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OPTIMIZING HYDROGEN PRODUCTION FROM PHOTOVOLTAIC-POWERED ALKALINE WATER ELECTROLYZER

OPTIMASI PRODUKSI HIDROGEN DARI SISTEM ELEKTROLISIS AIR ALKALI BERTENAGA SEL SURYA

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ABSTRAK

Transisi energi mengarah pada pengembangan teknologi hidrogen hijau melalui elektrolisis air menggunakan fotovoltaik. Namun, efisiensi sistem harus dikembangkan karena terpengaruh oleh sifat intermiten sinar matahari. Makalah ini mengkaji desain konverter SEPIC DC/DC untuk sel elektrolisis air dengan elektrolit basa KOH 3 M dan fotovoltaik 175 Wp berbasis silikon polikristalin. Simulasi dilakukan dengan Simulink MATLAB untuk pemodelan sel elektrolisis dan variasi penyinaran matahari 1000, 800, 600, dan 400 W/m^2. Hasil simulasi menunjukkan perlunya penurunan induktor dari 2,2 mH menjadi 1,1 mH dan peningkatan kapasitor dari 10 mF menjadi 27 mF ketika terjadi kenaikan penyinaran matahari. Efisiensi konverter mencapai 94,35% dalam kondisi dinamik. Hidrogen yang dihasilkan berkisar 4,81 hingga 5,93 kg H_2/tahun dengan peningkatan kapasitas sel elektrolisis dari 70,2 ke 174,9 W. Harga hidrogen terendah yang dapat dicapai adalah 13,08 USD/kg H_2.

Kata kunci: produksi hidrogen, fotovoltaik, elektrolit basa, konfigurasi optimal

ABSTRACT

Energy transition has led towards green hydrogen technology through photovoltaic water electrolysis. Efficiency of the system needs improvement due to fluctuative nature of solar radiation. This scientific article focuses on SEPIC DC/DC converter design in alkaline electrolyzer of 3 M KOH electrolytic cells and 175 Wp polycrystalline silicon PV module. Simulink MATLAB was used to model the electrolysis system and variation of solar irradiances of 1000, 800, 600 and 400 W/m^2. The results shows requirement of inductor reduction from 2.2 mH to 1.1 mH and capacitor increasement from 10 mF to 27 mF as the solar irradiance increased. Converter efficiency reached 94.35% under dynamic conditions. Furthermore, achieved hydrogen production are 4.81 to 5.93 kg H_2/year as the installed electrolytic cell's capacity increased from 70.2 to 174.9 W. Levelized Cost of Hydrogen under unlimited photovoltaic power capacity is 13.08 USD/kg H_2.

Keywords*: hydrogen production, photovoltaic, alkaline electrolyte, optimum configuration*

BACKGROUND

According to the Indonesia National Energy Council [1], the western part of Indonesia has the potential daily solar power of 4.5 kWh/m^2 while the eastern part could generate higher, up to 5.1 kWh/m^2. However, the current maximum national utilization of solar energy only reaches up to 100 MW, which is still far away from utilization target of 6.5 GW by 2025. It is important to increase the utilization of solar energy, both for electricity and chemical synthesis. Further example for the urgency of solar energy utilization, the East Nusa Tenggara (NTT) region as the highest potential of solar power in Indonesia still has the electrification ratio at 88%, when other areas have reached up to 99% [2]. Thus, solar power, especially using photovoltaic, will greatly

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contribute to the electricity supply in such regions. Although the development of renewable energy sources in 2020 is hampered by COVID-19, the installed capacity of photovoltaic and wind turbines is still predicted to exceed natural gas by 2023 and coal by 2024 [3]. Currently in Indonesia, the growth of solar photovoltaic utilization is taking the second fastest after hydropower.

The limitation on production time with fluctuating output become shared challenges among the new renewable energy sources, including photovoltaic. A storage system should support electricity generation by photovoltaic for night or cloudy days. Hydrogen is considered as potential energy carriers to solve the problem [4]. Electricity from photovoltaic is used for producing hydrogen via water electrolysis. The hydrogen then can be converted further into denser energy carriers such as ammonia, methanol, and methane to reduce transportation cost. However, the cost of hydrogen production using photovoltaic electrolysis is higher (up to USD 5.1/kg-H_2) compared to the hydrogen from fossil fuel sources, such as using coal gasification at USD 0.36/kg-H_2 or methane reforming at USD 0.9 – 3.2/kg-H_2. Despite the high production cost, photovoltaic hydrogen currently becomes attractive with diminishing of fossil fuel reserve.

