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POTENTIAL OF HYDROGEN PRODUCTION SYSTEM FROM PHOTOVOLTAIC POWER GENERATION

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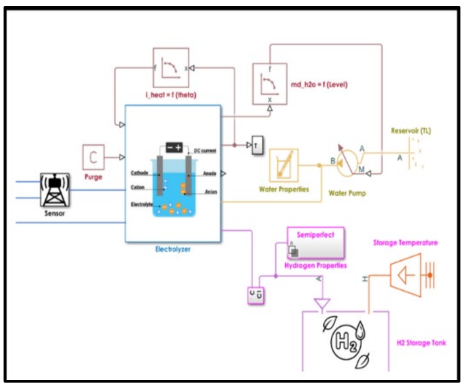
Graphical abstract



Abstract

Rising Carbon Dioxide (CO_2) levels and global warming concerns challenge the sustainability of fossil fuels as primary energy sources. Hydrogen is emerging as a crucial energy carrier, offering reduced carbon emissions and minimal harmful gases. Methods like hydrocarbon reforming and water electrolysis, especially when powered by renewable sources like wind and solar, enable hydrogen production. Hydrogen's purity and compatibility with fuel cells make it an eco-friendly alternative with high energy output. This project models a solar Photovoltaic (PV)-based hydrogen production system to address environmental concerns. Using MATLAB/Simulink for dynamic simulation, it accurately represents and analyses the hydrogen production for different regions which having different irradiances. Initial results highlight V-I and V-P curves for PV systems, revealing optimal conditions for efficient hydrogen production through electrolysis. This research advances sustainable hydrogen generation methods, emphasizing solar PV's potential to foster an eco-friendly and efficient energy landscape.

Keywords: Photovoltaic, Electrolysis, Hydrogen, Modelling, Simulink

Abstrak

Peningkatan Karbon dioksida *(CO_2)* dan kebimbangan pemanasan global mencabar kelestarian bahan bakar fosil sebagai sumber tenaga utama. Hidrogen, sebagai pengangkut tenaga penting untuk pembangunan lestari, mengurangkan pelepasan karbon dan gas berbahaya. Kaedah reformasi hidrokarbon dan elektrolisis air membolehkan penghasilan hidrogen dari sumber tenaga boleh diperbaharui seperti angin dan solar. Hidrogen, dengan keasliannya terhadap sel bahan api, adalah alternatif mesra alam dengan hasil tenaga tinggi. Projek ini memodelkan sistem pengeluaran hidrogen menggunakan tenaga fotovoltan solar (PV) untuk membangun, menganalisis, dan mengesahkan kecekapan model tersebut. MATLAB/Simulink digunakan sebagai alat simulasi dinamik untuk perwakilan dan analisis pengeluaran hidrogen untuk kawasan berbeza yang mempunyai sinaran cahaya solar yang berbeza-beza. Keputusan awal menunjukkan graf ciri V-I dan V-P sistem PV, menyoroti keadaan optimum bagi pengeluaran hidrogen yang efisien melalui elektrolisis. Penyelidikan ini menyumbang kepada kemajuan kaedah lestari dalam penghasilan hidrogen, menekankan potensi PV solar dalam mencapai landskap tenaga yang mesra alam dan cekap.

