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Experimental Performance of PV-Wind-Battery Hybrid System for Hydrogen Production in Tropical Climatic Condition through Water Electrolysis: A Case Study for Terengganu State, Malaysia

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Abstract – *This paper describes the performance of an integrated pv-wind-battery hybrid hydrogen energy production system through water electrolysis particularly in tropical climate situation. The system consists of photovoltaic array (PV), wind turbine (WT), custom-made proton exchange membrane (PEM) electrolyser, battery bank, hydrogen storage tank and an automatic control system for battery charging and discharging conditions. The DC current supplied to PEM electrolyser was obtained from the battery bank which charging by the 1 kW capacity photovoltaic array and wind turbine. The system produced 130-140 ml/min of hydrogen for an average global solar radiation and wind speed ranging between 200 to 800 W/m^2 and 2.0 to 5.0 m/s, respectively. Furthermore, a mathematical model for each component in the system was established and compared to experimental results.*

Keywords – Hydrogen production, performance, pv-wind-battery, water electrolysis.

1. INTRODUCTION

The last few years have seen the development of renewable energy (RE) systems based mainly on wind and solar power. Such systems are especially relevant to off-network communities, remote areas and island, which is particularly no grid connected available. These RE systems rely on highly transient energy sources and exhibit strong short-term and seasonal variations in their energy outputs. They thus need to store the energy produced in period of low demand in order to stabilize the output when the demand is high. While batteries are most commonly used for this purposed, they typically lose 1-5% of their energy content per hour and thus can only store energy for short periods of time [1], [2]. There are presently no practical means available for long term storage of excess electrical energy produced by the RE sources.

Few studies are related to the use of hydrogen for the electrical energy produced by RE sources such as wind and solar power [3]. Hydrogen is produced by an electrolyser powered by the excess electrical energy from the RE source. The excess energy available from the RE sources is directed to an electrolyser. The hydrogen produced is then stored in pressurized tank. The hydrogen can then be used to feed an energy conversion device (such as a fuel cell or an internal combustion engine), which will act as a secondary power source in periods of high demand. Such a system is set up for remote areas applications such as communication stations and others, [4]–[9]. This hydrogen can also be fed to a proton exchange membrane fuel cell (PEMFC) system that would be used as a load-leveling electrical system when unfavorable weather conditions arise.

Nevertheless, less studies are conducted on the generating hydrogen based on the DC current supplied by the battery bank which charging from the RE sources i.e., wind and solar power. The method proposed in the study can be considered as a suitable technique applicable particularly to regions which RE sources are moderate, fluctuates and seasonal.

Hence, these studies included the development and experimental testing of the producing hydrogen using the DC current supplied by the battery bank which charging from the hybrid RE source especially in tropical climate conditions. Here, an overview of the hybrid RE hydrogen production system as well as the performance of the system while operating in different conditions particularly in fluctuating of the wind speed and solar radiation is presented.

2. MATERIALS AND METHODS

The system in Figure 1 is located at the Kuala Terengganu, East Coast of Peninsular Malaysia, (4° 13.557'N 103° 26.048'E). The system is designed for an automatically controlled energy supplied to electrolyser based on state of charge (SOC) battery in producing of hydrogen. The PEM electrolyser has been designed to operate on constant current flow with 40 ampere. The 1 kW photovoltaic modules consist of 12 amorphous Silicon US-64 modules electrically connected into 2 series and 6 parallel to operate nominally at 24 VDC.

The 1 kW wind turbine energy system from Bergey Windpower Co., model has been used to couple with photovoltaic modules. The wind turbine system is composed of a permanent magnet WT that can deliver a maximum output power of 1000 W at 11 m/s of wind speed. The voltage produced by these sources is regulated and converted to 24 V on a power controlled center. A set of deep-discharge batteries bank with

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capacity 1000 Ah connected in a series/parallel configuration, act as a buffer between the PEM electrolyser and the power sources. The custom-made 1 kW PEM electrolyser consists of 10 cells stack with a membrane electrode assembly (MEA) area approximately 100 cm^2, which can deliver up to 0.5 m^3/h of purified hydrogen at ambient pressure. In order to prevent the batteries from over discharge conditions, a low voltage detector has been installed between the battery bank and PEM electrolyser.