Studies on photovoltaic hydrogen modeling have been carried out to increase solar to hydrogen conversion. Gül and Akyüz [5] studied hydrogen production from a small-scale photovoltaic/electrolysis-thermal (PV/T-E) combined system. The thermodynamic performance of the system was analyzed using numerical equations in MATLAB/Simulink. The results showed energy and exergy efficiencies of 57.7 – 69.69% and 54.4 – 60.7%, consecutively. It can achieve hydrogen production rate of 4.49 kg/year at cost 4.87 USD/kg-H_2. Sahin [6] also proposed a hydrogen production simulation using a photovoltaic-electrolysis system with load adjustment using a DC/DC converter type buck and the maximum power point tracking (MPPT) algorithm perturb & observe (P&O). The PV power transmission to the electrolysis cell can reach 93.2% at temperature of 75^{o}C and solar irradiation of 900 W/m^2.

Based on those literatures, the load compatibility between photovoltaic and electrolyzer will affect the techno-economic analysis of hydrogen production. Daily dynamic illumination in Indonesia and its effect on performance of DC/DC converters also need to be studied further. Through this study, modeling-based simulations will be explored to evaluate and optimize the process using SEPIC DC/DC converter. The combination of simulation of solar irradiation and ambient temperature and synchronization of electrolysis cell loads in dynamic conditions will allow technical and economic analysis to determine the optimum conditions for hydrogen production from photovoltaic power sources.

MATERIALS AND METHODS

The photovoltaic-electrolyzer system is modeled using an equivalent electrical circuit on the MATLAB/Simulink software. The simulation was carried out to calculate the amount of hydrogen production and the energy efficiency of each component. These results are then followed by an economic analysis of hydrogen production.

Electrolysis Cell Experiment

In this study, a simple electrolysis cell was modeled using Simulink MATLAB. The schematic diagram and experimental apparatus of the simple home-made electrolysis cell are shown on Figure 1(a) and 1(b), consecutively. Stainless steel and nickel electrode was used as in previous study with similar 3 M KOH electrolyte [7, 8]. A polypropylene container was used as chamber while PET based plastic bottle was used to separate hydrogen and oxygen gases. The simulation model was built based on the current (I) and voltage (V) characteristics of this electrolysis cell. Using power supplied by power supply CELLKIT 3005DK. The current passing through the cell was measured every 0.2 V increase in voltage until the voltage reached 7 V. The measured current and voltage will then be modeled into MATLAB/Simulink as variable resistor.

Process Simulation Method

The system consists of photovoltaic modules connected to a SEPIC DC/DC Converter and electrolysis cells (Figure 2.a). Maximum Power Point Tracker (MPPT) consists of a PWM

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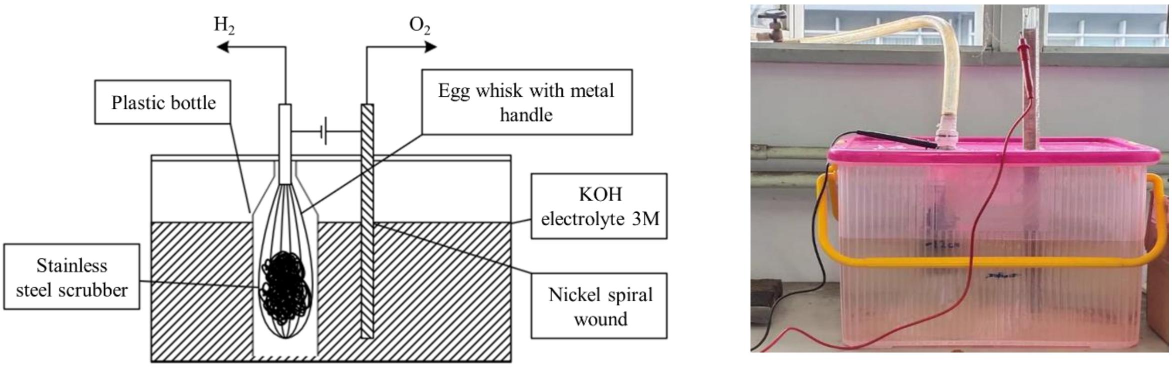
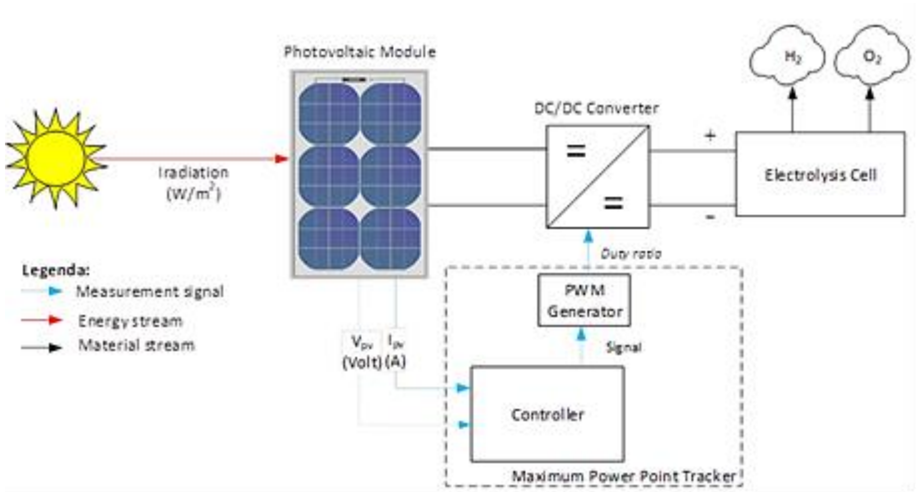