Kata kunci: Photovoltaik, Elektrolisis, Hidrogen, Pemodelan, Simulink

1.0 INTRODUCTION

Increases in the concentration of Carbon Dioxide (CO_2) in the atmosphere of the Earth, as well as concerns over the phenomena of global warming, are putting the continued dependence on fossil fuels as the dominant source of energy consumption across the globe in jeopardy. Within the framework of promoting sustainable development in the next years, it is projected that hydrogen will play a vital role as a carrier of energy. The use of this technology in combustion devices or fuel cells has the potential to result in the emission of carbon that is insignificant and the emission of other harmful gases that is restricted [1-5]. Creating hydrogen requires the use of alternative sources that are less harmful to the environment, which in turn entails the utilization of energy. Hydrocarbon reforming is a technique that is neither ecologically clean nor renewable when considering its life cycle, it is now possible to accomplish profitable generation of hydrogen by this method [3-7]. Electrolysis of water (H_2O) is another method for obtaining hydrogen. This method results in the separation of hydrogen (H_2) and oxygen (O_2) from water [8-12]. The electrolysis of water is a well-known technique that is noted for its ability to separate the molecules that make up water. In order to get the necessary energy for this electrolysis process, it is possible to obtain it from a wide range of renewable energy sources, such as wind, solar, hydro, and other sources that are beneficial to the environment [13-16]. This is one of the reasons why the academic community has shown a substantial amount of interest in the exploration of hydrogen synthesis that is obtained from renewable energy sources [17-20]. As a result of the fact that it does not produce any emissions of carbon dioxide, hydrogen is considered to be a completely pure form of fuel, making it an ecologically favourable alternative. Additionally, the fact that it is compatible with fuel cells makes it possible to generate enough amounts of electricity. The energy output of hydrogen is 122 kJ/g, which is much higher than the energy production of hydrocarbon fuels by a ratio of 2.75 [2, 8].

As a consequence of this, hydrogen provides advantageous qualities that distinguish it as a viable fuel alternative for internal combustion engines in the automobile sector [8-9]. By demonstrating characteristics that are comparable to those that are often associated with petrol, hydrogen has the potential to serve as a suitable fuel source for internal combustion engines [2, 8, 9]. One of the distinguishing features of hydrogen as a fuel for transportation is that it has a high effective octane rating, a rapid combustion rate, and no toxicity or tendency to produce ozone. Hydrogen also has a relatively low toxicity level [4, 8]. In comparison to methane (5.3-15% by volume) and petrol (1-7.6% by volume), this material has a much wider range of flammability in air, which is calculated to be between 4 and 75% by volume [9-10]. Several different types of material, both solid and liquid, have the capacity to store hydrogen via chemical or physiochemical processes. Carbon nanostructures, metal hydrides, alanates, borohydrides, methane, methanol, and light hydrocarbons are some of the substances that fall under this category [13,14,17].

2.0 METHODOLOGY

Figure 1 depicts the streamlined process of harnessing solar energy for hydrogen production. Solar panels capture sunlight and convert it into electricity, which is then channeled to a DC-DC (Direct Current to Direct Current) converter to regulate voltage levels for optimal performance. Subsequently, the electricity is directed to an electrolyzer where water undergoes electrolysis, splitting into hydrogen and oxygen. The produced hydrogen is stored efficiently for future use, ensuring a renewable and sustainable energy cycle. This integrated system underscores the potential for solar energy to drive clean hydrogen production, offering a promising avenue for green energy solutions.

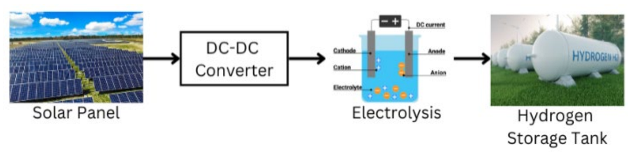


Figure 1 Project block diagram

A. Photovoltaic

In a photovoltaic panel, solar energy is converted into electrical power. Figure 2 shows the equivalent circuit of a photovoltaic cell, with the cell photocurrent represented by the current source I_{ph}. The intrinsic shunt and series resistances, R_{sh} and R_s, are typically very large and small, respectively, and can be disregarded for simplicity. PV cells are combined into larger units called PV modules, which are then connected in parallel or series to form PV arrays used in photovoltaic systems to generate power.

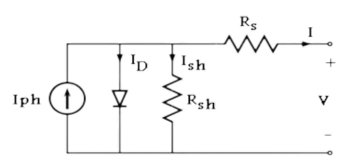


Figure 2 PV cell equivalent circuit

The following equation can be used to represent a photovoltaic panel PV:

$$I = I_{ph} - I_o\left[e^{\frac{q(V+IR_s)}{nKNT}} - 1\right] - I_{sh} \quad (1)$$

