GRID CONNECTED SOLAR HYDROGEN ENERGY SYSTEM

Tjukup Marnoto
Chemical Engineering Department, Faculty of Industrial Technology
Universitas Pembangunan Nasional, "Veteran"
UPN "Veteran", Jln. SWK 104 Condongcatur, Yogyakarta, Indonesia, 55283.
tjukup@gmail.com

Abstract

Solar-Hydrogen energy system has been regarded as the future energy system that is clean, friendly-environment, availability of renewable energy resources and easy to transfer or deliver to the end user. The grid connected solar hydrogen energy system (GCSHES) have the capability of overcoming the problems that occur on the grid connected power system (GCPS) when there is a black out of grid electricity. Moreover, stand alone power system (SAPS) requires batteries and larger hydrogen tank capacity is required for higher energy generation. An experimental GCSHES has been setup and tested. The GCSHES consists of subsystems photovoltaic (PV) array with 40 PV module type multycrystalin with its capacity of 5000 Wp, inverter capacity of 6000 W, electrolyzer capacity of 19 scf/h, hydrogen tank capacity of 1500 liter and fuel cell of 500 W. The characteristics equation and maximum power output of PV was presented The monthly efficiency and performance of PV array is 12.7% and 26%, while the efficiency and performance of inverter is 95.1% and 98%, respectively. The efficiency of electrolyzer subsystem and fuel cell is 51% and 25%, respectively. The techno economical analysis is indictated that the pay back period of this system is 18 years.

Keywords: Grid connected; Hydrogen; Photovoltaic, Electrolyzer, PEM Fuel cell.

1. Introduction

Solar hydrogen energy system is one of the renewable energies that identified as the clean energy sources [Barbir, 2005]. The grid connected solar hydrogen energy system has been developed in Malaysia to investigate the performance under the local climate conditions. The photovoltaic technology converts the direct solar energy to direct current (DC) electrical energy. Due to the reason that the solar energy functions in the noon light, the energy storage system is needed here so that energy still can be used if there is no sun light. The solar energy systems use photovoltaic with two systems i.e. grid connected power system (GCPS) and stand alone power system (SAPS). In GCPS, there is no energy storage [Urli and Kamenski. 1998, Erge, et.al. 2001, Pietruszko and Gradzki, 2003, Bakos, et.al. 2003, Al-Hasan, et. al. 2004, Yang,et. Al. 2004]. During the condition of excess electric supply, the excess supply will be delivered to the grid system and it will be re-delivered again if there is inadequate sun light. When the grid electric black out at the sun day, the excess of PV electric supply is not able to deliver to grid and if the grid electric black out during night day, there is no other electric sources used. In SAPS, electric energy is stored either using battery or hydrogen and battery [Vosen and Keller, 1999, Santarelli and Macagno, 2004, Zoulias, et. Al. 2006]. The capacity of battery to store energy is limited, so that the large number of batteries and bigger hydrogen storage tank are required for larger energy requirement. Hydrogen can be employed for other uses such as for household purposes and acts as a fuel in the fuel cell electric or hydrogen vehicle.

2. Grid connected solar hydrogen energy systems

The technology concept of connected solar hydrogen energy systems (SHES) consists of two stages. The first stage is the direct conversion of energy from DC electric energy to alternating current (AC) electric energy and delivers to the grid. The second stage is the indirect conversion of energy sources through certain stages of energy storage in the form of chemical energy (hydrogen energy technology: production, storage and utilization), and then the chemical energy can be converted again becoming the electric energy. The solar energy is converted to the electric energy by using the photovoltaic, when the excess electric supply occurs and this excess supply will be delivered to the grid or change to the chemical energy (hydrogen). The grid electric will be used whether there is adequate or inadequate solar energy. When there is no sun light and grid electric, for example the grid electric black out at night, hydrogen is reconverted to the electric energy by fuel cell. The produced hydrogen can be used too for other purposes, such as for stove, internal combustion engine and laboratory research study. The schematic of grid connected solar hydrogen energy systems is shown in Fig. 1.