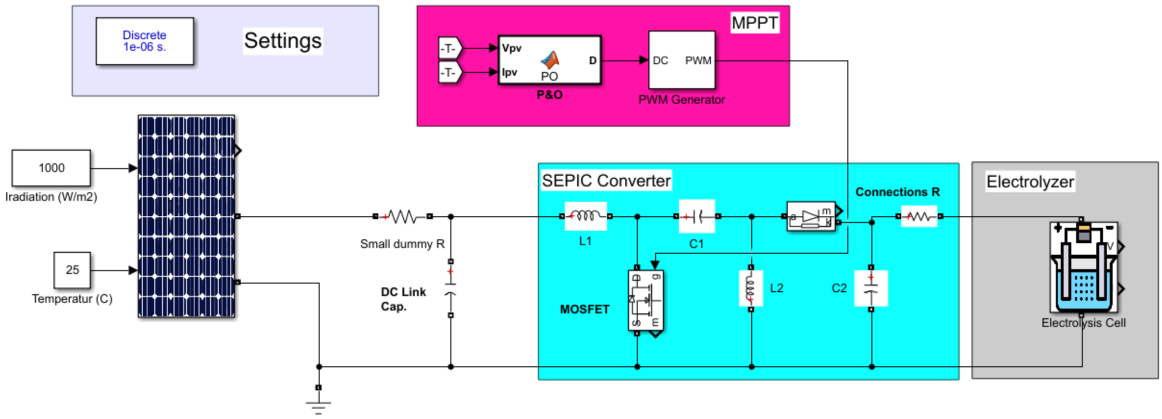
(a) (b)

Figure 1. (a) Schematic and (b) Photograph of Electrolysis Cell.

generator of 1 kHz and a controller with perturb and observe algorithm[9]. MATLAB/Simulink is used to simulate the model of hydrogen production (Figure 2.b). The detailed specification of each photovoltaic module. MPPT. and the converter used is given by Table 1. The electrolysis cell is modeled by a variable resistor and the measured current and voltage (I-V) from the experiment are used as input.



(a)



(b)

Figure 2. (a) Schematic Diagram of The Electrolysis System and (b) Simulink MATLAB Model

Table 1. Parameter for Simulink MATLAB Simulation

Specification	Value	Unit
SEPIC *Converter*		
DC Link capacitor	3000	mF
Inductor L_1	50	mH
Inductor L_2	50	mH
Capacitor C_1	10.000	mF
Capacitor C_2	10.000	mF
MPPT system		
PWM Period (frequency)	0.001 (1)	s (kHz)
PV module		
Maximum power	175.062	W
Area	1.28	m^2
Number of cells	72	-
Open circuit voltage (OCV)	44.3	V
Short circuit current (ISC)	5.29	A
OCV temperature coefficient	-0.374	V/^{o}C
ISC temperature coefficient	0.0889	A/^{o}C

Converter Sizing Calculation Method

There are limitations and essential considerations in determining parameter values in the SEPIC converter design. The schematic details and formulas regarding these limitations and concerns are shown as in Figure 3 and equations follows.