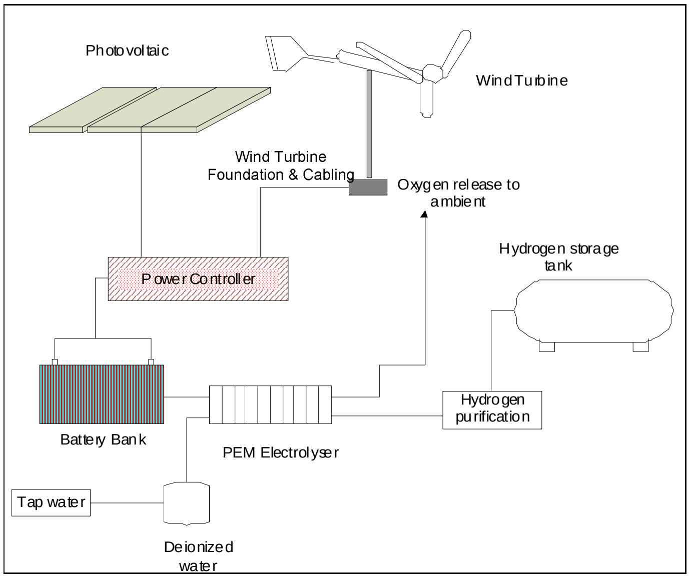

Fig. 1. Schematic diagram of the stand-alone hybrid pv-wind-battery hydrogen production system.

A complete model of the hybrid pv-wind-battery hydrogen production system was established in order to design and validate an adequate system operation. The model was built using sub-models for each individual component.

Photovoltaic Modules

The basic mathematical model was used to calculate the maximum power output from the photovoltaic modules. The power output of the photovoltaic module is based on the maximum point for current and voltage as followed [10].

$$I_{mp} = \frac{G_T}{G_{T,ref}}\left[I_{mp,ref} + \mu_{Isc}\left(T_C - T_{C,ref}\right)\right] \quad (1)$$

$$V_{mp} = V_{mp,ref} + \mu_{Voc}\left(T_C - T_{C,ref}\right) \quad (2)$$

$$P_{\max} = I_{mp}.V_{mp} \quad (3)$$

where, I_{mp} and V_{mp} are the maximum current (amp) and voltage (V) of photovoltaic module's, respectively. Meanwhile, $P_{\max}$ is the photovoltaic module's maximum power output (watt).

Wind Turbine

The power output from the wind turbine is referred on the principal formulation of the basis wind turbine power based on the Alfred Betz Law's as below [11].

$$P_{out} = \frac{1}{2}\rho AV^3(\eta_{mechanical} \quad C_P) \quad (4)$$

where, C_p is a power coefficient, A is a blade swept area (m^2), V is an average wind speed (m/s) and ρ is air density (kg/m^3).

Batteries Model

The batteries bank is the element linking together each component of the hybrid pv-wind-battery hydrogen production system. Since it is connected in series with the power center and PEM electrolyser and it acts as an energy buffer, the current flowing into or from the batteries is defined as [12]:

$$I_{Bat}(t) = I_{PV}(t) + I_{WT}(t) - I_{Electrolyser}(t) \quad (5)$$

where, $I_{PV}(t)$ is the photovoltaic module's current (amp), $I_{WT}(t)$ is the wind turbine's current (amp), and $I_{Electrolyser}(t)$ is the current supplied to electrolyser (amp). This current is positive when the batteries are charging and negative otherwise. Knowing the current, it is possible to deduce the voltage by:

$$V_{Bat}(t) = (1+\alpha t)V_{Bat,0} + R_i I_{Bat}(t) + K_i Q_R(t) \quad (6)$$

where, α is the self-discharge rate (Hz), $V_{Bat,0}$ is the open circuit voltage at time 0 (V), R_i is the internal resistance (Ω), K_i is the polarization coefficient (Ω h^{-1}), $Q_R(t)$ is the rate of accumulated charge.