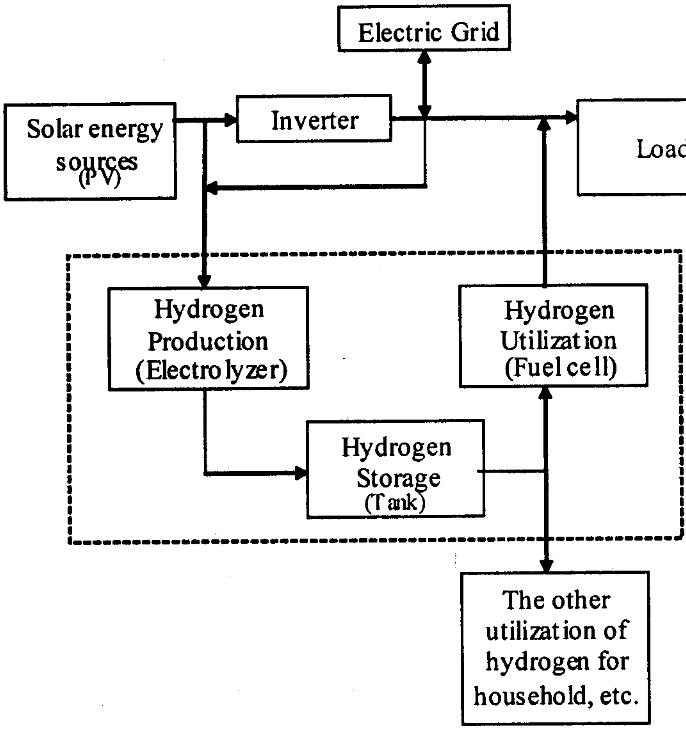

Fig.1 Schematic of grid connected solar hydrogen energy system

2.1 Photovoltaic Panels

Photovoltaic solar system employs module produced from semiconductor material to generate the electric energy from solar energy. The characteristic of semiconductor material if photon applied is release electron from the hole of electron connection. The electron released can move freely inside the compact semiconductor material. The effect of photon on the charge generator produced inside semiconductor will generate electricity. The solar light energy or photon in the PV is not changed totally to become electric energy, but it exists in the form of light reflected by the surface of solar cell and converts it to the thermal energy [Quaschning, 2004].

Table 1 Specification of PV Module

Type	Multy Christalyn
Total capavity (40 panel)	5 kWp
Maximum power (P_{MP})	120 Watts
Maximum voltages (V_{MP})	16.9 Volts
Maximum Current (I_{MP})	7.10 Amps
Open Circuit Voltage (V_{OC})	21.5 Volts
Current of Short Circuit (I_{SC})	7.45 Amps

The characteristic of PV is expressed by its relationship with current and voltage (I-V), power and voltage (P-V) of photovoltaic on the certain solar light and temperature. The equation of characterizing parameter model for PV was commonly used for research study in PV [Bilgen, 2001, Celik and Acikgoz, 2007, Duffie and Beckman, 1991, Mellit, et. Al. 2007] . The characteristic of PV follows the parameter model, with the modified equation for *a*, I_L, I_0 as follows:

$$I = I_L - I_0\left\{\exp\left(\frac{V + I.R_s}{a}\right) - 1\right\} \quad (1)$$

$$a = k_1.T_c \qquad I_L = k_2 G_T \qquad I_0 = k_3.T_C^{\,3}.\exp\left(-\frac{k_4}{T_C}\right) \quad (2)$$

PV operates in the condition of maximum power point (MPP). The equation to predict the MPP of PV can be mentioned as follows:

$$I_{MP} = \frac{a.\ln\left(\frac{\Delta I}{I_0}\right)}{\left(2.R_S + \frac{a}{\Delta I}\right)} \qquad V_{MP} = a.\ln\left(\frac{\Delta I}{I_0}\right) - I_{MP}.R_S \quad (3)$$

$$P_{MP} = I_{MP}.V_{MP} \qquad \Delta I = I_L - I_{MP} \quad (4)$$

The comparison of the experimental and computational data using Equation (1) and (2) is in a good agreement (Figure 2). Therefore, the appropriate constant i.e. k_1= 0.0065, k_2= 0.006, k_3=2858173.2394 and k_4=12959.7288 have been obtained. PV operation using the maximum power point tracker (MPPT), the output of PV array can be predicted using equation (3) and (4). The comparison of PV power data is shown in Fig. 3.