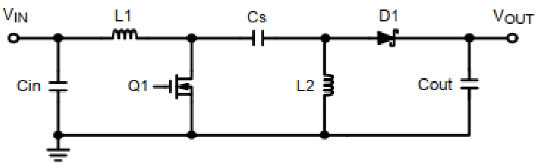


Figure 3. Schematic diagram of SEPIC DC/DC converter

For the SEPIC converter to operate in Continuous Conduction Mode (CCM) conditions, the duty cycle value used must meet the equation:

$$D=\frac{V_{out}+V_D}{V_{in}+V_{out}+V_D} \qquad \ldots(1)$$

where D is the duty ratio of the switch, V_{in} is the voltage input of converter, and V_{out} is the voltage output of converter, and V_D is the forward voltage drop of diode D_1. Based on equation (1), the maximum value of the duty cycle D_{max} can be obtained with the minimum voltage input $V_{in(min)}$ from equation:

$$D_{max}=\frac{V_{out}+V_D}{V_{in(min)}+V_{out}+V_D} \qquad \ldots(2)$$

In selecting a good inductor value used in the converter, it is essential to note that the peak-to-peak ripple value of the current passing ΔI_L through the inductor is around 40% of the maximum input current value I_N at minimum input voltage conditions. The value of the ripple current flowing in the inductor L_1 and L_2 can be obtained according to the equation:

$$\Delta I_L=I_N\times 40\%=I_{out}\times\frac{V_{out}}{V_{in(min)}}\times 40 \qquad \ldots(3)$$

where I_{out} is the output current value. Based on the above equation. The inductance L_1 and L_2 values can be determined according to the following equation.

$$L_1=L_2=L=\frac{V_{in(min)}}{\Delta I_L\times f_{sw}}\times D_{max} \qquad \ldots(4)$$

f_{sw} is the switching frequency. The formula of peak value of the current in the inductor ($I_{L1(peak)}$ and $I_{L2(peak)}$) to ensure that the inductor is not saturated is:

$$I_{L1(peak)}=I_{out}\times\frac{V_{out}+V_D}{V_{in(min)}}\times\left(1+\frac{40\%}{2}\right) \qquad \ldots(5)$$

$$I_{L2(peak)}=I_{out}\times\left(1+\frac{40\%}{2}\right) \qquad \ldots(6)$$

Assuming that L_1 and L_2 are in the same core (L'_1 and L'_2), the inductance value in the above equation can be substituted with 2L (mutual inductance). Therefore, the value of the inductance L can be calculated according to the following equation:

$$L'_1=L'_2=\frac{L}{2}=\frac{V_{in(min)}}{2\times\Delta I_L\times f_{sw}}\times D_{max} \qquad \ldots(7)$$

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The determination of the value of the capacitance parameter in the coupling capacitor depends on the value of the RMS current $I_{cout(RMS)}$ according to the equation:

$$I_{Cout(RMS)}=I_{out}\times\sqrt{\frac{V_{out}+V_D}{V_{in(min)}}} \quad \ldots(8)$$

In addition to the Equation (8), other limitations need to be considered. The limits can be expressed in the following equations.

$$ESR\leq\frac{V_{ripple}\times 0.5}{I_{L1(peak)}+I_{L2(peak)}} \quad \ldots(9)$$

$$C_{out}\geq\frac{I_{out}\times D}{V_{ripple}\times 0.5\times f_{sw}} \quad \ldots(10)$$

where V_{ripple} is voltage ripple. The design parameters of the coupling capacitors must meet the equations of RMS current, ESR (Equivalent Series Resistance) and C_{out} capacitance.

RESULT AND DISCUSSION

Electrolysis Cell Experiment

An experimental model of a simple electrolysis cell using CELLKIT 3005DK power supply as the power source has been built. The current measured at every 0.2 V increment from 0 to 7 V is displayed in Figure 4. The current potential (I-V) curve represents the characteristics of the experimental electrolyzer model.

Using the obtained I-V curve, a simulation model is then built in MATLAB/Simulink software as block 'variable resistor' inside the system. With the assumption of homogenous concentration & temperature throughout the chamber and constant electrode performance, the model then be used to study the effect of electrolysis cell configuration and the effect of DC/DC converter on PV efficiency and H_2 production.

