System Modelling, Simulation and Feasibility Study for Seawater to Hydrogen Offshore Solar Harvesting System

Hou Pin Yoong, Kiam Beng Yeo, Wai Heng Choong, Kenneth Tze Kin Teo, Cheah Meng Ong
Material and Mineral Research Unit,
School of Engineering and Information Technology,
Universiti Malaysia Sabah, Kota Kinabalu, Malaysia.
yoongpin@ums.edu.my, nooryeo@yahoo.com, whchoong@ums.edu.my, ktkteo@ieee.org

***Abstract* — Solar hydrogen harvesting system converts solar energy and stored them in the form of hydrogen gas instead of charges in batteries. Furthermore, oxygen released during the electrolysis process is a non-polluting element. This paper presents the feasibility study of solar hydrogen harvesting system using seawater instead of clean water to produce hydrogen. Besides, the system is proposed to operate on offshore to avoid deforestation. In this system, solar irradiance collected by the Photovoltaic (PV) panel is firstly used to pump the seawater into the distillation tank. The distillation process of seawater takes place with direct sunlight via evaporation. Clean water obtained will be directed into electrolysis chamber and process into hydrogen, which will be stored in metal hydride canister. The system model, overall process flow chart and total system efficiency had been studied and described. Results from the study showed that the total system efficiency is about 5%. From the efficiency, the feasibility of the system is studied, which shows a slow return of about 50 years. The finding could be premature, since the motivation by the PV technology where high efficient and low cost PV modules are possible to be produced.**

Keywords - solar, photovoltaic, distillation, electrolysis, hydrogen

I. INTRODUCTION

Lately, green energy had become a necessity for global concern and focus. People are now more aware about the health of the earth and are taking steps to reduce the damage to the Mother Nature. Green energy emphasize on how to sustain human basic needs without damaging the planet. However, some alternatives such as geothermal, wind, wave and hydro energy harvesting are very limited to geographical location, while the application of bio-fuel and nuclear are leading to deforesting and radioactive contamination problem, respectively. The most viable solution still lies in the solar energy due to its most abundant and safe energy available.

Energy from the sunlight can be harvested by using photovoltaic panel or by absorbing the thermal energy from the sun. Storage for the energy harvested is crucial as there is only limited time a day to harvest the solar energy. One of most popular storage system is the battery storage. However, batteries are expensive and have limited life cycle. To improve the storage problem, solar energy can be stored in the form of hydrogen gas. Hydrogen gas as an energy carrier is a most appealing option when it is utilized either in fuel cells or Internal Combustion (IC) engines. The only by-product generated by the fuel cell and IC engines is pure water, which is environmental friendly and can be used for overcoming clean water shortage.

Existing solar energy harvesting systems often requires large land area to accommodate the PV array, which eventually leads to deforestation. Existing systems also rely on large quantity of clean water supply as feed for electrolysis process; whereas there is still shortage of clean water supply globally. Therefore, the novelty of this solar hydrogen harvesting system is deforestation free and does not consume clean water. This is attributed to the concept proposed by operating on the sea and clean water is obtained from distillation of seawater.

The proposed system gives a rounded sustainable green energy technology. This system provides the green energy available without compromising the limited land area and precious clean water. Besides that it is able to produce temporary and permanent positive effect to the Mother Nature. The system process produces zero carbon dioxide, this will not worsen the global warming effect, and thus it has a permanent positive effect. The system also instantly releases oxygen into the atmosphere during the electrolysis process. This creates a temporary addition of oxygen that could enrich the ozone formation.

This system is also friendly to mankind. There is no land competition in between energy farming and agriculture farming. This will also reduce clean water crisis due to the system not only not consuming clean water, but instead producing clean water at the end of the energy cycle. The only concern is whether this system is feasible? Thus, the system is studied, and presented in this paper on the system modelling and feasibility study of solar hydrogen harvesting system using seawater.

II. RELATED WORKS

Throughout the years, many authors had contributed in the studies of solar energy harvesting systems. Those presented systems have variations covering the different architecture, such as acrylic spherical tank reactor suggested by Kelly and Gibson [1] who suggested having better light focusing ability. Pyle *et al.* [2] came out with a battery and hydrogen hybrid system that charged the backup batteries at the same time producing hydrogen gas using the solar thermal hydrogen system. Another researcher [3] makes use of both the solar irradiance and solar thermal energy in driving mechanical shaft to generate electricity for powering the electrolyzer.

Modelling of components in solar hydrogen harvesting systems such as efficiency and cost of the system are also well described. Meanwhile, Baykara [4] concluded that solar hydrogen system could only be preferred in near future when more solar plant fields in convenient areas in regards to sunlight and water supply is established. Houcheng *et al.* [5] also evaluated different expressions of efficiency of a typical water electrolysis system under configurations. Whilst authors of [6] optimised the performance of the solar hydrogen system under different applications by considering the possibility of combining battery and hydrogen storage system and Joan [7] investigated the relationship of price and performance of every components in the solar hydrogen system with the payback of the system.

On the other hand, Sebastian *et al.* [8] focus more on the optimisation of micro-scale solar harvesting system with proposed dimensioning process software. Chao *et al.* [9] studies also introduced several maximum power point tracking methods of micro-scale solar hydrogen harvesting. A virtual solar hydrogen modelling and software implementation mentioned in [10] effectively helps in the analysis and optimisation in the design of solar hydrogen harvesting system. The results showed a very high consistency with data available in his literature.

