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Performance Study of Photovoltaic-Water Electrolysis System for Hydrogen Production: A Case Study of Egypt

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Abstract

Solar-hydrogen is expected to play an important role as an energy carrier of the future and is considered an ultimate solution for many energy and environmental problems. Photovoltaic-water electrolysis is a suitable method for solar-hydrogen production in Egypt due to the availability of a lot of water sources such as Lake Nasser, Red Sea, and Mediterranean Sea. Moreover, Egypt is endowed with high solar radiation intensity of 2000-3200 kWh/m2/year from north to south. This Paper presents a small photovoltaic-water electrolysis system for the process of water electrolysis and hydrogen production; the system is designed and installed in the solar energy laboratory of desert research Center. The performance of the generation system is investigated under the climatic conditions of Cairo city, Egypt for a sample day. Hourly variation of solar radiation intensity, photovoltaic module output current, and hydrogen production rate are measured accurately and recorded for analysis. It is found that the minimum and maximum hydrogen production rate values are 1.3 ml/min and 3.4 ml/min, respectively. The maximum hydrogen production rate (which is 3.4 ml/min) is obtained at the maximum photovoltaic module output current (which is 0.35 A) that obtained at the maximum solar radiation intensity (which is 980 W/m2) at the solar noon. The effect of solar radiation intensity on the photovoltaic module efficiency and overall system efficiency are also investigated. It was found that the smaller photovoltaic module efficiency decreases the overall system efficiency.

Keywords: *Hydrogen production, water electrolysis, solar energy*

1. Introduction

Egypt depends on fossil fuels as its primary energy source. Since these resources are finite and are being depleted at an ever-growing rate, Egypt may face an energy deficit soon. Renewable energy is attracting more attention as alternative energy sources, decreasing dependence on fossil based fuels. It becomes a priority for Egypt to exploit this energy resource. Solar energy is considered the most abundant, clean and inexhaustible renewable energy resource [1]. The intermittent nature of solar energy is one of the main issues of sustainable energy and hence, a storage medium or an energy carrier is required to overcome this problem. Hydrogen produced from solar energy is considered to be the ultimate solution for sustainable energy [2]. Solar-hydrogen production methods from water (the most abundant source of hydrogen on earth) include photovoltaic-water electrolysis, photoelectrolysis, biophotolysis, thermolysis and thermochemical cycles [3]. Photovoltaic-water electrolysis is one of the most promising methods for large-scale hydrogen production in Egypt. The solar radiation intensity map for Egypt indicates that, Egypt is endowed with high solar radiation intensity of 2000-3200 kWh/m^2/year from north to south. Moreover, Egypt has a lot of water sources, Lake Nasser that containing more than 120 billion cubic meters of renewable water. Also, Egypt is surrounded from the north by the Mediterranean Sea over 995 km and from the east by the Red Sea over 1941 km. Therefore, all the requirements for establishing solar-hydrogen-energy systems in Egypt are available [4].

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Various theoretical and experimental references studied the process of hydrogen production via Photovoltaic-water electrolysis method in Egypt [5–9]. the main objectives of this work are to analyze the performance of the photovoltaic-water electrolysis system for the hydrogen production process under the climatic conditions of Cairo, Egypt and then investigate the effect of solar radiation intensity on both the photovoltaic module efficiency and overall system efficiency.

2. Experimental Setup

The experimental photovoltaic-water electrolysis system is built in our solar energy laboratory of desert research Center (Cairo, Egypt) for the purpose of solar-hydrogen production. Fig. 1 shows a schematic diagram for the experimental system which consists of:

i. The photovoltaic module.

ii. The water electrolyzer.

iii. The measuring instruments.

