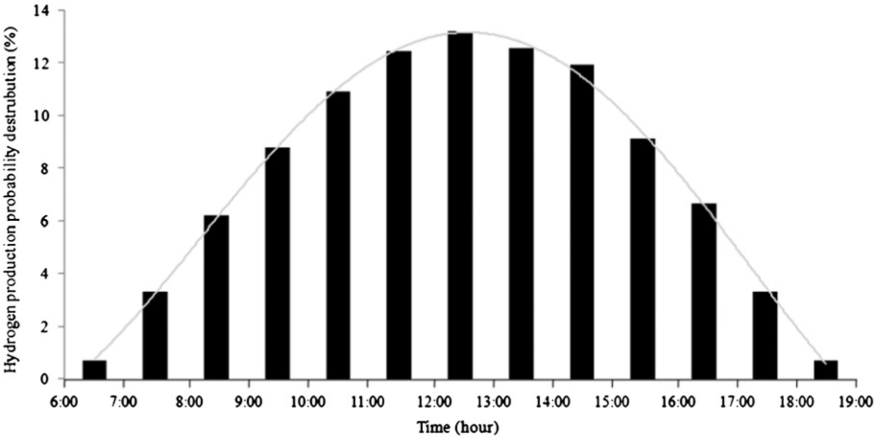

Fig. 8 – Variation of hydrogen production probability distribution with time of day for the month of June.

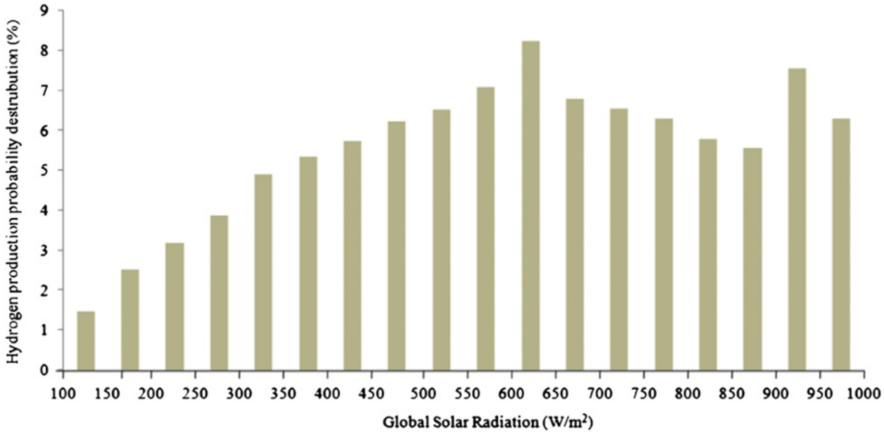

Fig. 9 – Variation of hydrogen production probability with intensity of solar radiation.

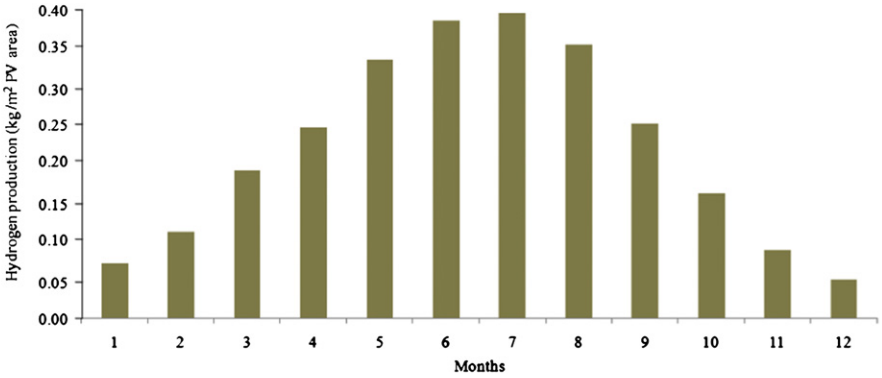

Fig. 10 – Variation of monthly hydrogen production.