The Effect of Electrolysis Cells Configuration

Series and parallel electrolysis cell circuits do not affect the efficiency of the cell, but rather affect the efficiency of power transmission from the PV to the electrolysis cell (Figure 5.a). As the number of electrolysis cells increases, cells addition on parallel circuit reduces the efficiency of the PV system (Figure 5.b). The condition is caused by the shifting on resistance slope on the I-V curve of the electrolysis cell, away from intersection with the maximum power point of the PV module (Figure 6). The highest efficiency of the system is achieved when the slope matches with the maximum power of PV module. It this case, the maximum efficiency is reached when 5 electrolysis cells are connected in series.

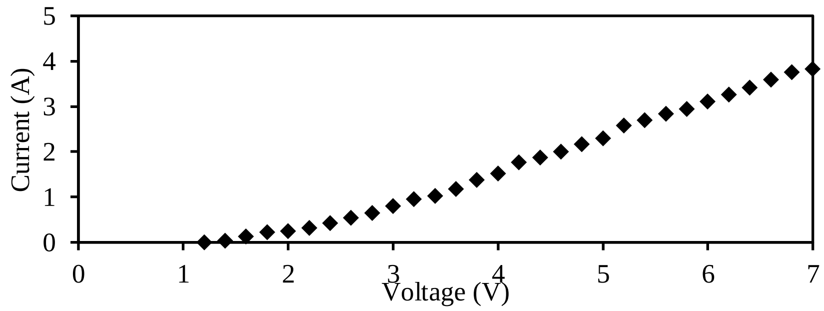

Figure 4. Current and Voltage Characteristics of the Experimental Model at 27°C

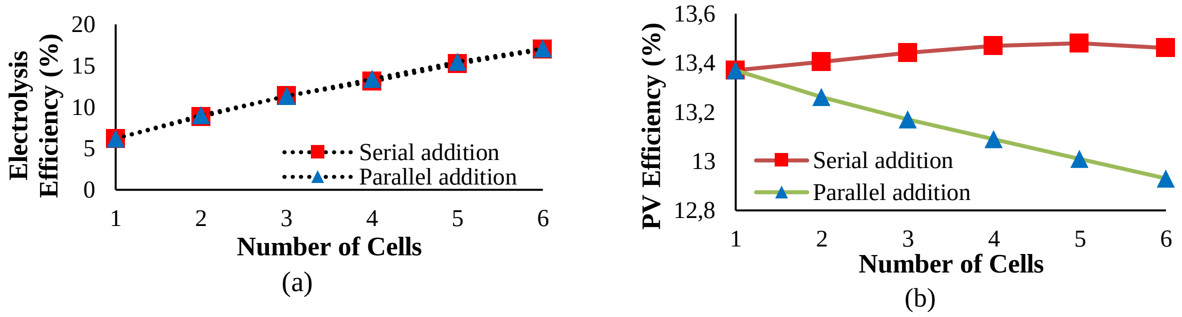

Figure 5. Electrolysis Cells Configuration Effect on (a) Electrolysis Efficiency and (b) PV Efficiency