The total energy stored in the batteries is given by:

$$E_{Bat}(t) = E_{Bat,0} + \frac{1}{3600}\int I_{Bat}(t)dt \qquad (7)$$

where, $E_{Bat,0}$ is the batteries' initial energy (Ah). Substituting Equation 5 into Equation 7, it is possible to express the batteries' energy as following:

$$E_{Bat} = E_{Bat.0} + \frac{I_{PV} + I_{WT} - I_{Electrolyser}}{3600\ s} \qquad (8)$$

Finally, this energy can be expressed as a state-of-charge using the following equation:

$$SOC_{Bat} = 100 \times \frac{E_{Bat}}{E_{Bat.max}} \qquad (9)$$

where, $E_{Bat\max}$ is the total capacity of the batteries (Ah).

PEM Electrolyser

This part of the system can be represented by a current source from the batteries bank feeding to the PEM electrolyser. The PEM electrolyser is modeled as an ideal device to produce the hydrogen based on the first Law of Faraday as given by [13]:

$$h_2\,prod = \eta_F \frac{n_c(RITt)}{Fpz} \qquad (10)$$

where η_F is a Faraday efficiency, n_c is a number of PEM electrolyser cell stacks, *R* is a gas constant (Joule/mol. Kelvin), *I* is a current supplied to electrolyser (amp), *T* is a temperature in Kelvin (273 + °C), *t* is a period of time current supplied to electrolyser (second), *F* is a Faraday constant, 96485 Coulombs per mol, *p* is a ambient pressure, 1×10^5 Pa (1 Pa = 1 Joule/meter^3), *z* is a excess number of electron which 2 for hydrogen and 4 for oxygen. Meanwhile the Faraday eficiency can be defined as:

$$\eta_F = \frac{1.482}{V_{sel}} \times \frac{i_{experiment}}{i_{theory}} \qquad (11)$$

where 1.482 is a thermo neutral voltage (amp), $i_{experiment}$ (amp) is actual current supplied to PEM electrolyser, V_{sel} is voltage which applied to each cell stacks and i_{theory} is a theoretical current supplied to PEM electrolyzer.

3. RESULTS AND DISCUSSIONS

The performance of the system was evaluated by in-situ measurements technique during a few days in monsoon season which occurred in the month of September until March and non-monsoon season 2006 (April until August). Relevant data for one day in non-monsoon season (August 15) are presented in Figures 2, 3 and 4. Figure 2 shows the evolution of the global radiation, wind speed, ambient temperature, photovoltaic temperature, and power output from wind turbine and photovoltaic as a function of time. The weather conditions were sunny in the afternoon and slightly cloudy in the late afternoon. The average and maximum global radiation were 130 W/m^2 and 500 W/m^2, respectively.

The measurements started at 2:00 pm. The average power produce from the wind turbine was 5.739 W with the energy average was 0.137 kWh-days. Meanwhile, the average power and energy output from the solar modules were 47 W and 1.1 kWh-days, respectively. Therefore, the total amount of energy charged to battery was 1.2 kWh-days. The average of photovoltaic modules and ambient temperature recorded were 25.5 – 34.8°C and 29.3 – 31.5°C, respectively.