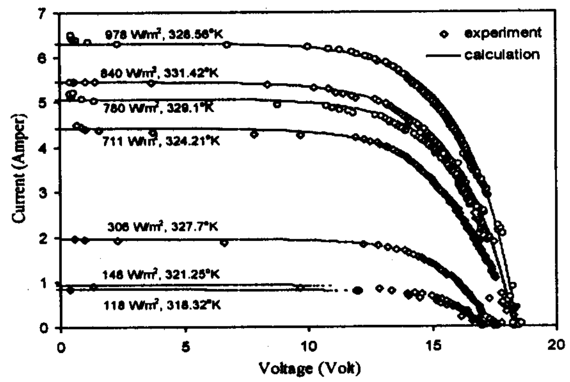

Fig.2 Comparison of I-V graph on various solar light level and temperature

The output energy of PV is the total of power during certain period. Hourly power is the operation time for every hour, while daily power is the operation time for one day. The PV efficiency is calculated by the ratio of PV output energy and solar energy per PV area and can be state in the equation as follows:

$$\eta_{PV,d} = \frac{E_{PV,d}}{E_{SR,d}} = \frac{\sum_{t=0}^{t} P_{PV}(t)}{\sum_{t=0}^{t} A_{PV} G_T(t)} = \frac{\int_0^t P_{PV}(t).dt}{A_{PV}\int_0^t G_T(t).dt} \qquad (5)$$

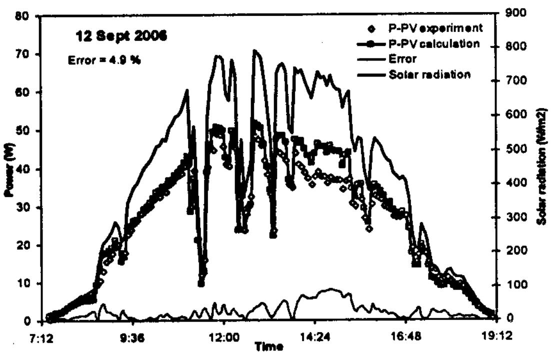

Fig 3. Comparison of PV module power between experimental and predicted data.

2.2 Inverter

Inverted used in the grid connected solar hydrogen energy system consists of maximum power point tracker (MPPT) and alternating current electric wave synchronization unit. MPPT employed for the optimization of photovoltaic module power output. The alternating current electric wave synchronizer was utilized to synchronize the wave frequency of output AC current from inverter and electric grid current. The inverter efficiency is the ratio of AC inverter output power and DC input power and depends on the input power. The empirical equation of inverter efficiency is shown in equation (6) and (7). Fig. 4 depicts the comparison of inverter efficiency between prediction and experimental. The energy efficiency and performance work of PV can be seen in Fig. 5.

Table 2 Specification of Inverter (Sunny Mini Central SMC 6000)

Maximum PV Power (PPV)	7000 Wp
PV Voltage range, MPPT (UPV), at 230 V AC	246 V- 600 V
PV Voltage range, MPPT (UPV), at 250 V AC	270 V- 600 V
Maximum Input Current (IPV-Max)	26 A
Continuous AC Power (PAC-max)	6000 W at 45 °C
Nominal AC Power (PAC – Nom)	5500 W
Range AC Voltage (UAC)	180 V – 265 V
AC Frequency (fAC)	49.8Hz – 50.2 Hz
Possible range of AC frequency	45.5 Hz – 54.5 Hz