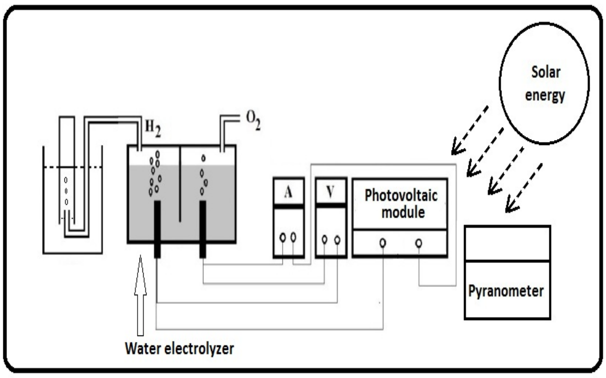

Fig. 1. A schematic diagram for the photovoltaic water electrolysis system

2.1. Photovoltaic module

A Photovoltaic module (Fig. 2) is used to supply power to the water electrolyzer. The photovoltaic module is a mono-crystalline silicon type with maximum output power of 8 W with an open circuit voltage of 4.0 V and short circuit current of 6.0 A at STC. The photovoltaic module is supported upon a tilted structure from steel frames. The tilt angle is fixed at 30 degree with horizontal and the structure is mounted such that the module is facing south direction.

Fig. 2. The Photovoltaic module

2.2. Water electrolyzer

The water electrolyzer is used for the process of water electrolysis and hydrogen production. As shown in Fig. 3, the electrolyzer consists of a Plexiglas box with the dimensions of 15x5x20 cm3. The box is divided into two equal chambers by a Plexiglas separator to separate the produced hydrogen from oxygen. Graphite and stainless (316L) are used as electrodes (anode and cathode). The specifications of electrodes were: shape is cylindrical, diameter is 6 mm and height is varied from 25 mm to 40 mm. The two electrodes are immersed in the electrolyte and are fitted on the chambers surface by means of rubber stoppers. Potassium hydroxide (KOH) solution with different concentrations is used as the electrolyte due to its higher conductivity, it is a strong electrolyte; this means that it is essentially 100 % ionized in solution and thus is a good conductor of electricity; the ionic conduction is then carried by hydroxide ions (OH-) and potassium ions (K+).

Fig. 3. The water electrolyzer

2.3. Measuring instruments

- The photovoltaic module and the electrolyzer voltages and currents are measured using digital voltmeter and ammeter.
- A type K thermocouple is used to measure the photovoltaic module surface and ambient temperatures.
- Solar radiation intensity is measured by a pyranometer.
- Hydrogen collector is used to collect and measure the volume of the produced hydrogen through the water displacement method.

2.4 Calculation of the efficiency

2.4.1. Electrolyzer efficiency:

It is the ratio of the energy of hydrogen produced to the electrical energy input to the electrolyzer; it can be calculated as follows:

$$\eta_e = (Q \cdot E) / (Voper \cdot Ioper) * 100\ (\%) \quad (1)$$

2.4.2. Photovoltaic module efficiency:

It is the ratio of the module output power to the input power from the sunlight; it can be calculated as follows:

$$\eta_m = (Vm \cdot Im) / (G \cdot A) * 100\ (\%) \quad (2)$$

2.4.3. Overall system efficiency:

It is the ratio of the energy of hydrogen produced to the incident solar radiation from the sunlight; it can be calculated as follows:

$$\eta_t = (Q \cdot E) / (G \cdot A) * 100 \ (\%) \qquad (3)$$

Where,

η_e: Electrolyzer efficiency, %

η_m: Photovoltaic module efficiency,

η_t: Overall system efficiency, %

Q: Hydrogen production rate, ml/sec

G: Solar radiation intensity, W/m2

A: Photovoltaic module area, m2

E: Calorific value of Hydrogen, J/ml

V_{oper}: Operating voltage, V

I_{oper}: Operating current, A

V_m: Module voltage, V

I_m: Module current, A

3. Results and discussion

The electrolyzer is considered to produce hydrogen using photovoltaic module. The photovoltaic module converts sunlight into electrical energy which will be utilized for the electrolyzing process. The effect of solar radiation intensity on the hydrogen production rate and on the system efficiency under the climatic conditions of Cairo, Egypt is studied. The process of water electrolysis using photovoltaic module is operated during a sample day in the summer season (26/9/2016) from 8:00 AM until 3:00 PM. Figs. 4 to 8 show the hourly variation of solar radiation intensity, hydrogen production rate and output current with local time. Fig. 4 identifies variation of solar radiation intensity with local time, the maximum solar radiation is about 1000 W/m2 at the solar noon. Fig. 5 shows the photovoltaic output current variations with local time, the maximum output current (0.35 Amp) is obtained at the solar noon. This is due to as shown in Fig. 6 the photovoltaic output current is directly affected by the solar radiation intensity. Fig. 7 shows the variation of the hydrogen production rate with local time. It can be noticed that the maximum hydrogen production rate (3.0 ml/min) is obtained at the solar noon. This is due to as shown Fig. 8 the hydrogen production rate is directly affected with photovoltaic output current.

