Results in Engineering 24 (2024) 103460

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

# Unveiling the future: A simulation and analysis of hydrogen production using 1kW electrolyzer with MATLAB approach

Yaw Chong Tak [a,*], Johnny Koh Siaw Paw [a,*], K. Kadirgama [b,c,d], D. Ramasamy [b], Oday A. Ahmed [e], Jagadeesh Pasupuleti [a], F. Benedict [f], L. Samylingam [g], Chee Kuang Kok [g]

[a] *Institute of Sustainable Energy, Universiti Tenaga Nasional (The Energy University), Jalan Ikram-Uniten, Kajang 43000, Selangor, Malaysia*
[b] *Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia*
[c] *Centre for Sustainable Materials & Surface Metamorphosis (CSMSM), Chennai Institute of Technology, Chennai*
[d] *Centre for Research in Advanced Fluid and Process, University Malaysia Pahang Al-Sultan Abdullah, Lebuhraya Tun Razak, Gambang, Kuantan 26300, Pahang, Malaysia*
[e] *Department of Electrical Engineering, University of Technology- Iraq, 35299 Baghdad, Iraq*
[f] *Enhance Track Sdn. Bhd., No. 9, Jalan Meranti Jaya 12, Meranti Jaya Industrial Park, Puchong 47120, Malaysia*
[g] *Centre for Advanced Mechanical and Green Technology, Faculty of Engineering and Technology, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, 75450 Melaka, Malaysia*

## ARTICLE INFO

*Keywords:*
Fuel cell
Hydrogen production
Membrane
Environmentally

## ABSTRACT

This research concentrates on optimizing hydrogen production via a 1kW electrolyzer powered by renewable solar energy, specifically targeting efficiency enhancement through adjusting membrane area. The rising global demand for clean energy solutions has positioned hydrogen as a pivotal element in the shift toward sustainable energy systems. Nonetheless, the efficacy of hydrogen generation via electrolysis continues to pose a challenge, particularly at reduced scales. This research involved the creation of a comprehensive simulation model utilizing MATLAB Simulink to investigate the impact of membrane area variations on hydrogen production and overall system efficiency. The simulation results indicate that optimizing the membrane area can substantially enhance hydrogen production rates. The system was capable of producing up to 2.5 kg/h of hydrogen, signifying a substantial enhancement over traditional methods. Moreover, incorporating solar energy as the principal power source diminishes environmental repercussions while guaranteeing a sustainable and clean approach to hydrogen production. This research introduces an innovative method for optimizing small-scale electrolyzers, offering insights applicable to industrial hydrogen production and the integration of renewable energy. The findings facilitate the advancement of sustainable hydrogen production technologies, consistent with international initiatives to diminish dependence on fossil fuels.

## 1. Introduction

Rising living standards, population expansion, and global economic development contribute to increased energy demand. Nowadays, most industrial and household energy demands are satisfied by fossil fuels. Unfortunately, because of their exceptional restrictions, carbon emissions are restricted and are about to catch up with this huge energy demand [1]. The growing demand for clean and renewable energy sources has placed hydrogen at the forefront of sustainable energy solutions [2]. However, the efficiency of hydrogen production, particularly through electrolysis, remains a significant challenge, especially in small-scale systems like the 1kW electrolyzer [3]. Traditional electrolyzer designs often suffer from inefficiencies related to membrane performance, leading to suboptimal hydrogen output and increased operational costs [4]. Furthermore, the integration of renewable energy, such as solar power, into these systems presents additional technical complexities in maintaining consistent production rates [5]. Addressing these issues is critical to ensuring that hydrogen production becomes a viable and scalable solution for energy generation. This study seeks to resolve these challenges by optimizing the membrane area within a

---

* Corresponding authors.