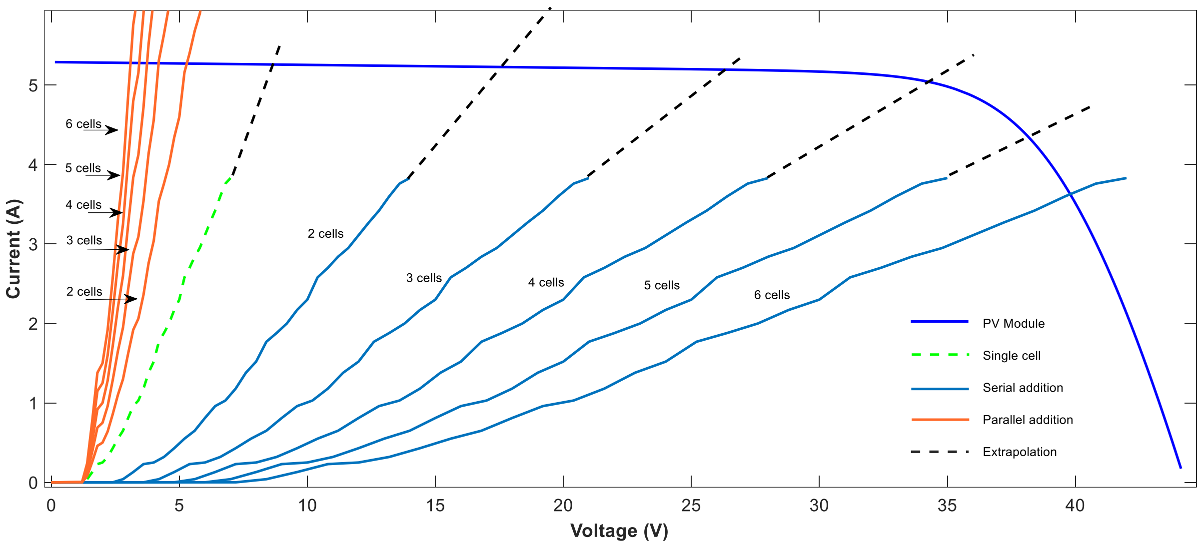

Figure 6. I-V curve of PV Module and Electrolysis Eells in Different Configuration

To optimize the photovoltaic efficiency, it is necessary to calculate the required number of cells both in series (n_{serial}) and parallel ($n_{parallel}$). It can be done by modifying the electrolysis curve intersecting the maximum PV power point. The number of cells in series and parallel are related respectively to the voltage and current of the PV module at the maximum power point. Thus, in an electrolysis system that uses a PV module with optimum power P_{PV} at the PV voltage of V_{PV}, the number of electrolysis cells required in series and parallel can be calculated by the Equations (11). Number of cells in parallel can be calculated by Equation (12) as the electrolysis current I_{cell} is related to its voltage.

$$n_{serial}=\frac{V_{PV}}{P_{PV}} \quad \dots \qquad (11)$$

$$n_{parallel}=\frac{P_{PV}}{I_{cell} \text{ x } V_{PV}} \quad \dots \qquad (12)$$

The thing that needs to be set is that the working voltage of the cell corresponds to the desired electrolysis efficiency. A working voltage of 1.481 volts can be selected for the reaction to occur isothermally[10]. Although low voltage provides higher efficiency (Figure 7.a), the total number of cells needed increases (Figure 7.b) and thus affects the stack cost. Moreover, the electrolysis curve should remain intersecting with the maximum PV power point by this method to optimize the process.

In a typical electrolysis cell with operation under the maximum current density, the cell current corresponds with the voltage used. The higher the voltage leads to the higher cell current and thus higher hydrogen production. Most industrial electrolyzer are advanced alkaline electrolyzer type that could operate at pressure up to 7 bar and temperature of 80^o C. Typically, the electrolyzer have zero spacing geometry to minimize current loss from spacing in between electrode and bipolar or in series configuration to reduce overall module space and achieve higher current densities [11-13]. In example, The PHOEBUS plant in Jülich electrolyzer[14] with such features could achieve current density close to 300 mA/cm^2 using 1.7 V/cell, operating condition of 7 bar and 80^o C. In theory, the cell with zero gap can be operated up to 1 A/cm^2 under 8 bar at minimum loading of 10% [12].

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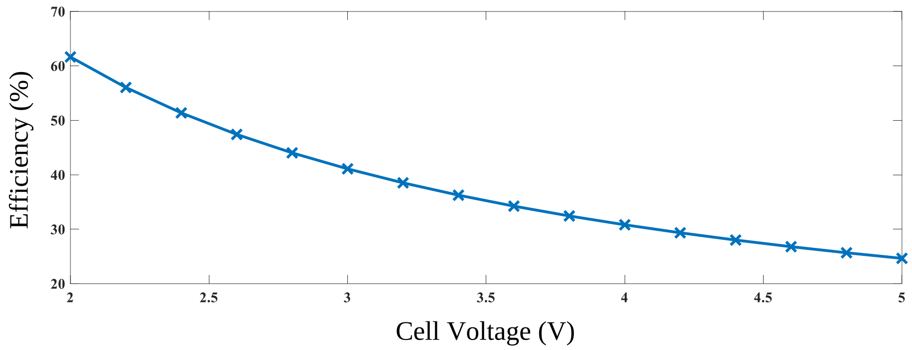
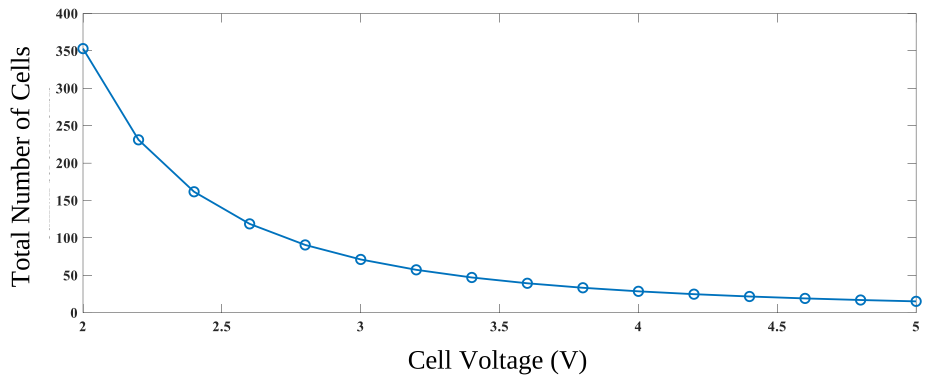