The photo-current, I_{ph} is defined as follow in the equation:

$$I_{ph} = [I_{sc} + ki(T - 2980)]\frac{G}{1000} \quad (2)$$

The saturation current, I_o is defined by the equation:

$$I_o = I_{rs}\left[\frac{T}{T_n}\right]3e^{\left[\frac{qEgo\left(\frac{1}{T_n}-\frac{1}{T}\right)}{nK}\right]} \quad (3)$$

The reverse saturation current, I_{rs} is expressed by the equation:

$$I_{rs} = \frac{I_{sc}}{e^{\left(\frac{qV_{OC}}{nNsKT}\right)-1}} \quad (4)$$

The current through shunt resistor, I_{sh} can be calculated using the equation:

$$I_{sh} = \left(\frac{V+I_{Rs}}{R_{sh}}\right) \quad (5)$$

B. DC-DC Converter (Buck Converter)

A buck converter regulates and optimizes voltage from PV panels to match the electrolyzer's requirements. It uses a switch, inductor, diode, and capacitor. The switch opens and closes periodically, charging the inductor when closed and discharging through the diode into the output capacitor when open, thus stepping down the voltage. The voltage conversion ratio (D) of the buck converter can be calculated using the following formula:

$$V_{out} = V_{in} \times D \quad (6)$$

Where:
V_{out} = Output voltage after the conversion
V_{in} = Input voltage from solar panel
D = Duty cycle

Adjusting the buck converter's duty cycle (D) is precisely controls the output voltage for the electrolyzer, which efficiently utilizing solar energy from PV panels and enhancing the hydrogen production system's performance.

C. Electrolysis (Electrolyzer)

In the process of electrolysis, water molecules are split up into hydrogen and oxygen gases by the utilisation of electrical energy as shown in Figure 3. It is comprised of two electrodes that are immersed in water. The electrolyzer has a water reservoir that is continuously replenished. Water temperature is regulated by diverting current through a thermal resistor. Generated hydrogen is stored in a temperature-controlled tank. Hydrogen production increases with input current, represented as a direct current load. The electrolyzer's electrical efficiency is calculated using equation (7):

$$\eta E_{lz} = \eta l \times \eta V \quad (7)$$

The current efficiency at 313.15K is given by the following equation (8):

$$\eta l = 9.65 \times \exp\left(\frac{0.09}{lE_{lz}} - \frac{75.7}{l^2E_{lz}}\right) \quad (8)$$

To minimize the complexity of analyzing the system, set the current efficiency ηl = 100%. The working voltage of electrolyzer defined in the equation (9):

$$VH = -\frac{\Delta H}{2\times F} = \frac{285.84\frac{kj}{mol}}{2\times 96487} = 1.48V \quad (9)$$

The electrolyzer voltage efficiency is represented by the equation (10):

$$\eta V = \frac{1.48}{VE_{lz}} \times 100\% \quad (10)$$

In this work, the voltage efficiency is 74%. Therefore, the working voltage VEl_{ez} is equal to (1.48/0.74). The amount of hydrogen generated by the electrolyzer during one hour may be determined following equation (11):

$$\eta H_2 = \frac{lE_{lz}\times NE_{lz}}{2\times F} \times \eta l \times 3600 \quad (11)$$

The electrolyzer's power is determined by with equation (12):

$$PE_{lz} = IE_{lz} \times VE_{lz} \times NE_{lz} \quad (12)$$

As a consequence, the flow rate of hydrogen produced an electrolyzer of rated power of 200kW as follows:

$$\begin{aligned}\eta H_2 &= \frac{lE_{lz}\times NE_{lz}}{2\times F} \times \eta l \times 3600 \quad (13)\\ &= \frac{PE_{lz}}{VE_{lz}\times 2\times 96487} \times 1 \times 3600\\ &= \frac{200\times 1000\times 3600}{2\times 2\times 96487}\\ &= 1865.53(mol/h)\end{aligned}$$