Researchers are mainly emphasized on optimising the system for yielding higher performance. However, this paper is highly concentrated on a system that is really "green" to the environment. Most of the individual module in this system had been undertaking intensive research work. The effort here is to find a combination of those system that can be put together to form an all rounded system to provide sustainable green energy for mankind and friendly to the Mother Nature.

III. System Modelling

The concept design of the system is carefully drawn with the studies of current green technology and their limitations. The work is then followed by the modelling of each module in the solar hydrogen harvesting system. Thus, in this section, the above work is presented starting by introducing the overall concept of the system with a process flow chart. Later in this section detail modelling from photovoltaic panel to metal hydride hydrogen storage are discussed.

A. Process Flow Chart

A process flow chart is tabulated as in Fig. 1, showing the total process of the solar hydrogen harvesting system. The process starts with PV arrays generating electricity from solar irradiance. Then, a maximum power point tracking (MPPT) system, which is the DC-DC converter, is used to regulate and maximize the harvested power from PV array. Subsequently, the regulated power is then used to power up the distillation chamber, electrolysis chamber and hydrogen gas compressor.

In the distillation chamber, seawater is pumped into a distillation tank and undergoes a desalination process. Clean water collected is then use for the electrolysis. Hydrogen is produced from the electrolysis and finally compressed for effective storage. A process flow diagram in the Fig. 2 illustrates the conceptual system.

B. Photovoltaic Panel

According to [11] the electrical power available from a photovoltaic cell can be modelled with the equivalent circuit as shown in the Fig. 3. The equivalent circuit consists of a photo current, a diode, a parallel resistor and a series resistor describing an internal resistance to the current flow. The output current can be described by (1) and (2):

$$I_{cell} = I_L – I_{ss}\{\exp[(V_{cell}+Ir_s)/(\eta V_t)]-1\} – (V_{cell}+Ir_s)/r_{sh} \quad (1)$$

$$V_t = kT_{cell}/e \quad (2)$$

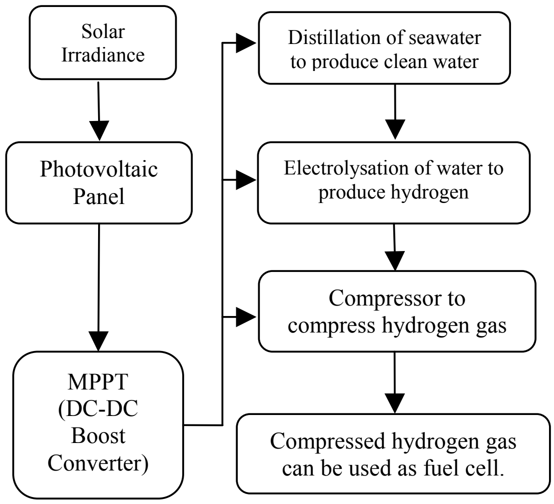

Figure 1. Process flow chart of solar hydrogen harvesting system.

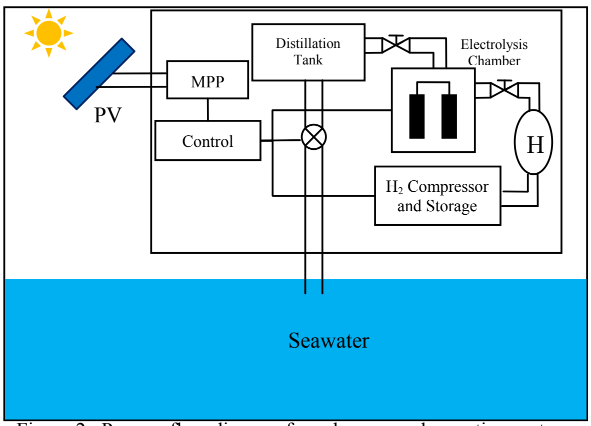

Figure 2. Process flow diagram for solar energy harvesting system.

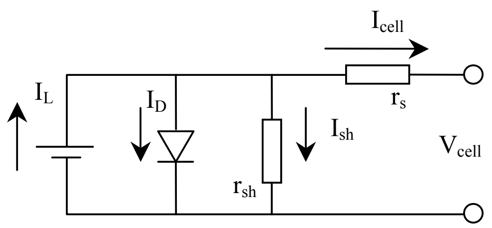

Figure 3. Photovoltaic cell equivalent circuit.

The value of I_L mainly depends on the solar irradiance and the temperature of the photovoltaic cell. It can be represented by (3):

$$I_L = (G/G_{ref})[I_{sc} + \mu_{sc}(T_{cell}-298)] \tag{3}$$

For a photovoltaic panel with N_s number of photovoltaic cells connected in series, the series resistance, parallel resistance, voltage and current can be represent as:

$$(r_s)^{Panel} = N_s \text{ x } r_s \tag{4}$$

$$(r_{sh})^{Panel} = N_s \text{ x } r_{sh} \tag{5}$$

$$V^{Panel} = N_s \text{ x } V_{cell} \tag{6}$$

$$I^{Panel} = I_{cell} \tag{7}$$

Furthermore, for a photovoltaic array with M_s number of photovoltaic panels connected in series and M_p of photovoltaic cells connected in parallel, then the key elements to find out I are shown in (8), (9), (10), and (11).

$$(r_s)^{Array} = (M_s \text{ x } (r_s)^{Panel}) / M_p \tag{8}$$

$$(r_{sh})^{Array} = (M_s \text{ x } (r_{sh})^{Panel}) / M_p \tag{9}$$

$$V^{Array} = M_s \text{ x } V^{Panel} \tag{10}$$

$$I^{Array} = M_p \text{ x } I^{Panel} \tag{11}$$

Therefore, by combining (4) to (11), a general equation that described the output current and output voltage of the photovoltaic array is formed.