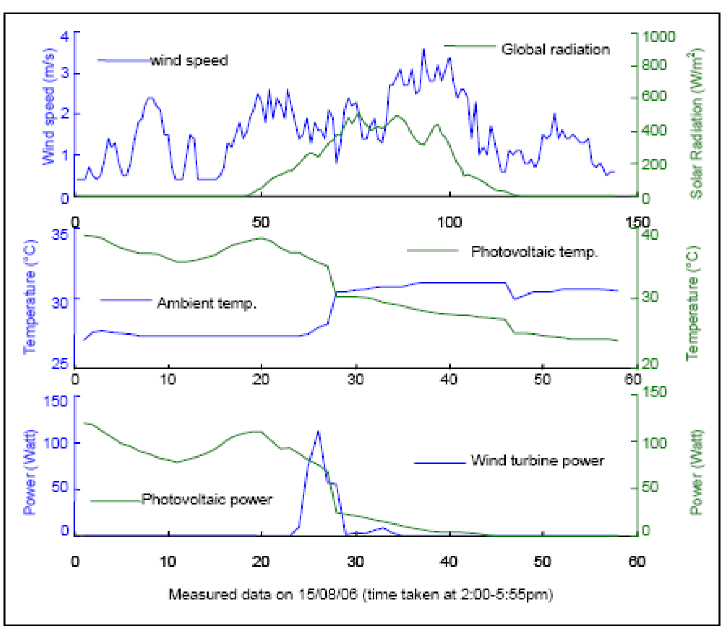

Fig. 2.Wind speed, global radiation, power output from wind turbine and photovoltaic on August 15th 2006.

The hydrogen production process started once the DC source from battery was connected to the anode and cathode plate of PEM electrolyser. The initial values of parameter such as voltage, current and power of the electrolyser while starting the experiment can be seen in Figure 4. It was shown that, at the beginning the voltage and current for electrolyser were 25 V and 23 amps, respectively.

It was observed that, the voltage decreased continuously on the duration the experimental was carried out, except at time 2:30 pm until 3:15 pm the voltage shown almost constant due to high wind speed as a result of more power produced for charging the battery. The current from battery supplied to electrolyser was found constant and slightly decreased as the voltage was dropped as a function of time and insolation as well as wind conditions until the late afternoon.

A similar evolution was observed on the power of electrolyser as the power is a product of voltage times current. The flow rate of hydrogen shown was constant as the current supplied to electrolyser in stable condition. The Faraday efficiency of the system was 23-33% with the average current supplied was 14-21 amp and cumulative current was 300-480 amp-hour with hydrogen generated was 136-137 ml/min.

Electrolyser efficiency was 25-40% with average power within 300-500W. Voltage efficiency (electrolyser cell voltage) was 60-65% with the electrolyser voltage average was 22-24 V and the hydrogen production efficiency was shown constant at 7 %. In overall, the system operated with the amount of energy supplied to electrolyser was 8-11 kWh with the system efficiency about 4-6 %. In addition, the energy generated from solar modules and wind turbine were 1-4 kWh and 0.58-5.49 kWh, respectively.

After completion running an experiment on the non-monsoon season, some continuous test runs were performed to see the performance of the system operated on the monsoon season. November 18, 2006 was chosen for analyzing the data due to very promises of wind availability with high wind speed. It was found that the average wind speed was about 1.58 – 4.72 m/s at 8:00 am – 12:50 pm in the morning. It was also observed that the average wind speed increased to 1.16 -6.62 m/s at 1:00 pm – 5:50 pm in the late afternoon. During this monsoon season, the high wind speed had occurred in the night time with the average 1.42 – 5.29 m/s. These conditions had contributed a very good power generated with 245.17 W up to 540 W maximum. The average of energy produced was 3.28 kWh-days with the maximum generated was 136.68 W.

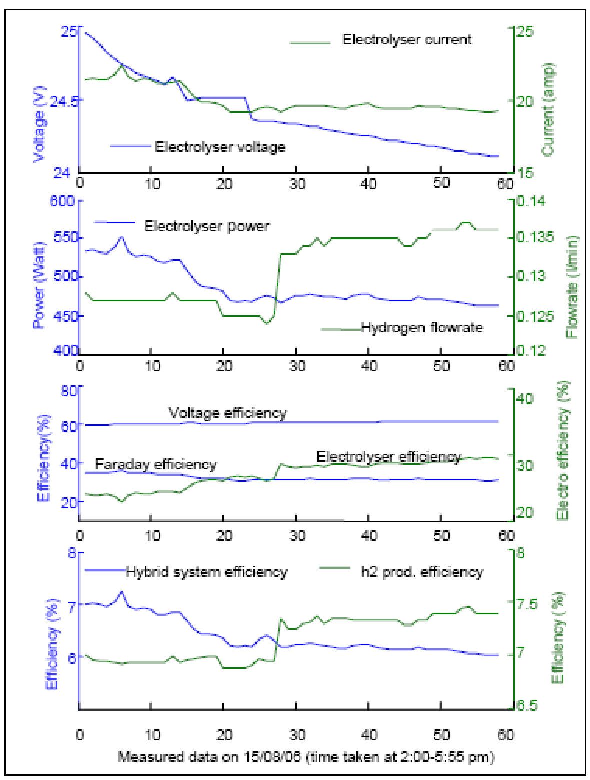

Fig. 3. Electrolyser current, voltage, power, hydrogen flow rate and efficiency on August 15th 2006.