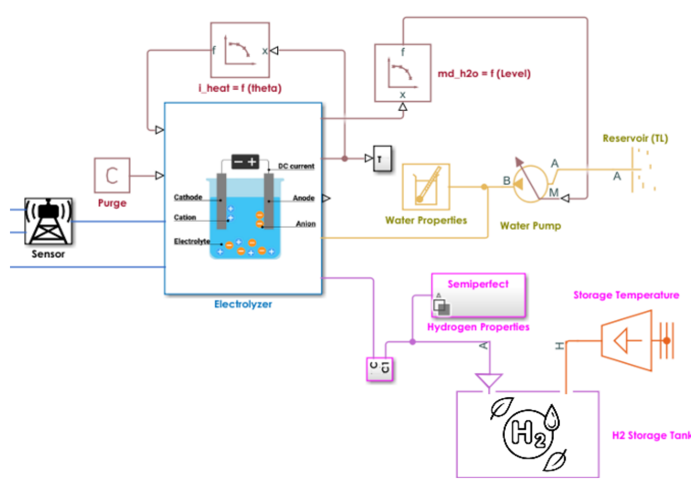


Figure 3 Sub-system electrolyzer

3.0 RESULTS AND DISCUSSION

Each element of the hydrogen production and storage system is independently simulated in MATLAB/Simulink as presented in Figure 4. Each block, including water electrolysis, hydrogen tank, DC-DC buck converter and photovoltaic panels, is meticulously developed and validated for compatibility. The simulation is versatile, representing various scenarios and the key model inputs are shown in Table 1.

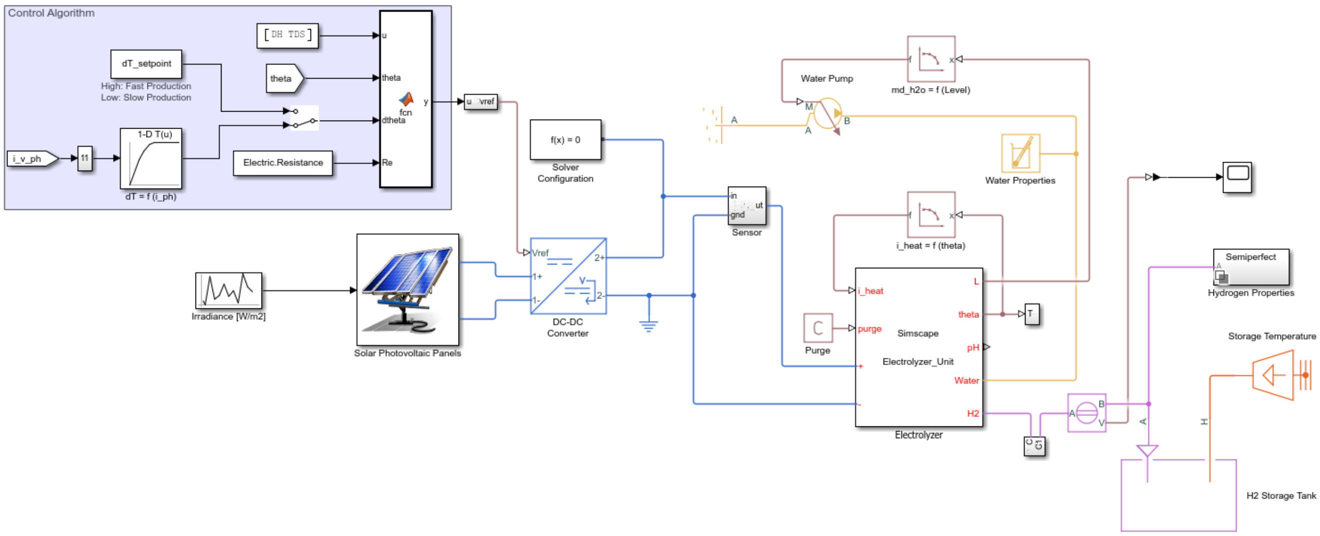


Figure 4 Simulation diagram [20]

Table 1 Simulation parameters

No	PV Panel	Value
1	Number of solar panel	1
2	Number of solar cells	70
3	Short circuit current, I_{SC} (A)	3.8
4	Open circuit voltage, V_{OC} (V)	0.586
5	Max power (W)	150
	Electrolyzer	
6	Rated power (kW)	200
7	Number of cells	50
8	Number of Electrode pairs	2
9	Resistance (Ω)	0.25
10	Heat Resistance (Ω)	25
	Hydrogen Storage Tank	
11	Volume (m³)	1
12	Temperature (K)	273.15
13	Initial state of charge (soc)	0%
14	Minimum limit of soc	30%
15	Maximum limit of soc	95%

There are five different types of cases involving varying levels of irradiance observed at different locations as shown in Table 2. The cases are; Case1: Kelibi, Tunisia, Case2: Chuping, Perlis, Case3: UTeM, Melaka, Case4: Sibu, Sarawak and Case5: Kota Kinabalu, Sabah.