$$I_{out} = M_pI_L - M_pI_{ss}\{\exp[(V_{cell}/(M_sN_s) + (M_sN_sI_{cell}r_s)/M_p^2) / (nV_t)] - 1\} - [M_p(N_sV_{cell} + Ir_s)] / r_{sh} \tag{12}$$

$$V_{out} = M_sN_sV_{cell} \tag{13}$$

For photovoltaic cell, Ns = Ms = Mp = 1; photovoltaic panel, Ms = Mp = 1; and finally from I_{out} and V_{out}, the expression for power can be obtained:

$$P = V_{out}I_{out}/ \gamma V_{oc}I_{sc} \tag{14}$$

$$\gamma = V_{out}I_{out}/V_{oc}I_{sc} \tag{15}$$

For simulation purposes, the BP4180T photovoltaic panel manufactured by BP solar is referred. The specifications of the photovoltaic panel under standard test condition are described in Table 1.

By using equations described above, the MATLAB© simulation of the PV panel under varying solar irradiance and temperature is carried out. From the Fig. 4, the power generated increased with increasing solar irradiance; the current increased from around 1.2A to 5.5A while the voltage increased from around 39V to 44V as G changes from 200W/m^2 to 1000W/m^2. In Fig. 5, for the first half of the graph, the current remains almost the same with increasing temperature, but started to drop drastically when the voltage reaching maximum power point voltage. The curves obtained are well agreed with the curves provided by the manufacturer, several discrete points are compared and all of them show excellent correspondence.

Table 1. BP4180T photovoltaic panel specifications.

Maximum Power (P_{max})	180W
Voltage at P_{max} (V_{mpp})	35.8V
Current at P_{max} (I_{mpp})	5.03A
Short Circuit Current (I_{sc})	5.58A
Open circuit voltage (V_{oc})	43.6V
Module efficiency	14.4%

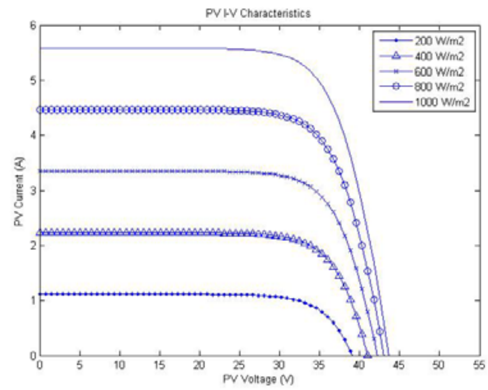

Figure 4. PV panel I-V characteristics with varying solar irradiance.

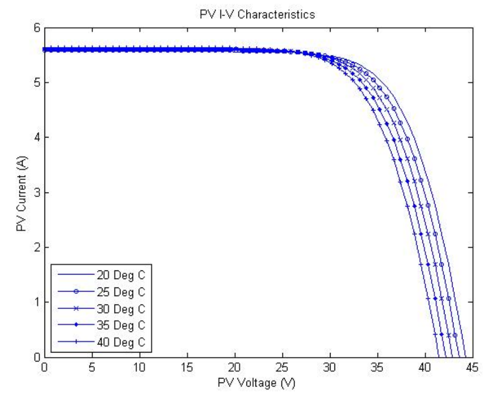

Figure 5. PV panel I-V characteristics with varying temperature.

C. Maximum Power Point Tracking (MPPT)

A DC to DC boost converter is used to increase the voltage obtained from the PV array and a MPPT controller with Perturb & Observe (P&O) algorithm is used to maintain the maximum power supplied possible to the load. The schematic circuit of the boost converter is illustrated in the Fig. 6. The P&O algorithm maintain the power by first comparing the present power with the previous power. If the present power is larger than the previous power, it will increase the voltage and vice versa. The process is repeated until the power is be able to maintain around the maximum power point. The flow chart of the MPPT P&O algorithm is shown in Fig. 7.

Duty ratio of the DC-DC boost converter is used to control the voltage of the photovoltaic array. The duty ratio of the boost converter can be derived as:

$$D = 1 - V_{so}/V_{out} \tag{16}$$

The inductor and capacitor of the boost converter act as a filter to reduce the output voltage ripple. The inductance and capacitance are defined in (17) and (18):

$$L = [D(1-D^2)R]/2f \tag{17}$$

$$C = D/Rf \tag{18}$$

Simulation is carried out to study the performance of the MPPT system under constant and varying solar irradiance. Simulation results are shown in the Fig. 8 and Fig. 9. Results showed that the MPPT system is able to keep track of the changes of input power and able to alter the duty cycle fast enough to maintain maximum power delivery to the load.

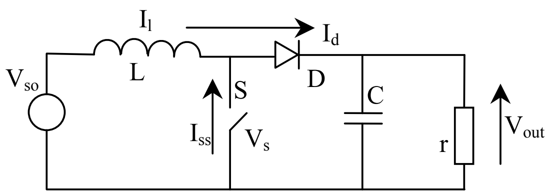

Figure 6. Schematic circuit of DC-DC boost converter.

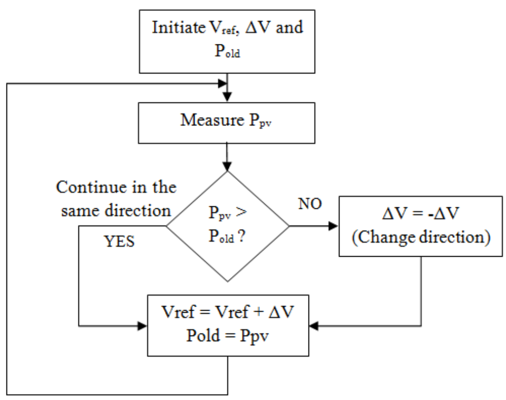

Figure 7. MPPT perturb & observe algorithm flow chart.