(a)



(b)

Figure 7. Relation Between the Electrolysis Cell Voltage to (a) Cell Efficiency and (b) Total Number of Cells

Table 2. Parameter for Photovoltaic Hydrogen Generator System

PV			Electrolysis load		Converter Components			ns	np	Avg. System Eff. (%)	H_2 Prod. (kg/y)	Cell capacity (W)
Irradiation (W/m^2)	Voltage (V)	Power (W)	Voltage (V)	Current (A)	L_1 (mH)	L_2 (mH)	Cs (mF)					
1000	35.8	175.1	35.8	4.9	1	1	27	16.6	11.3	92.1	5.9	175.0
800	36.0	140.8	36.0	3.9	1.2	1.2	20	16.6	9.1	92.0	5.7	140.8
600	35.9	105.8	35.9	2.9	1.5	1.5	15	16.6	6.8	91.8	5.3	105.8
400	35.7	70.2	35.7	2.0	2.2	2.2	10	16.6	4.5	91.2	4.8	70.2

The Effect of Converter Sizing to System Efficiency

Based on the simulation carried out, the detailed data of photovoltaic hydrogen system is shown in Table 2. The use of SEPIC DC/DC converter in a single electrolysis cell would give a significant increase in the efficiency of power transmission. One simulated a similar system in a buck converter and achieved 90.4% to 90% efficiency at temperatures of 25 °C to 50 °C on 1000 W/m^2 irradiance. Other literature observed boost-based (step-up) DC/DC converter at higher switching frequency of 100 kHz and achieved 85% efficiency with the basic boost converter [15]. When modified, boost derived MIESC SC-cell converter could have up to 96% efficiency on a photovoltaic system[16]. However, the calculated efficiency in this study is lower than the average[17]. High resistance of our electrolyzer is supposed to reduce the utilization of solar energy on the system.

Based on simulation, even if P&O method performs better in accuracy than peak current control method, SEPIC converter is more suitable due to our low-power system [18]. The SEPIC converter can directly convert input to output without the requirement of temporary energy storage in an inductor, reducing energy losses.

Therefore, further study was performed based on this converter type.

Annual hydrogen production is estimated based on Equations (13) to (15). P_{PV} is power of photovoltaic system (kWp), P_{EL} is power usage on electrolyzer (kW), Levelised Cost of Hydrogen (LCOH) is capital and production cost of photovoltaic hydrogen (USD/kg-H_2), and $\dot{m}H_2$ is daily average of hydrogen production in optimum condition. The calculated LCOH as function of power ratio of electrolyzer to PV is shown in Figure 9.

$$P_{EL}=P_{PV}\times 1,15\times\left(1-\exp\left(-0,5479\times\left(\frac{P_{PV}}{1000}\right)^{0,2612}\right)\right) \quad \ldots(13)$$

$$LCOH=13,08\times\left(1+\left(\frac{19,35}{P_{PV}}\right)^{0,24358}\right) \quad \ldots(14)$$