$$\eta_{inv} = 104.78 P_{PV}^{\ 0.1562} \qquad P_{PV} < 0.53kW \qquad (6)$$

$$\eta_{inv} = 1.0501 P_{PV} + 93.66 \qquad P_{PV} \geq 0.53kW \qquad (7)$$

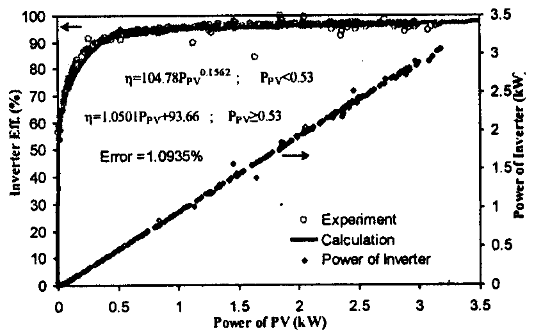

Fig 4. Inverter efficiency on various power supply (PV power)

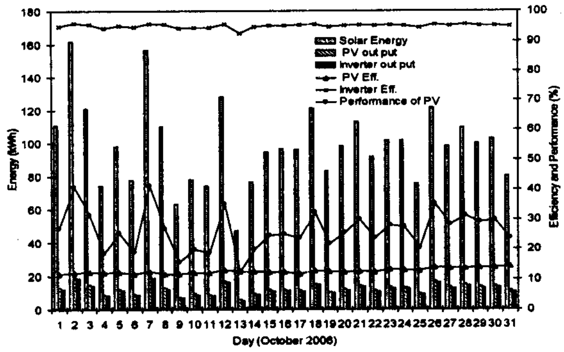

Fig 5. Solar energy, PV, inverter, PV efficiency, inverter and PV performance

2.3 Electrolyzer

Electrolyzer system was exploited for the purpose of hydrogen production from water. It usually consists of water supply unit, electric supply, oxygen gas disperser from water and hydrogen purification unit. The hydrogen production is delivered to the hydrogen storage tank, whereas oxygen gas is stored whether in oxygen storage tank or released to the atmosphere air. The schematic of electrolyzer specification is shown in Table 4.

Table 4. Specifications of HOGEN S Series PEM electrolyzer.

Electrolyte	Proton Exchange membrane (PEM)
Hydrogen production	19 scfh Hydrogen
Hydrogen purity	> 99.99%
Supplied water quality	Deionized
AC electric power	190 – 240 V AC, 1 phase 50/60 Hz
DC electric power	60 – 200 V DC
Operating condition	5-50°C, 0–95 % humidity

The efficiency of stack and electrolyzer subsytem is the ratio of energy contained in the produced hydrogen with the electric supply of stack electrolyzer, and supplied energy to system. The efficiency of stack and electrolyzer subsytem found from the present study is 66.605% and 51.03 %, respectively. The power and operating pressure of the electrolyser is shown in Fig 6.

$$\eta_{el} = \frac{\sum_{t=0}^{t_{op}} P_{H_2}}{\sum_{t=0}^{t_{op}} P_{el,in}} = \frac{\int_0^{t_{op}} P_{H_2} dt}{\int_0^{t_{op}} P_{el,in} dt} \qquad (8)$$

$$\eta_{sys,el} = \frac{\sum_{t=0}^{t_{op}} P_{H_2}}{\sum_{t=0}^{t_{op}} P_{sys,el,in}} = \frac{\int_0^{t_{op}} P_{H_2} dt}{\int_0^{t_{op}} P_{sys,el,in} dt} \qquad (9)$$

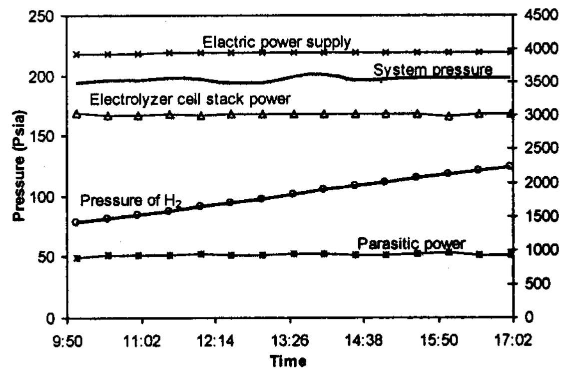

Fig. 6. Power and operating pressure of electrolyzer subsystem

2.3 Fuel cell subsystems

The fuel cell subsystems consists of fuel cell stack (FC), hydrogen and oxygen delivery unit, water cooler and inverter to convert the DC electric to AC. Fuel cell subsystems is employed to convert the re-convert hydrogen chemical energy to electric energy. This subsystem is operated during grid electric disconnection occurs.