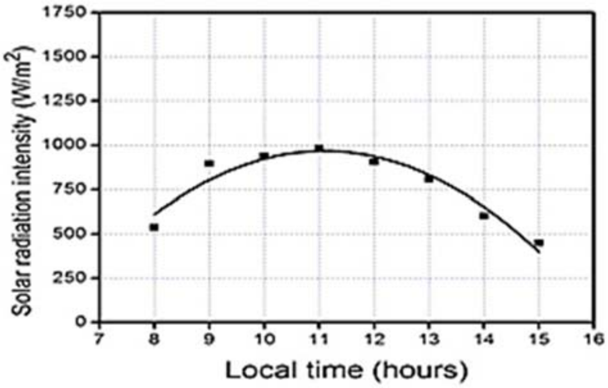

Fig. 4. Variation of solar radiation intensity with local time

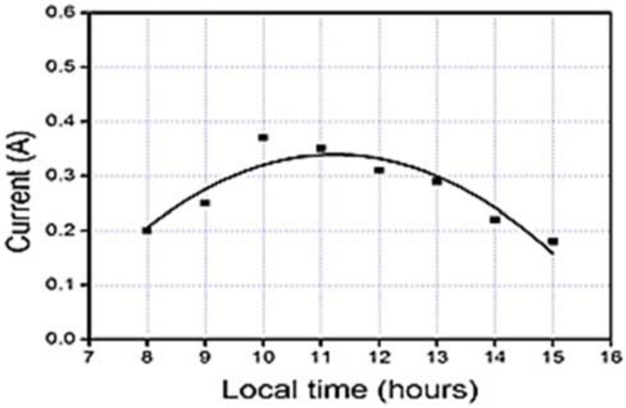

Fig. 5. Variation of photovoltaic output current variations with local time

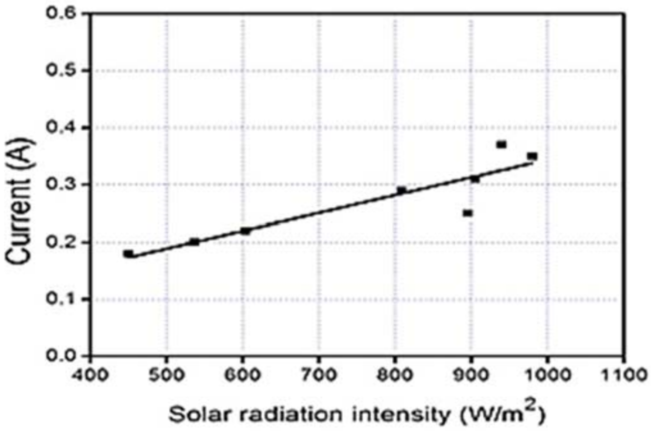

Fig. 6. Variation of photovoltaic output current with solar radiation intensity

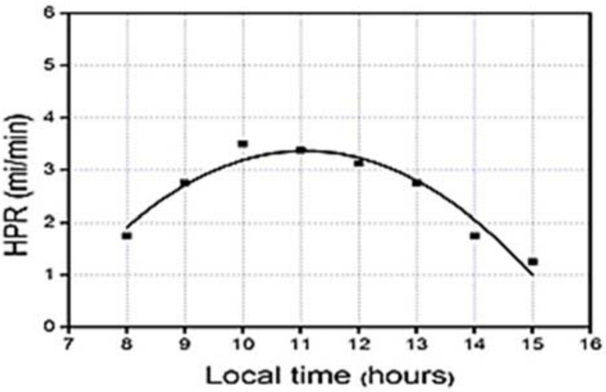

Fig. 7. Variation of hydrogen production rate with local time

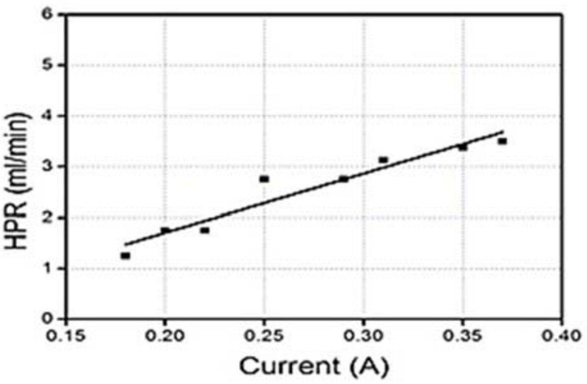

Fig. 8. Variation of hydrogen production rate with photovoltaic output current

Figs. 9 to 11 show the variation in the electrolyzer efficiency (η_e), module efficiency (η_m) and overall system efficiency (η_t) versus solar radiation intensity. It is clear that the smaller photovoltaic module efficiency decreases the overall system efficiency.

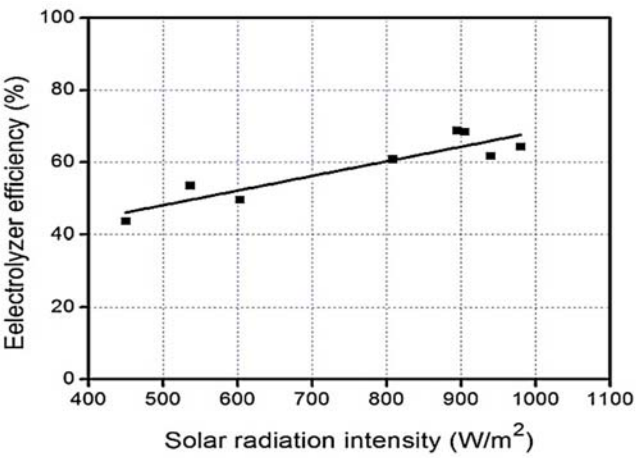

Fig. 9. Variation of electrolyzer efficiency with solar radiation intensity

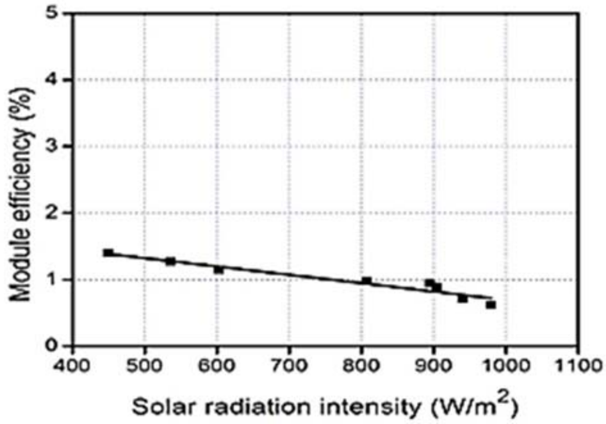