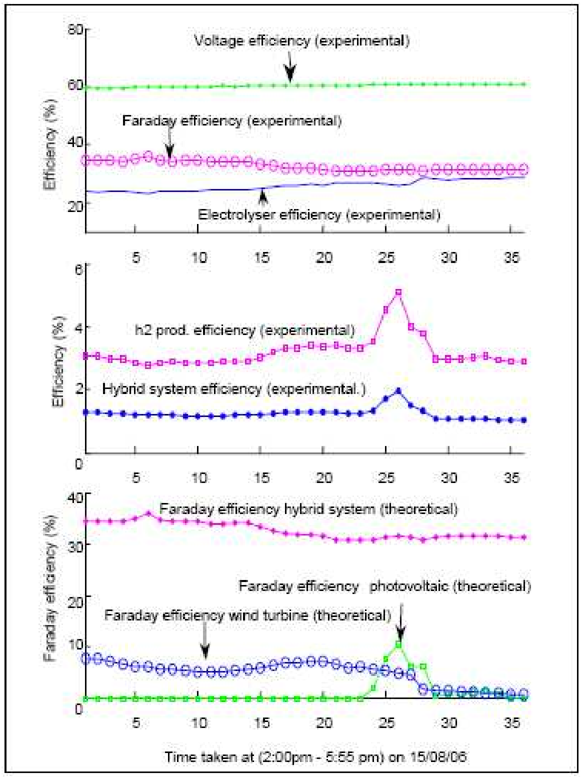

Fig. 4.Comparison system efficiency between an experimental and theoretical.

Global solar radiation varies between 100 – 550 W/m^2 in the morning and slightly decreased in the afternoon due to cloudy weather conditions. The average photovoltaic and ambient temperature were 22-40°C and 26- 31°C, respectively. These conditions lead to less power generated from photovoltaic modules. The daily behavior of system operation and performance for a typical day in monsoon season is displayed in Figures 5, 6 and 7. Total amount of energy flow to electrolyser was 0.23 kWh-days with the average of the current was 228.78 amp-hour.

In addition, the average of voltage and current were 23.76 V and 9.53 amp, respectively. Power to electrolyser was 226.64 W with hydrogen flow rate was 134 ml/min. Faraday, electrolyser, and voltage efficiency were 15.34%, 59.92%, and 62.37%, respectively. Due to the windiest weather and less solar radiation during this experimental period, the efficiency of hybrid system decreased to 3.16%. Nevertheless, hydrogen generated efficiency shown slightly increased from 7.0% to 7.78%.

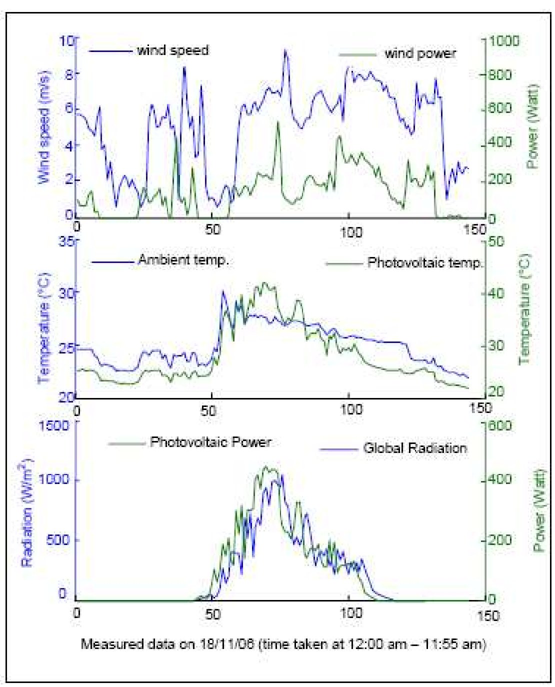

Fig. 5. Wind speed, global radiation, power output from wind turbine and photovoltaic on November 18th 2006.