$$\dot{m}H_2=804,65\times 10^{-3}\times P_{PV} \quad \ldots(15)$$

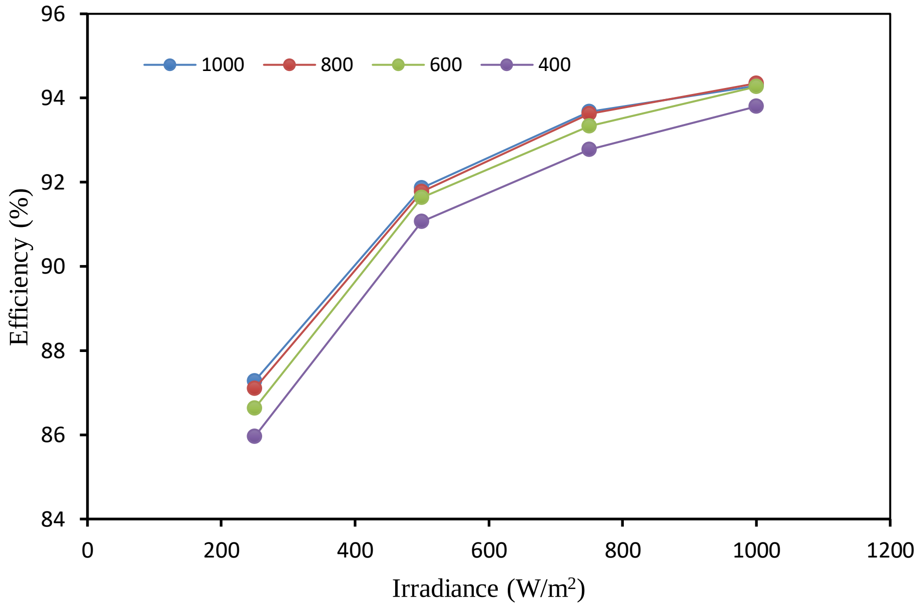


Figure 8. Relation Between the Irradiation and Photovoltaic Hydrogen Generator System Efficiency

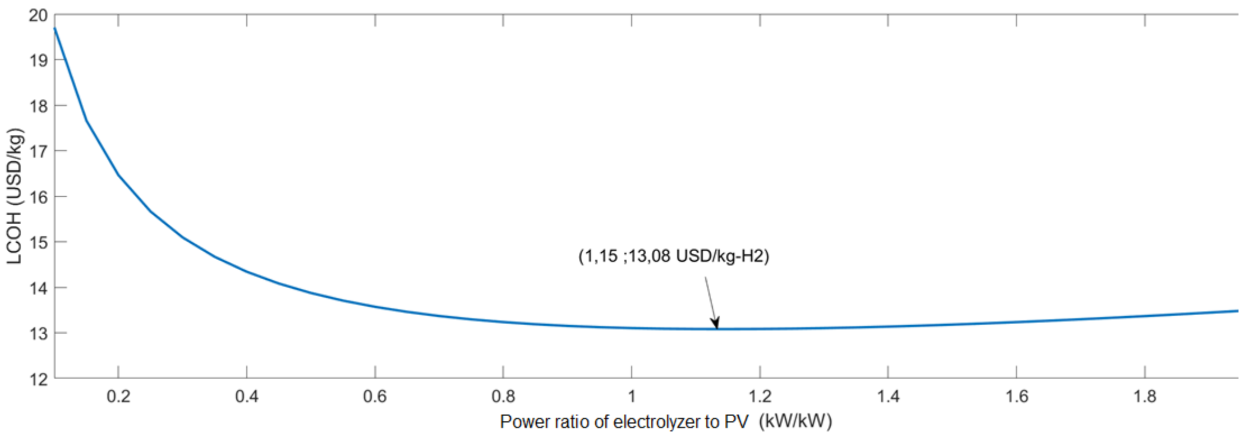


Figure 9. Levelized Cost of Hydrogen (LCOH) under Unlimited Photovoltaic Capacity

Each combination of photovoltaic and electrolyzer has optimum power ratio which provide the lowest production cost. Based on the simulation, the optimum condition is achieved at lower electrolyzer power when photovoltaic capacity is lower than 151.32 MWp. At certain photovoltaic power capacity, production cost decreases with increasing installed electrolyzer due to increasing of efficiency. Increasing the ratio of photovoltaic to electrolyzer however slightly increases capital cost, as well as LCOH. The LCOH under unlimited photovoltaic power capacity shows that the lowest production cost is 13,08 USD/ kg-H_2 (Figure 9). The high production cost is caused due to the electrolyzer cannot be operated 24 hours a day and low efficiency of the electrolyzer.

CONCLUSIONS

Synchronization of photovoltaic and electrolyzer power is essential for efficient photovoltaic hydrogen production system. The use of SEPIC DC/DC converter can increase the efficiency up to 95% (Figure 8). The SEPIC converter is the most suitable for low power system because it can transfer energy directly from input to output, reducing energy losses. On the most optimum condition for the simulation, LCOH is 13,08 USD/kg-H_2 when the electrolyzer power 1.15 times of the photovoltaic power.

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