radiation exceeds 5 kWh/m^2/d, there is a little change for both functions.

$$m_{H2} = -0.06 \cdot S_t^2 + 0.87 \cdot S - 0.23 \quad (6)$$

$$C_{H_2} = 0.19 \cdot S_t^4 - 4.62 \cdot S_t^3 + 41.12 \cdot S_t^2 - 163.61 \cdot S_t + 291.37 \quad (7)$$

Here, m_{H2} and C_{H_2} indicates annual hydrogen production and cost of hydrogen, respectively. The results of the Matlab-Simulink simulation for the annual H_2 production and the H_2 production cost are compared with the HOMER software [23] to test for the reliability and its validity. The HOMER simulation software is used to assess the techno-economic viability and for sizing of the renewable energy system [20]. The HOMER was developed by the National Renewable Energy Laboratory (NREL) as a potential simulation and optimization

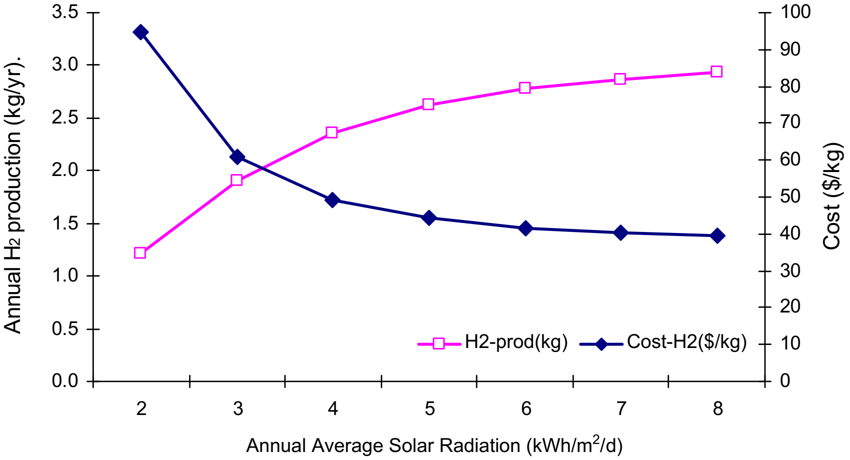

Fig. 11 – Variation of annual hydrogen production and its cost with annual average solar radiation.

tool for renewable energy systems. There is 4.5–4.7% difference between the reality and the results of the software. This difference is in an acceptable range for the calculations regarding the selected system.

6. Conclusions

This paper has been the first study in the literature to define the amount of hydrogen production in terms of the intensity of the solar radiation for a PV assisted electrolyser system. In this regard, a new approach has been proposed where the intensity of the solar irradiance is a parameter for the calculation of the amount of hydrogen production. Some concluding remarks of this study are given below:

- The hydrogen production probability distribution function is time dependent. On the other hand, it does not present itself with any general trend regarding the intensity of the solar radiation.
- The highest amount of hydrogen production occurs at a range between 600 and 650 W/m^2 intensity of solar radiation for the selected year. This amount is equal to 8.5% of the total annual amount of hydrogen production.
- It is also noted that the overall energy efficiency of the system is about 8.1%, annually.
- The average energy efficiency of the selected PEM electrolyser system is determined as 60.5% with 0.48 A/cm^2 of current density.
- The cost of hydrogen is calculated as 43.9 ($/kg) for Balikesir region, Turkey.

For future investigations, the size optimization of the PV-electrolyser system could be studied.

Acknowledgements

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Nomenclature

A	area, m^2
CRF	capital recovery factor (-)
I	current, A
LCC	life cycle cost (US$)
MPPT	maximum power point tracker
N	economic evaluation
R	discount rate (%)
S_t	global solar radiation, W/m^2
T	temperature, °C
TPV	total present value (US$)
V	voltage, V
Greek letters	
η_{pv}	energy efficiency of PV (-)
Subscripts	
a	ambient
m	maximum

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