Table 2 Different type of cases for Input (PV)

Case	Average Irradiance (W/m2)	Voltage (V)	Current (A)	Energy Consumed (kWh)
1	787	546.7	496.1	1163
2	699	563.3	439.2	1060
3	648	569.2	408.9	994.3
4	630	572.4	397.7	973.4
5	519	593.6	328.7	831.7

To compare the performance of photovoltaic (PV) systems and hydrogen production via electrolysis across five locations, key factors such as average irradiance, PV voltage, PV current, energy consumption, electrolysis voltage and current, hydrogen pressure, mass rate, and volumetric rate are evaluated as recored in Table 3 and 4. Each location's unique climate affects PV and electrolysis performance.

Table 3 Different type of cases for Output (Electrolysis)

case	Voltage (V)	Current (A)	Energy Consumed (kWh)
1	240.1	1094	1138
2	240.1	995.5	1035
3	240	935.7	969.7
4	240	914.4	948.7
5	239.9	777.8	806.7

Table 4 Different type of cases for Output (Hydrogen)

case	Pressure (bar)	Mass Rate (kg/hr)	Volumetric Rate (m³/hr)
1	98.39	2.022	0.6033
2	89.36	1.838	0.5887
3	83.66	1.725	0.5803
4	81.83	1.685	0.5748
5	69.37	1.429	0.5586

Case 1: Kelibi, Tunisia, the highest average irradiance of 787W/m² results in substantial PV voltage (546.7V), current (496.1A), and energy consumption (1163kWh). Electrolysis consumes 1138kWh, producing hydrogen at 2.022kg/hr and 0.6033m³/hr at 98.39bar. Kelibi's high irradiance boosts both PV and electrolysis performance.

Case 2: Chuping, Perlis, irradiance is 699W/m², yielding a PV voltage of 563.3V, current of 439.2A, and energy consumption of 1060kWh. Electrolysis consumes 1035kWh, producing 1.838kg/hr and 0.5887m³/hr at 89.36bar. Slightly lower irradiance results in reduced efficiencies.

Case 3: UTeM, Melaka, irradiance is 648W/m², resulting in a PV voltage of 569.2V, current of 408.9A, and energy consumption of 994.3kWh. Electrolysis consumes 969.7kWh, producing 1.725kg/hr and 0.5803m³/hr at 83.66bar. Lower irradiance decreases performance.

Case 4: Sibu, Sarawak, irradiance is 630W/m², leading to a PV voltage of 572.4V, current of 397.7A, and energy consumption of 973.4kWh. Electrolysis consumes 948.7kWh, producing 1.685kg/hr and 0.5748m³/hr at 81.83bar. Performance is slightly lower than in UTeM.

Case 5: Kota Kinabalu, Sabah, the lowest irradiance of 519W/m² results in a PV voltage of 593.6V, current of 328.7A, and energy consumption of 831.7kWh. Electrolysis consumes 806.7kWh, producing 1.429kg/hr and 0.5586m³/hr at 69.37bar. The low irradiance leads to the lowest performance.

In summary, higher irradiance, as seen in Kelibi, leads to better PV and electrolysis performance, while lower irradiance, as in Kota Kinabalu, results in reduced efficiency and hydrogen production.

Figure 5 shows the relationship between hydrogen pressure (bar) and irradiance (W/m²) across five locations. Each data point represents a location's average irradiance and hydrogen pressure. The positive trend line indicates that higher irradiance generally leads to higher hydrogen pressure. This trend is evident as the data points closely follow the line, demonstrating a clear relationship between irradiance and hydrogen pressure.