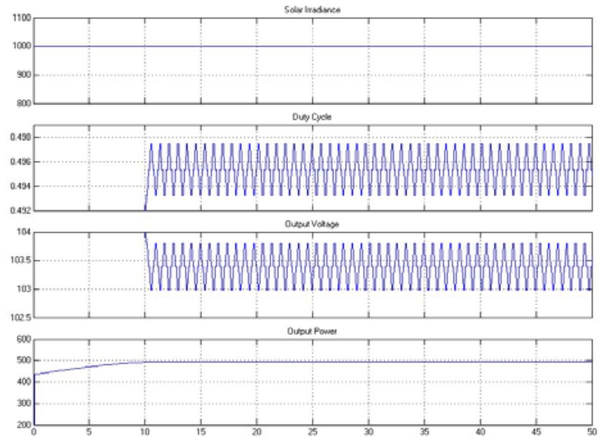

Figure 8. Simulation results with constant solar irradiance

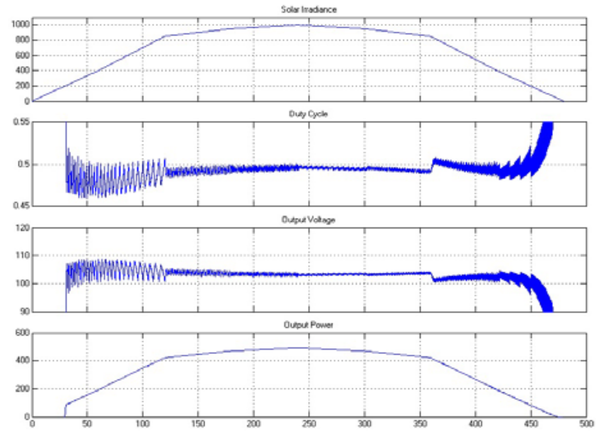

Figure 9. Simulation results with varying solar irradiance.

D. Load of the System

The loads of the solar energy harvesting system are divided into three parts, which are the distillation chamber, electrolysis chamber and hydrogen compressor. The solar irradiance varies over the day. At certain time of the day the irradiance level is insufficient to powered up all the loads at the same time; thus, logics is used to compute the operating conditions of each of the loads. Smart power management can be archived where the power generated is fully utilized.

The power supply priority is set first for the distillation process. Because a minimum amount of clean water is needed before the electrolysis can take place. The second priority is set for the electrolysis process. This is to produce hydrogen gas from the clean water. The last priority is set for the hydrogen compressor to turn on when certain amount of hydrogen is produced. The conditions of the system are stated as below:

$W_{S1,}$	Seawater level in tank
$P_{D,}$	Distillation power
$W_{2,}$	Water level in tank
$P_{E,}$	Electrolyzer power

H_2, Hydrogen gas level
P_C, Compressor power
D, Distillation chamber output
E, Electrolysis chamber output, and
C, Hydrogen Compressor output

Thus, the sums of product expression for the outputs are shown below.

$$D = W_{s1}P_D\overline{W_2} \quad (19)$$

$$E = W_2P_E\overline{P_C} + W_2P_E\overline{P_D} \quad (20)$$

$$C = H_2P_C\overline{P_D} + H_2P_C\overline{W_2} + P_EH_2P_C\overline{W_{s1}PW_2} \quad (21)$$

E. Distillation of Seawater

The Fig. 10 shows the distillation of seawater, the solar still consists of a steel basin and a glass cover. The interior of the steel basin is coated with heat absorption material to maximise heat collection from the sunlight. Water pump is used to pump the seawater into the solar still and water vapour will condense on the glass cover and flow into the collector. The energy balance of each components of the solar still is described as follow:

(a) Basin

$$a_bG = q_b + q_{loss} \quad (22)$$

(b) Water in basin

$$a_wG + q_b = (MC)_w dT_w/dt + q_{rw} + q_{cw} + q_{evp} \quad (23)$$

(c) Glass cover

$$a_gG + q_{rw} + q_{cw} + q_{evp} = q_{rg} + q_{cg} \quad (24)$$

The amount of clean water produced depends on the temperature of the glass cover and the temperature of the seawater in the solar still. The larger the difference between these two temperatures will result in more clean water produced. Frenandez and Chargoy [13] suggested that the temperature of glass cover and seawater in the basin can be determined by (25), (26), (27) and (28).

$$T_g = (a_gG + h_{tw}T_w + h_{tg}T_a)/(h_{tg}+h_{tw}) \quad (25)$$

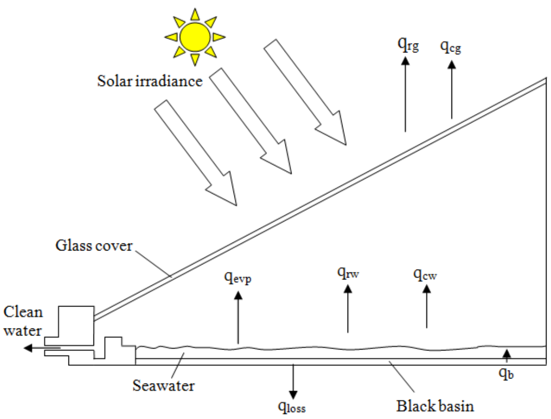

Figure 10. Sketching of distillation tank and the distillation process.