*E-mail addresses:* chongty@uniten.edu.my (Y.C. Tak), johnnykoh@uniten.edu.my (J.K.S. Paw), kumaran@umpsa.edu.my (K. Kadirgama), deva@umpsa.edu.my (D. Ramasamy), Oday.a.ahmed@uotechnology.edu.iq (O.A. Ahmed), jagadeesh@uniten.edu.my (J. Pasupuleti), lingenthiran@mmu.edu.my (L. Samylingam), ckkok@mmu.edu.my (C.K. Kok).

https://doi.org/10.1016/j.rineng.2024.103460
Received 1 September 2024; Received in revised form 9 November 2024; Accepted 19 November 2024

small-scale electrolyzer, thereby improving hydrogen production efficiency while utilizing renewable solar energy. The research provides insights into how such optimizations can enhance the performance of electrolyzers, contributing to the broader goal of developing more efficient and sustainable hydrogen production systems.

Due to its plentiful supply and minimal end-use emissions, hydrogen is a feasible energy carrier. Innovation in hydrogen generation is crucial to solving environmental issues in a reliable, quick, clean, and economical way [6]. Furthermore, the electrolyzer in this research is powered by solar energy. Solar energy is directly converted into electricity using concentrated solar power from the sun. A concentrated solar system uses mirrors, lenses, and a tracking system to focus a lot of sunlight onto a hot point, which is usually used to power up the mechanism. The primary motivation for using solar energy in this project is to reduce its negative environmental consequences because it is a renewable energy source [7]. Most notably, because this device emits no emissions and primarily powers the electrolyzer with solar energy, it only needs little maintenance. Because electrolysis generates large electrochemical potentials, strong oxidants like superoxide and ozone, and strong reductants like solvated electrons, it speeds up chemical processes [8].

Electrons are pure, diverse, and redox agents that may speed up and clean up processes. The use of energy worldwide depletes carbon stocks. Until technology to trap and utilize carbon dioxide emissions is developed, natural gas and coal cannot be used externally. Methods for this re-use include the catalytic synthesis of methanol from carbon dioxide and hydrogen, as well as the electrolysis or photo-electrolysis of carbon dioxide with water to make "synthesis gas" (syngas), formic acid, or methanol [9]. These methods rely on the direct or indirect usage of electricity, which is now mostly produced by burning fossil fuels, in electrolyzers (which produce hydrogen through water electrolysis). Future eco-friendly electrolysis applications need to be fueled by solar photochemical or photobiological processes or "renewable" energy sources including hydro, solar, wind, and waves . Hydrogen might be produced from these energy sources by electrolysis or another technique.

Several studies have explored various methods of hydrogen generation, with electrolysis emerging as one of the most promising approaches due to its ability to produce hydrogen with minimal environmental impact. Pareek et al. [8] provided a comprehensive overview of renewable hydrogen energy, emphasizing the role of electrolysis in achieving carbon-neutral energy systems. Their research highlighted the integration of renewable energy sources, such as solar and wind, into electrolysis processes, which is an approach also adopted in this study. The optimization of electrolyzers for hydrogen production has been extensively studied, with a focus on improving efficiency and reducing operational costs. Bessarabov and Millet [10] examined the performance degradation of Proton Exchange Membrane (PEM) electrolyzers under high pressure and current density, concluding that membrane optimization is crucial to maintaining high hydrogen production rates. Similarly, Bernt et al. [11] analyzed gas permeation phenomena in PEM electrolyzers and emphasized the importance of membrane stability in long-term operations. These studies underscore the relevance of membrane area in enhancing electrolyzer performance, which aligns with this study's focus on membrane optimization in a 1kW system. Brauns and Turek [12] conducted an extensive review of alkaline water electrolysis powered by renewable energy, providing insights into the efficiency improvements achieved through advanced system designs. Their work also pointed to the increasing use of solar and wind energy in driving electrolysis processes, a strategy adopted in this study. The integration of solar power into electrolyzer systems is further supported by research from Daneshpour and Mehrpooya [13], who designed and optimized a combined solar thermophotovoltaic power generation system for hydrogen production. This demonstrates the growing interest in leveraging renewable energy to make hydrogen production more sustainable. In terms of modeling and simulation, Mazumder et al. [14] explored the development and performance analysis of a low-cost hydrogen generation system using locally available materials. Their research focused on the use of MATLAB Simulink for simulating hydrogen production processes. MATLAB Simulink has been widely adopted for modeling electrochemical systems, as it allows for precise control over variables and the ability to test different operational scenarios.