Fig. 10. Variation of module efficiency with solar radiation intensity

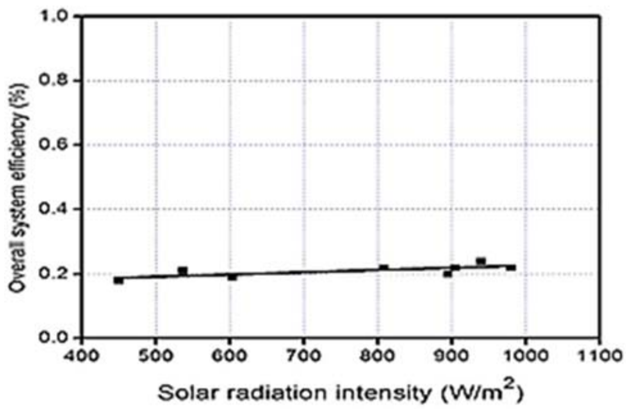

Fig. 11. Variation of overall system efficiency with solar radiation intensity

4. Conclusion

In this paper, the process of water electrolysis using solar photovoltaic energy for the purpose of hydrogen production has been examined under the climatic conditions of Cairo, Egypt. Experimental results showed that:

- Egypt has a huge solar energy potential which has an effective conversion to chemical energy, such as hydrogen.
- The environmental conditions such as the solar intensity, has a significant effect on the system performance and the rate of hydrogen production.
- The photovoltaic module efficiency has a significant effect on the overall system efficiency.
- The maximum hydrogen production rate is at the solar noon where the solar radiation intensity and the photovoltaic module output current are maximum.

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