The characteristic of fuel cell follows the equation proposed by Ulleberg (1998) as shown in Equation (9) as [Ulleberg, 1998]:

$$V = A - b.\ln(i) - R.(i) \qquad (10)$$

The comparison of experimental data and predicted is shown in Fig. 7 and obtained that the appropriate constants value of A = 15.0756 Volt, b = 0.84768 and $R = 3.8526.10^{-7}$.

Scott (2004) mentioned that the delivered electric current is depend on the amount of hydrogen molecule that consumed by fuel cell [Scott, 2004]. The ideal current delivered by fuel cell is at the voltage of 1.23 V if assuming the exergy efficiency equal to 100%. Conversely, fuel cell delivers the electric current with voltage below 1.23 V. Therefore, the exergy efficiency of fuel cell is straightforwardly assumed to be equal with the produced cell voltage ratio and supplied hydrogen energy.

$$\eta_{FC,ex} = \frac{V_{Cell}}{1.23}.100\% \qquad (11)$$

$$\eta_{p,FC} = \frac{\int_{t_0}^{t_n} P_{FC,out} dt}{\int_{t_0}^{t_n} P_{H_2,in} dt}.100\% \qquad (12)$$

The efficiency of fuel cell exceeds above 25% with the voltage of 13 V and current of 10 Ampere. At the power around 500 W, the efficiency of fuel cell is 25.35%. The efficiency of exergy and fuel cell power in detail is shown in Fig. 8.

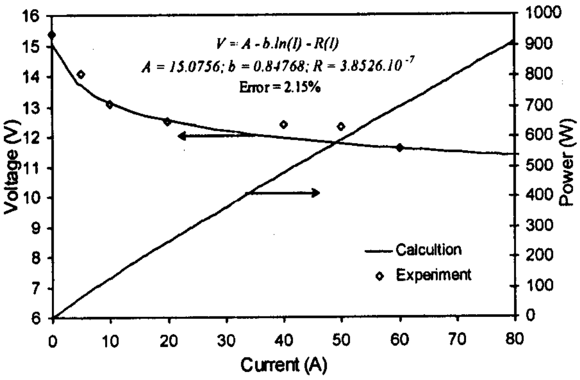

Fig 7. Characteristic of voltage-current (V-I) and power-current (P-I) of fuel cell stack

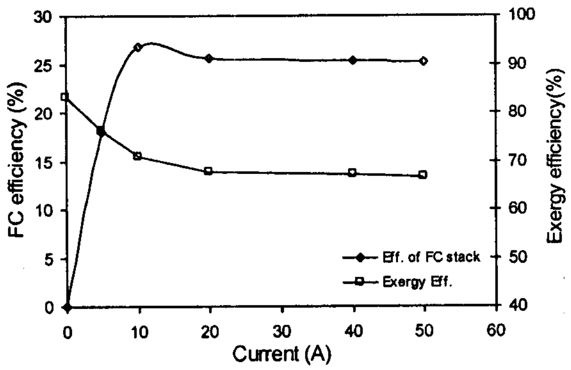

Fig 8 Efficiency of exergy and fuel cell energy (PEMFC)

3. Economical Analysis

The grid connected solar hydrogen energy system was analyzed using the life cycle cost (LCC) method by referring to the present worth value. This energy system generates the electric and chemical (hydrogen) energy. Hydrogen can be either reconverted into electric as a storage if the grid electric disconnects) or used for any other purposes. The analysis of profit or saving system is based on the present electric rate (RM 0.285/kWh) and hydrogen (RM 36,-/Nm^3). The economical analysis of this grid connected solar hydrogen energy system predicts the payment period (PP), which is time required for the annual payment flow with cumulative saving system to become positive [15]. The operation of this system can be simulated into three parts as follows:

1. The system operates in concentrating the electric generation only, while hydrogen produced is stored to be used when grid electric disconnected. This system does not employ hydrogen for any other purposes.
2. The system operates in generating electric and hydrogen continuously. Some part of hydrogen was stored for purposes when the grid electric cut off and the other part was used for any other purposes or trade.
3. The system if considered as grid connected photovoltaic energy system (electrolyzer subsystem, fuel cell and tank) is not taken into account in the economical analysis.

The cost of present worth (C_{PW}) in this system is the cost of photovoltaic system, inverter, electrolyzer system, hydrogen tank, fuel cell system and installation cost. The cost of duration payment is available for supplier's water filter maintenance (RM 600) for every 5 years.

$$LCC = C_{PW} + R_{PW} = \text{RM}.246715,- \quad (13)$$

Annual cost:

$$ALCC = \frac{M}{PWF(N,0,m)} = RM.17876.2 \quad (14)$$

(N = 30 year and m = 6%)

Fuel saving:

SS = electric energy cost + hydrogen cost – grid electric cost

$$ASS = C_{Es,y} + C_{H_2,y} - C_{EG,y} \quad (15)$$

$$PW_{SS} = ASS * (1+d)^j \quad (16)$$

The system profit is fuel saving subtracts with mortgage payment:

$$PW_{SS,K} = ASS(1+d)^j - ALCC \quad (17)$$

Cumulative of system profit:

$$CPW_{SS,K} = \sum_{j=1}^{N}\left(ASS(1+d)^j - ALLCC\right) \quad (18)$$

The economical analysis was carried out by referring to the market discount of 7%, interest rate of 6%, electric rate of RM 0.285/kWh and hydrogen rate of 36,-/Nm^3, life cycle of 30 years. It is obtained that the payback period for B and C simulation is 18 and 21 years, respectively. The payback period for A simulation was not achieved during life cycle. Therefore, it can be concluded that the grid connected solar hydrogen energy system is better to be used for hydrogen production for the other purposes or can be sold.

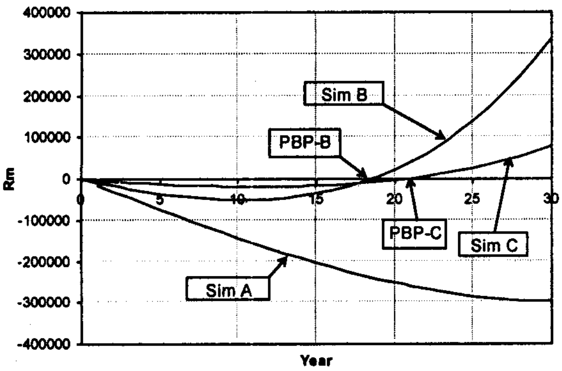

Fig 9. Cumulative system saving of A, B and C simulation

4. Conclusions

The GCSGES system is the clean and friendly-environment energy system and it is knows as the appropriate future energy system to be implemented on the transmission system from the use of conventional fuel to the renewable energy. This system can reduce the air pollutant so that the warming global and climate changes can be slowed down and diminished. The performance and mathematical equations of the subsystems is required for the design of GCSHE system and renewable energy system. The characteristic equation and MPP from PV has been determined and the constant of $k_1 = 0.0065$, $k_2 = 0.006$, $k_3 = 2858173.2394$ and $k_4 = 12959.7288$ is specifically calculated for the multi crystal photovoltaic. The techno economical analysis was performed by referring to some economical factors, which is market discount of 7%, interest rate of 6%, electric rate of RM 0.285/kWh and hydrogen rate of 36,-/Nm^3, life cycle of 30 years. The operation time of electrolyzer by 2.6 hour per working day obtained the payback payment period of 18 years.

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