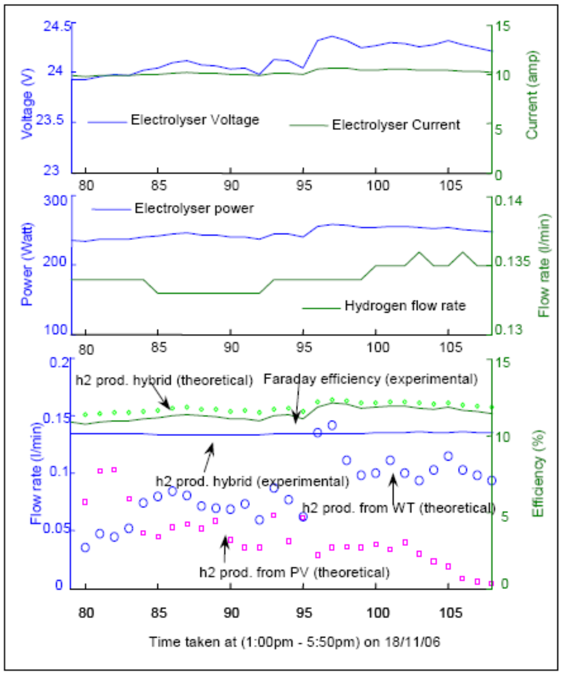

Fig. 6. Electrolyser current, voltage, power, hydrogen flow rate and efficiency on November 18th 2006.

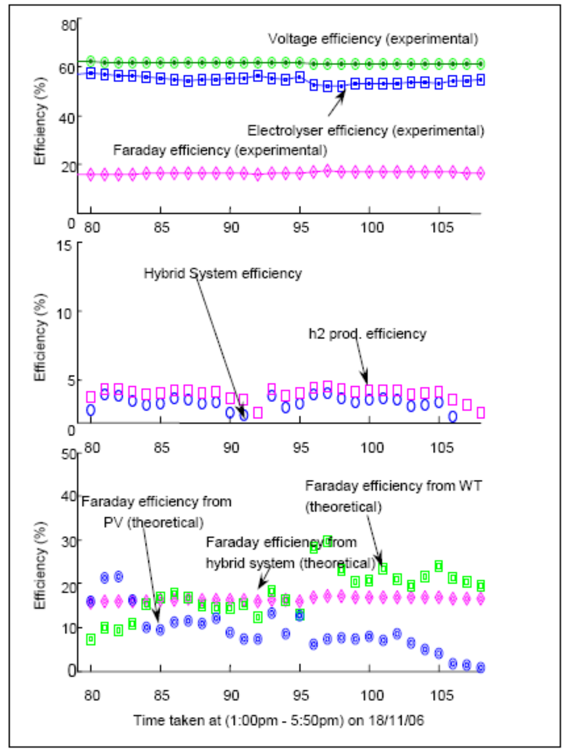

Fig. 7.Comparison system efficiency between an experimental and theoretical.

4. CONCLUSION

In general, both electrolyser and hybrid system efficiencies were very encouraging when compare with those obtained in similar experiences. From the experience with this study, it may be concluded that there are no insurmountable technical problems associated with hydrogen production by hybrid pv-wind-battery electrolyser. Field observations show that hybrid systems are feasible and reliable enough, and required less maintenance.

Electrolyser technology appears to be mature enough for hybrid system application. On the other hand, the electrochemical effects of operation for periods with an intermittent power sources can be overcome by using a battery bank as a buffer prior supplied to electrolyser. Although the electrolyser was demonstrated to be reliable and its operation satisfactory, improvement on the stacks assemble need to be done to avoid hydrogen leaking which lead to less amount of hydrogen collected.

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