Another study by Khan et al. [1] looked into designing optimal integrated electricity supply configurations for renewable hydrogen generation, with a focus on minimizing energy losses during the electrolysis process. Their findings indicated that system optimization, particularly in terms of energy input, plays a critical role in maximizing hydrogen production efficiency. In addition, research by Biswas et al. [15] reviewed the synthesis of methane as a pathway for renewable energy storage, with a particular focus on solid oxide electrolytic cell-based processes. Although their work centers on methane, the parallels with hydrogen production highlight the broader trend of using electrolysis to convert renewable energy into storable chemical fuels. This further contextualizes the importance of optimizing electrolyzer performance. Moreover, Bisquert [7] examined the role of voltage and capacitors in solar energy conversion, discussing the potential for these technologies to enhance the efficiency of hydrogen production systems. His work on the physics of solar energy conversion is particularly focused on the integration of solar power into the electrolyzer system. Other studies, such as those by Çelik and Yıldız [16], have explored green chemistry principles in hydrogen production methods, further emphasizing the need for sustainable approaches to hydrogen energy. Finally, McHugh et al. [17] explored electrochemical methods for water splitting, emphasizing the significance of Gibbs free energy and Faraday efficiency in optimizing the electrolysis process. Their work provided a strong theoretical foundation for the electrochemical models used in this study.

This study addresses the optimization of hydrogen production in a small-scale 1kW electrolyzer, powered by solar energy, by focusing on the impact of membrane area. One of the main challenges in this field is achieving high hydrogen production efficiency while using renewable energy sources that can be intermittent, such as solar power. Traditional electrolyzer designs often face inefficiencies due to the variability in renewable power and the constraints in membrane material and structure. In response to these challenges, our study employs a simulation-based approach that allows for precise control over variables, focusing on membrane area optimization without the limitations of physical experimentation. This method enables a practical examination of how small-scale electrolyzers can maximize efficiency and sustainability. The novelty of this work lies in its unique focus on membrane optimization specifically for small-scale systems, filling a gap in current research by demonstrating how membrane adjustments can support renewable energy integration in hydrogen production.

In this study, we hypothesize that by optimizing the membrane area of a 1kW electrolyzer, hydrogen production efficiency can be significantly enhanced, particularly when powered by renewable energy sources such as solar energy. This hypothesis is based on the premise that key operational parameters, including membrane area and temperature, play crucial roles in the overall efficiency of hydrogen production. We aim to achieve higher hydrogen output by systematically manipulating these parameters while minimizing the environmental impact. The originality of this work lies in several key contributions. First, this research presents a novel approach focusing on membrane area optimization within a small-scale electrolyzer system. While many studies have explored hydrogen production through electrolysis, few have specifically examined the impact of membrane area on hydrogen output, particularly in the context of a 1kW electrolyzer. By addressing this gap, we provide valuable insights into the scalability of hydrogen production systems. Second, this study integrates renewable solar energy as the primary power source for the electrolyzer, emphasizing the potential for hydrogen production to align with global shifts toward cleaner energy solutions. By simulating a system powered by renewable energy, we demonstrate how solar energy can be harnessed effectively for hydrogen production, contributing to the reduction of greenhouse gas emissions. Lastly, the use of MATLAB Simulink as a tool for modeling and optimizing the hydrogen production process is another innovative aspect of this research. This approach allows for precise simulation and control over the electrolysis process, offering a flexible framework that can be adapted to various operational conditions. By employing this methodology, we not only validate the hypothesis but also provide a practical tool for future research and industrial applications. These contributions underscore the novel nature of this work, positioning it as a meaningful step forward in the field of hydrogen production and renewable energy integration.

## 2. Methodology

This study utilized MATLAB Simulink to model and simulate the hydrogen production process using a 1kW electrolyzer powered by solar energy. The key focus of the experiment was to investigate the effects of varying membrane area on hydrogen production efficiency. The simulation was designed to reflect real-world operating conditions, optimizing the membrane area for higher hydrogen output. The experiment was divided into several stages. First, a mathematical model was developed to describe the electrochemical reactions occurring in the electrolyzer. Key parameters such as temperature, pressure, membrane area, and current were incorporated into the model. The governing equations for hydrogen production, including Gibbs free energy, enthalpy, and Faraday efficiency, were used to calculate the expected hydrogen output. The electrolyzer's performance was simulated based on the input electrical energy and the chemical properties of water.