$$T_w = (f(t)/p) \times [1-\exp(-pt)] + T_{w0}\exp(-pt) \quad (26)$$

$$p = U_l/(MC)_w \quad (27)$$

$$f(t) = [(\alpha\tau)_{eff}G + U_lT_a]/(MC)_w \quad (28)$$

The relation between the amount of clean water produced with the temperature of glass cover and seawater is described below:

$$m\square_{evp} = h_{evp}(T_w-T_g)/h_f \quad (29)$$

F. Photon Exhange Membrane (PEM) Electrolysis

The water electrolysis operation is an electrolytic process, which decomposes water H_2O molecule into oxygen O_2 and hydrogen H_2 gasses with the help of an electric current, Fig. 11 show the electrolysis process. In PEM electrolysis cell, the electrolyte is a solid membrane. The H^+ ions are used for electricity conductivity.

The water decomposition process can be described by (26). At the anode, oxidation occurs where the water molecule losses electrons and reduction occurs in cathode where the H^+ ions gained electrons.

$$2H_2O + \text{electric energy} \rightarrow 2H_2 + O_2 \quad (30)$$

There will be a voltage drop across the PEM when a potential different is applied across it. These drops are characterized by a reversible drop V_{rev}, an activation drop V_{act}, a diffusion drop V_{diff} and an ohmic losses V_{ohm}. With U as the supply voltage, the model can be represented by the (31). According to Houcheng *et al.* [14], the outlet flow rate of hydrogen gas depends only on the supplied current. PEM electrolysis has advantages over alkaline electrolysis because first it does not need corrosive catalysts. Secondly, it has high current density at higher efficiency and thirdly it has good chemical and mechanical stability.

$$U = V_{rev} + V_{act} + V_{diff} + V_{ohm} \quad (31)$$

$$F_{H2} = I/2F \quad (32)$$

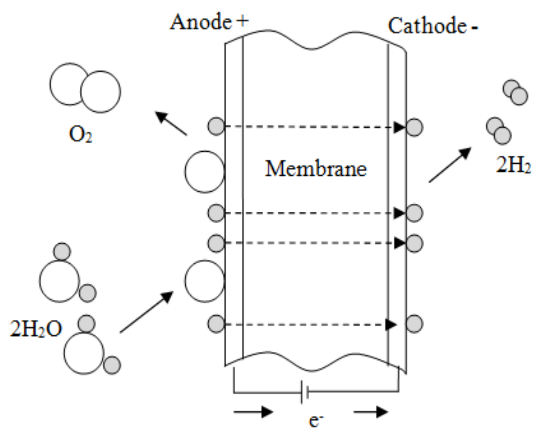

Figure 11. Schematic representation of PEM electrolysis process.

G. *Hydrogen Gas Compressor*

The hydrogen gas compressor is considered as a system within a control volume, since the mass is crossing the system boundary during the compression process. Besides, there is only one inlet and one exit and hence,

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m}_{comp} \quad (33)$$

The energy balance for this steady flow system under stated assumptions and observations can be expressed as a rate of change from (34). Where, the rates of net energy transfer by heat, work and mass equal to the rate of change in the internal kinetic energy.

$$\dot{E}_{in} = \dot{E}_{out} = dE_{sys}/dt \quad (34)$$

Since the system is in steady state, thus $dE_{system}/dt = 0$. The equation becomes:

$$\dot{E}_{in} = \dot{E}_{out} \quad (35)$$

$$P_{comp} + \dot{m}_{comp}e_{in} = Q_{out} + \dot{m}_{comp}e_{out} \quad (36)$$

$$P_{comp} = Q_{out} + \dot{m}_{comp}(e_{out}-e_{im}) \quad (37)$$

IV. RESULT AND DISCUSSION

The simulation results of the overall solar hydrogen harvesting system are mentioned in this section. Besides that, the final system efficiency of the solar hydrogen harvesting system in terms of performances, cost and technology are also discussed.

A. *Overall System Simulation*

The overall system simulation is conducted using MATLAB©, which covers the output power of the photovoltaic array, the temperature of seawater in solar still, the mass of clean water produced, the amount of hydrogen gas produced and the amount of hydrogen gas stored. The input of this simulation is the solar irradiance for a day from 8am in the morning until 6pm in the evening. The solar irradiance used is based on total average of solar irradiance for a year, from October 2011 until September 2012, Table 2. It was taken everyday, every two hours, from 8am until 6pm at Kota Kinabalu, Sabah, Malaysia.

Figure 12 showing the interpolation of the total average solar irradiance of a day. Due to the solar irradiance recorded is discrete and not continuous, thus a regression model is computed for the simulation purpose. Equation (38) represents the polynomial regression model of the total average of solar irradiance of a day, in one year, from October 2011 until September 2012.

Table 2. Average solar irradiance (October 2011 until September 2012).

Time	Solar Irradiance (W/m^2)
8am	651.0
10am	773.1
12pm	862.3
2pm	760.3
4pm	420.4
6pm	45.2

$$y = -(5.25x10^{-3})x^2 + 2.14x + 651 \quad (38)$$

From the Fig. 12, the sunlight at 8am in the morning is 651W/m^2. This is considered strong since the sunrise in Sabah, Malaysia starts around 5am in the morning. The solar irradiance is at its peak during noon, which is averagly 862.3W/m2 and begins to drop afterwards. During certain sunny days, the solar irradiance can reach up to 1200W/m^2. However, due to the tropical weather, Sabah also has some rainy days; thus, the average maximum solar irradiance is around 900W/m^2.