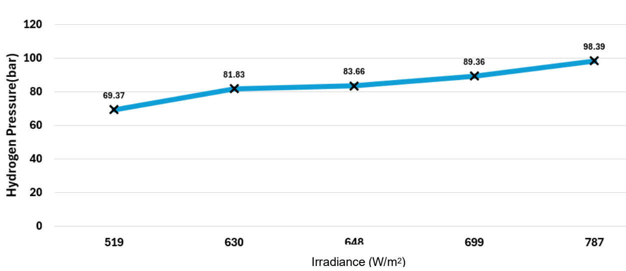


Figure 5 Hydrogen Pressure(bar) vs Irradiance(W/m²)

Figure 6 shows the correlation between hydrogen mass rate (kg/hr) and irradiance (W/m²). As irradiance increases from 519 W/m² to 787 W/m², the hydrogen mass rate also rises. At 519 W/m², the rate is 1.429 kg/hr; at 630 W/m², it's 1.685 kg/hr; at 648 W/m², 1.725 kg/hr; at 699 W/m², 1.838 kg/hr; and at 787 W/m², it peaks at 2.022 kg/hr. This trend indicates that higher irradiance leads to increased hydrogen production. The higher the irradiance provides more photons to excite electrons in photocatalytic materials, which will increas the rate of water splitting reactions. Thus, to optimize the hidrogen production is by controlling the solar source or collecting system to suite with operational intensity.

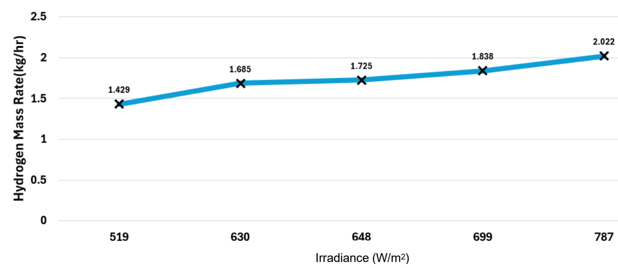


Figure 6 Hydrogen Mass Rate(kg/hr) vs Irradiance(W/m²)

Figure 7 shows the relationship between solar irradiance and hydrogen production rate (m³/hr) across five locations. As irradiance increases, so does the hydrogen volumetric rate. At 519 W/m² (Kota Kinabalu), the rate is 0.5586 m³/hr. At 630 W/m² (Sibu), it rises to 0.5748 m³/hr. At 648 W/m² (UTeM), it reaches 0.5803 m³/hr. At 699 W/m² (Chuping), it increases to 0.5887 m³/hr. At 787 W/m² (Kelibi), it peaks at 0.6033 m³/hr. This trend highlights the strong influence of solar irradiance on hydrogen production. The increase in irradiance results in higher hydrogen volumetric rates because greater light intensity provides more energy to power the reactions involved in hydrogen generation, such as photocatalysis or photoelectrochemical processes. Areas with high solar irradiance also can maximize hydrogen output, making renewable hydrogen production more viable on a large scale.

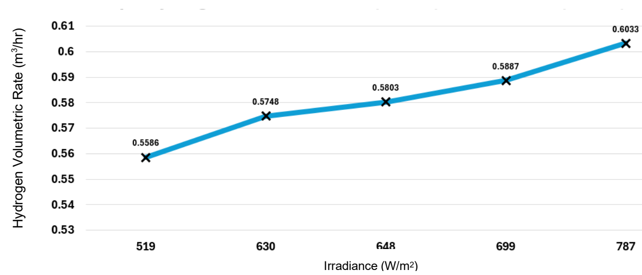


Figure 7 Hydrogen Volumetric Rate(m³/hr) vs Irradiance(W/m²)

Figure 8 shows the relationship between average PV voltage and hydrogen pressure across five locations. As PV voltage increases, hydrogen pressure decreases. At 546.7V (Kelibi, Tunisia), the pressure is highest at 98.39 bar. At 563.3V (Chuping, Perlis), it drops to 89.36 bar. At 569.2V (UTeM, Melaka), it further decreases to 83.66 bar. At 572.4V (Sibu, Sarawak), it is 81.83 bar, and at 593.6V (Kota Kinabalu, Sabah), the pressure is lowest at 69.37 bar. This negative correlation indicates that higher PV voltages lead to lower hydrogen pressures, showing the significant influence of voltage on the electrolysis process.