Next, a series of simulations were run using MATLAB Simulink to study the effect of changing the membrane area while keeping other parameters constant. The membrane area was varied in increments to assess its impact on hydrogen production efficiency, with the output being measured in terms of hydrogen mass rate (kg/h) and volumetric rate ($m^3$/h). The experiment also monitored the temperature, current, and pH values throughout the electrolysis process to ensure stable operation and to identify any potential optimization opportunities. Additionally, a renewable solar energy system was modeled to simulate the power supply for the electrolyzer. The integration of this system into the simulation allowed for an analysis of the electrolyzer's performance under renewable energy conditions. The use of solar energy aligns with the growing emphasis on sustainable and environmentally friendly hydrogen production methods. Data from the simulations were collected and analyzed to determine the relationship between membrane area and hydrogen production efficiency.

The proton exchange membrane plays a critical role in the electrolyzer by facilitating the transport of protons from the anode to the cathode while preventing the mixing of hydrogen and oxygen gases. This selective permeability is essential for the efficient operation of the electrolysis process. In this study, Nafion, a widely used PEM material, was selected due to its high proton conductivity and stability under operating conditions typical for hydrogen production systems. Nafion is known for its chemical resistance and durability, making it an ideal choice for ensuring long-term electrolyzer performance. The membrane's ability to operate effectively in a wide range of temperatures and maintain high proton conductivity contributes significantly to the efficiency of hydrogen production in this system. The choice of Nafion also aligns with other studies in the field, where it has been shown to enhance the overall efficiency of electrolyzers operating with renewable energy sources.

Nafion was chosen as the PEM material in the simulation model due to its well-documented proton conductivity and durability under electrochemical conditions typical for hydrogen production. A single-layer configuration was modeled to simplify the system while maintaining realistic efficiency. The catalysts used in the simulation were platinum-based, placed on both the anode and cathode, aligning with industry standards for PEM electrolyzers. These specifications allowed this study to focus on optimizing the membrane area in a small-scale electrolyzer context, maintaining realistic parameters for efficient hydrogen production.

### 2.1. Mathematical modelling

In summary, a mathematical model is constructed to depict the process of hydrogen generation in a hydrogen cell. These equations include the following factors: entropy, electrolysis resistance, hydrogen enthalpy, electrode area, electrolytic temperature, and input voltage and current. The equations are as follows:

$$\mathrm{H_2O(l)} + \text{electrical energy} \rightarrow \mathrm{H_2(g)} + \tfrac{1}{2}\,\mathrm{O_2\ (g)} \tag{1}$$

a. Diffusion using GIBBS free energy

The greatest non-expansion work that can be extracted from a closed system, or the maximum non-expansion work that can be gained by a completely reversible process, is known as the Gibbs free energy given by:

$$\Delta \mathrm{G} = \Delta \mathrm{H} - (\Delta \mathrm{S} \times \mathrm{Telct}) \tag{2}$$

This is given by,
$\Delta$H: Difference of enthalpy
$\Delta$S: Difference of entropy
$\Delta$G: Total energy exchange
T: Temperature

b. Voltage of Thermo Neutral Cell

The smallest potential difference between the anode, where oxygen is released (oxidation), and the cathodes, where hydrogen is released (reduction), is known as the thermoneutral cell voltage given in the following :

$$\Delta \mathrm{H} = \mathrm{z}FVtn \tag{3}$$

This is given by,
$z$ = number of electrons
$F$= Faraday Constant

c. Variable voltage of the cell

Reversible cell voltage, or emf (V) for a reversible electrochemical process is given by calculation,

$$\begin{aligned} VrevzF &= \Delta G \\ Vrev &= 237.2(\mathrm{kJ/mole})/2 \times 9648(\mathrm{C/mole}) \\ &= 1.229V \end{aligned} \tag{4}$$

* For water splitting, the conventional Gibbs energy is 237 kJ mol−1. To make the concept practical, we need to divide water at a voltage greater than 1.229V.