The output power of the photovoltaic array is very much dependent on the weather. The brighter the sunlight, the more solar irradiance it can capture. Thus, by looking at Fig. 13, the graph of output power of the PV array follows well the shape of Fig. 12. One module of the proposed system consists of eight 180W of PV panel, so that the total maximum power from the PV array could be 1440W. During the 240 minutes of simulation time, which is the peak of the whole simulation, the output power is achieved around 1200W, corresponds with a 862.3W/m^2 of solar irradiance. In the case of the first 200 minutes of simulation, the output power fluctuates a little. This could be attributed to the temperature of the PV array being not stable.

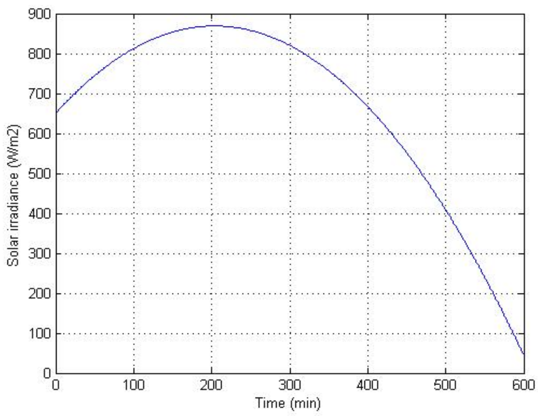

Figure 12. Total average of solar irradiance versus time.

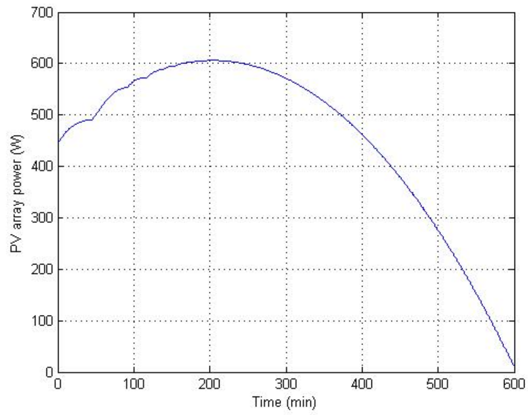

Figure 13. Photovoltaic array output power versus time.

The output of a single slope solar still in the distillation chamber is also highly dependent on the solar irradiance. Although solar still is selected for this process to reduce cost and burden on the PV. Figure 14 shows that in the solar still, the temperature of the seawater can reach between 55□C and 67□C in temperature for the glass cover. So, in ten hours, with an area of $0.25m^2$, the solar still managed to distil 1.9kg of seawater as shown in Fig. 15. The glass cover thickness of the solar still is limited to around 5mm for good heat dissipation to ensure high condensation rate.

On the other hand, for 10 hours of simulation, the PEM electrolyser managed to produce only 722 standard litres of hydrogen gas. From Fig. 16, the electrolyser only operates for around six hours, approximately from 60^{th} minute of simulation until 420^{th} minute of simulation. This is due to the high power consumption of the electrolyser. The control system is distributing the power based on the power available and the conditions of all the loads. During the beginning of the simulation, although the electrical power is enough, but there is insufficient amount of clean water for the electrolysis process. Longer operating hours of the electrolyser is possible with more PV panel installed, but it will increase the cost of the system in the other hand.

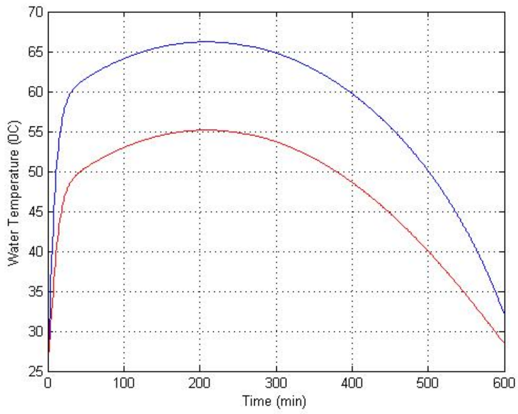

Figure 14. Temperature of seawater in solar still and temperature of glass cover versus time.

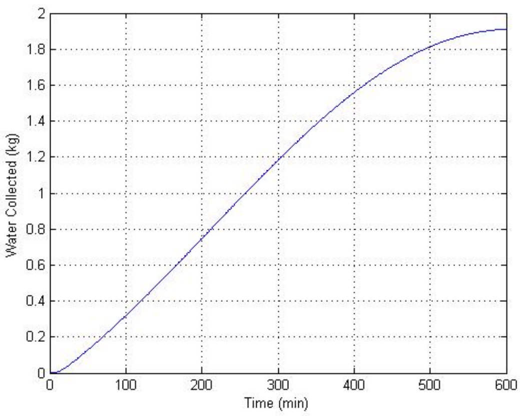

Figure 15. Mass of clean water collected versus time.

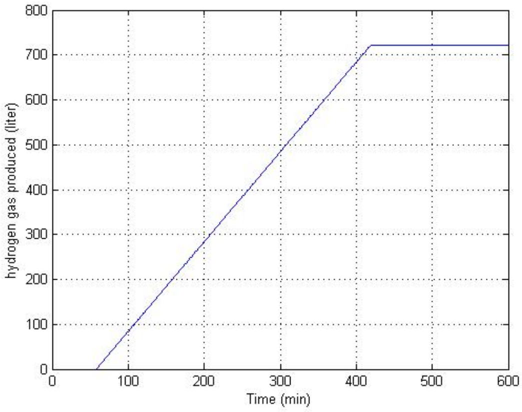

Figure 16. Amount of hydrogen gas produced versus time.