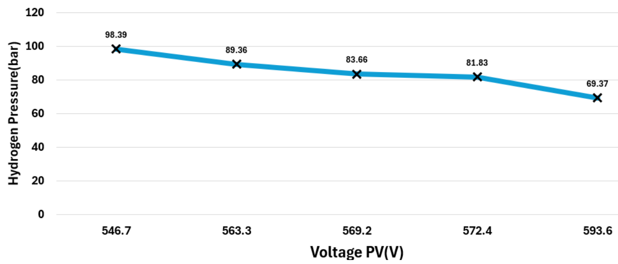


Figure 8 Hydrogen Pressure(bar) vs Voltage PV(V)

Figure 9 shows the relationship between average PV voltage and hydrogen mass production rate across five locations. As PV voltage increases, the hydrogen mass rate decreases. At 546.7V (Kelibi, Tunisia), the rate is highest at 2.022kg/hr, dropping to 1.838kg/hr at 563.3V (Chuping, Perlis), 1.725kg/hr at 569.2V (UTeM, Melaka), 1.685kg/hr at 572.4V (Sibu, Sarawak), and lowest at 1.429kg/hr at 593.6V (Kota Kinabalu, Sabah). This negative correlation indicates that higher PV voltages reduce the efficiency of hydrogen production. This is because, the higher PV voltage can sometimes be associated with increased heat generation in the system, which might degrade the performance of the electrolyzer or other system components, further lowering hydrogen production rates.

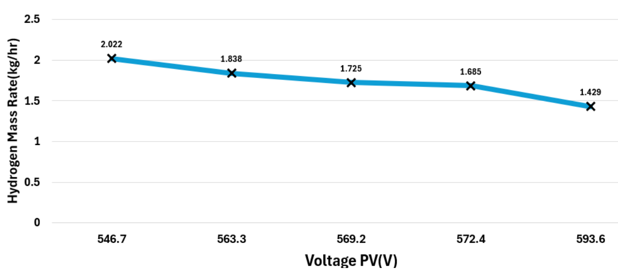


Figure 9 Hydrogen Mass Rate(kg/hr) vs Voltage PV(V)

Figure 10 shows the relationship between the Hydrogen Volumetric Rate (m^3/hr) and Voltage PV (V). At 546.7V, the rate is 0.6033m^3/hr, decreasing to 0.5887m^3/hr at 563.3V, 0.5803m^3/hr at 569.2V, 0.5748m^3/hr at 572.4V, and 0.5586m^3/hr at 593.6V. Higher voltages result in lower hydrogen production rates, indicating an inverse relationship between voltage and hydrogen production efficiency.

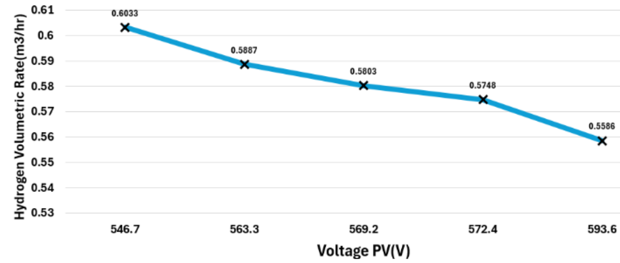


Figure 10 Hydrogen Volumetric Rate(m^3/hr) vs Voltage PV(V)

4.0 CONCLUSION

In conclusion, the analysis demonstrates a clear correlation between solar irradiance and hydrogen production. Locations with higher average irradiance and lower PV voltages, such as Kelibi, Tunisia, exhibit higher hydrogen volumetric rates compared to regions with lower irradiance and higher PV voltages, like Kota Kinabalu, Sabah. This trend underscores the importance of optimizing solar conditions and voltage levels to maximize hydrogen generation. Regions with higher solar irradiance provide more energy for hydrogen production, resulting in higher volumetric rates, while higher PV voltages, often associated with lower irradiance areas, tend to reduce production efficiency.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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