Metal hydride type of hydrogen storage is also chosen because its ease to transport compared to compressed hydrogen and liquid hydrogen; low pressure (10-30bar) during charging and discharging process. Due to the low pressure, the compressed air can be directly applied in fuel cell applications. Metal hydride canister with bigger volume can also be used to store hydrogen produced from multiple modules of the proposed system. The used of large canister can save cost and it is more convenient during the transportation.

B. System Efficiency for Solar Energy Harvesting System

The overall efficiency of a system is obtained by multiplying all the component efficiency together. The total system efficiency of solar energy harvesting can be represented by the (39),

$$\eta_{system} = \eta_{pv} \times \eta_{DC} \times \eta_{pump} \times \eta_{electrolysis} \times \eta_{compressor} \quad (39)$$

From the simulation, a single module of the proposed system with ten hours of average irradiance per day, the total system efficiency obtained is 5.24%. The efficiency is not high, mainly due to the low efficiency of the market available PV. Indeed there are many types of load in the system. Power loss in the water pump and the hydrogen compressor are unavoidable. Meanwhile, the MPPT system is the major contributor in the system efficiency, which is around 97%.

The overall system efficiency is expected to increase when more effective PV panel is used and perhaps better hydrogen storage with lower operating pressure is available. The present PV panels has about 15% of efficiency, this figure directly implies that even if the other loads can achieve 100% efficiency, still the system cannot overcome the low efficiency of PV panel. Other sources of renewable energy could be added into the system to compensate the PV panel. For example wave energy could be harvested to pump water into the distillation tank.

DOI 10.5013/IJSSST.a.13.3B.01 ISSN: 1473-804x online, 1473-8031 print

C. Feasibility Study

The solar hydrogen harvesting system is viable in terms of technology, but the implementation cost has yet to be studied. The cost of PV panels is the main contribution to the overall cost. Therefore, the optimum number of PV panels has to be determined in order to minimize the cost of the system. Equation (40) described the relationship between the number of PV panels with the power consumption of electrolyser, the minimum solar irradiance level and the maximum power generated by one PV panel under standard test condition.

$$n_{pv} = (G_{ref} \text{ x } P_{elec})/(P_{max} \text{ x } S_{lv}) \quad (40)$$

In the system, the electrolyser consumes the most electrical power, and because the hydrogen gas produced is the final output of the system, so it is very important to consider the operating hours of the electrolyser per day. The minimum solar irradiance level that is able to turn on the electrolyser is directly related to the number of PV.

Equation (38) described the profile of the solar irradiance in a day. From the profile, the output power of the PV array at any moment can be calculated using (41). The value is then compared with the power consumption of the electrolyser; hence, the operating hours of the electrolyser in a day is determined.

$$P_{pv}(t) = n_{pv} \text{ x } P_{max} \text{ x } G(t)/G_{ref} \quad (41)$$

For the amount of hydrogen gas produced per year by a single module of this system can be determined by using (42) and (43). Finally, the Return of Investment (ROI) can be calculated by dividing the cost of the system with the annual cash inflows, as shown in (44). The Fig. 17 shows the relationship between numbers of PV panels in the module with the ROI of the module. The graph shows that, the optimum number of PV panels is eight with the ROI of 50.95 years. With the same load, increasing of PV panels will only result in extra power generated and increased cost. The module will not function if the number of PV panels is less than six as it cannot meet the minimum load power consumption.

$$v_{H\_yr} = v_{H\_hr} \text{ x } t_H \text{ x } 365.25 \quad (42)$$

$$m_{H\_yr} = v_{H\_yr}/22.4 \text{ x } 2\text{x}10^{-3} \quad (43)$$

$$ROI = m_{H\_yr} \text{ x } K_{H\_kg} / K_{total} \quad (44)$$

The module in this simulation consists of eight 180W photovoltaic panel, one MPPT controller, one solar still with area of $0.25m^2$, 800W PEM water electrolyser with production rate of 120 standard litres per hour and 1000sl of metal hydride hydrogen storage canister. An estimation cost on the system is quoted to examine the ROI of this system. The estimated total cost of such system is about RM64, 000.

From the simulation model, the maximum amount of hydrogen gas obtained per day is about 920 standard litres per day, without considering the status of other loads and is averagely 30 kg per year. Thus, the annual cash inflows expected to be about RM1,260 by estimating a profit of RM42 for one kilogram of hydrogen gas. The optimum calculated payback period is 51 years. The ROI of the system is not viable at current state of solar energy harvesting technology.

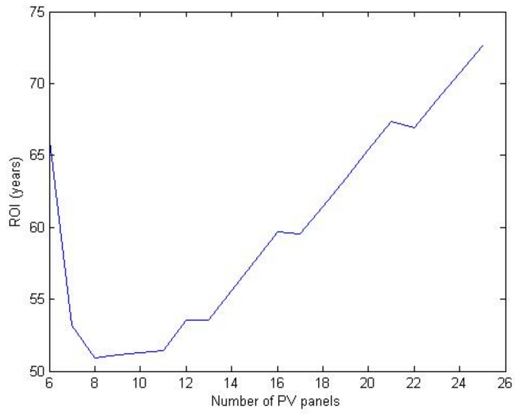

Figure 17. Return of investment versus number of PV panels plot.

Among the parts of the system, the PV panels and the solar still showed the lowest efficiency. Nevertheless, the cost efficiencies of the PV panel and seawater distillator can be improved due to mass-production, and the costs can be reduced with the rapid increase of research on the PV panel.

V. Conclusion and Future Work

From the above, the solar hydrogen harvesting system using seawater is concluded as not feasible to produce hydrogen gas using only solar irradiance at current art of technology. The system model is developed based on the number of PV panels used and the duration of sunlight available in a day. Results showed that with the ROI more than 50 years, this solar hydrogen harvesting system is not possible to substitute fossil fuel currently. However, the model of the system can become a watch dog to alert the use of this system once the solar panel technology reaches its mature stage in terms of efficiency and cost.

Acknowledgement

The authors gratefully acknowledge Material and Mineral Research Unit, Universiti Malaysia Sabah for providing facilities and support for this project. This project is also funded by the Ministry of Higher Education Malaysia under Fundamental Research Grant Scheme. The grant number is FRG0310-TK-1/2012, titled “Feasibility study for off shore hydrogen harvesting system via photovoltaic using seawater”.

References

[1] Kelly NA, Gibson TL, “Solar energy concentrating reactors for hydrogen production by photoelectrochemical water splitting”, Int J Hydrogen Energy 2008. 33(22). 6420-31.

[2] Walt Pyle, Jim Healy and Reynaldo Cortez, 1994, “*Solar hydrogen production by electrolysis*”, Home Power #39.

[3] Joshi AS, et al. 2010. "*Solar hydrogen production: A comparative performance assessment, International Journal of Hydrogen Energy*", international journal of hydrogen energy xxx (2010) 1e12.

[4] S.Z. Baykara, "*Hydrogen production by direct solar thermal decomposition of water, possibilities for improvement of process efficiency*", International Journal of Hydrogen Energy 29 (2004) 1451-1458.

[5] Houcheng Zhang, Guoxing Lin and Jincan Chen, "*Evaluation and calculation on the efficiency of a water electrolysis system for hydrogen production*", international journal of hydrogen energy 35 (2010) 10851-10858.

[6] Jeremy Lagorsea, Marcelo G.Simoesb, Abdellatif Miraouia and Philippe Costerg, "*Energy cost analysis of a solar-hydrogen hybrid energy system for stand-alone applications*", International Journal Of Hydrogen Energy 33 (2008) 2871 – 2879.

[7] Joan M. Ogden, "*Cost and performance sensitivity studies for solar photovoltaic/electrolytic hydrogen systems*", Solar Cells, 30 (1991) 515-523.

[8] Sebastian Bader, Torsten Scholzely and Bengt Oelmann, "*A Method for Dimensioning Micro-Scale Solar Energy Harvesting Systems Based on Energy Level Simulations*", 2010 IEEE/IFIP International Conference on Embedded and Ubiquitous Computing.

[9] Chao Lu, Vijay Raghunathan, and Kaushik Roy, "*Maximum Power Point Considerations in Micro-Scale Solar Energy Harvesting Systems*", ISCAS 2010: 273-276.

[10] S. Pedrazzi, G. Zini and P. Tartarini, "*Complete modeling and software implementation of a virtual solar hydrogen hybrid system*", Energy Conversion and Management 51 (2010) 122–129.

[11] Duffie, J.A., Beckman, W.A., 1991. Solar Engineering of Thermal Processes, second ed. John Wiley & Sons Inc., New York.

[12] Radwan S.M, Hassanain A.A and Abu-Zeid M.A, 2009, *"Single Slope Solar Still for Sea Water Distillation"*, World Applied Sciences Journal 7 (4): 485-497.

[13] Fernandez J and Chargoy N., 1990. "*Multistage, Indirectly Heated Solar Still*", Solar Energy 44: 2-215.

[14] Houcheng Zhang, Shanhe Su, Guoxing Lin, Jincan Chen, "*Efficiency Calculation and Configuration Design of a PEM Electrolyzer System for Hydrogen Production*", Int. J. Electrochem. Sci., 7 (2012) 4143 – 4157.

NOMENCLATURE

A_g	area of glass, m^2
a	absorpitivity
C	capacitance, F
D	duty ratio
$\dot{E}$	rate of change of kinetic energy, J/s
F	Faraday's constant, 96485 C/mol
F_{H2}	Hydrogen gas flow rate, m^3/s
G_{ref}	reference solar irradiance, 1000W/m^2
h	enthalpy, W/m^2.K
K	cost
k	Boltzmann's constant, 1.38×10^{-23}J/K
L_w	latent heat of vaporization, J/kg
L	inductance, H
M_p	number of photovoltaic panel in parallel
M_s	number of photovoltaic panel in series
m□	mass flow rate, kg/s
N_s	number of photovoltaic cell in series
n	ideality factor
P	power, W
Q	heat transfer rate, J/s
q	heat flux, W/m^2
R	universal gas constant, 8.314 J/mol.K
r	resistant, Ω
S_{lv}	minimum solar irradiance level, W/m^2
T	temperature, K
Δt	time interval, s
v	volume, m^3

Greek symbols

γ	photovoltaic cell fill factor
η	efficiency, %
μ	temperature coefficient, %/ºC
ρ	density, kg/m^3

Subscripts

b	basin
cell	photovoltaic cell
cg	convection process of glass
comp	compressor
cw	convection process of water
D	diode
diff	diffusion
dist	distillation
elec	electrolysis
evp	evaporation
L	photovoltaic cell generated
oc	open circuit
rg	radiation process of glass
rw	radiation process of water
s	series
sc	short circuit
sh	parallel
so	source
ss	photovoltaic cell saturation