d. The Electrolyzer voltage calculations

The electrolysis cell's input voltage is given by,

$$Velectrolysis = Vrev + [\ \underline{(\mathrm{r}1}\pm \underline{(\mathrm{r}2{*}}A\ \underline{elect)})\ X\ I\ electrolysis] + 2\ \mathrm{s}\ [\ \log [\ ^{t1+\ t2/\mathrm{T}+\ t3/\mathrm{T}}]\ X\ I + 1]\ A\ electrolysis \tag{5}$$

e. Faraday Efficiency

$$\eta_F = \frac{\left(\frac{I_{ely}}{A}\right)^2}{f_2 + \left(\frac{I_{ely}}{A}\right)^2} f_2 \tag{6}$$

The ratio of "the actual quantity of material released" to "the theoretical quantity of material that should have been released, based on Faraday's laws of electrolysis" is known as the Faraday Efficiency of electrolysis.

f. Hydrogen Flow Rate (l/h)

$$Q = \frac{Iely}{zF} \times 3600 \times 0.224136 \times 1000 \tag{7}$$

· Total Efficiency

$$\eta total = \frac{Q \cdot E}{A \cdot G} \tag{8}$$

## 3. Results and discussions

Fig. 1

Using the Simulink model that illustrates the construction of a Proton Exchange Membrane (PEM) electrolyzer system by connecting a membrane electrode assembly (MEA) to two distinct moist air networks and a thermal liquid network is found. As a component of an electrical system, a hydrogen electrolyzer model offers a framework for conducting trade studies to reduce water usage, hydrogen generation, and electrolyzer stack efficiency. To model a green hydrogen production system like a microgrid, a hydrogen electrolyzer with electrochemical reactions, water and hydrogen handling, and thermal management systems can be coupled with an energy storage system and a renewable energy source like a solar array or wind farm [18].

### 3.2. Data obtained on electrolyzer

**Table 1**
Data obtained on electrolyzer performance.

| Parameter | Initial Value | Final Value | Observation |
|---|---|---|---|
| Current (A) | High (initial) | Low (steady) | Significant decrease after 8000s indicating stabilization. |
| Temperature (K) | 300 | 340 | Gradual rise, improving electrolysis efficiency. |
| pH level | 6.1 | 6.1 | Stable, indicating proper electrolyte balance. |

Table 1 shows the data obtained on electrolyzer performance. Fig. 2 shows the outcome of the electrolyzer, and it explains the data collected from the electrolyzer to produce hydrogen. The first data shows the current flow; it clearly states that steady flow is obtained after 8000s runtime. Next, the data obtained for the pH value of the water was slightly above 6, which shows the property water obtained was alkaline for the entire electrolysis process [19]. Lastly, the electrolyzer's temperature data was collected, showing temperature increases when time goes long. As temperature increases, the efficiency of the electrolyzer also increases in generating hydrogen. The first graph shows the variation of the current (i_heat) over time, measured in amperes (A). Initially, the current is high, indicating that a significant amount of electrical energy is being supplied to the electrolyzer [20]. As time progresses, the current gradually decreases, which suggests that the system is becoming more efficient in utilizing the electrical energy for hydrogen production. The steady decline in current could be attributed to several factors, including stabilizing the electrolyzer's internal processes, improving electrolyte solution conductivity, or optimizing the membrane electrode assembly [21]. The reduction in current over time is a positive indicator, as it implies that less electrical energy is required to maintain the hydrogen production process [22]. This can lead to cost savings and increased overall efficiency of the electrolyzer system. It also suggests that the electrolyzer is operating stably, with minimal fluctuations in energy consumption, which is essential for consistent hydrogen production. The pH level remains relatively constant, slightly above 6, throughout the simulation. This stability in pH indicates that the electrolyzer effectively maintains the acidity or alkalinity of the electrolyte solution, which is crucial for the efficient functioning of the electrolysis process. A stable pH level is important because significant fluctuations can affect the efficiency of the hydrogen production process [23]. For instance, if the pH were to become too acidic or too alkaline, it could lead to increased resistance within the electrolyzer, thereby requiring more energy to sustain the production process [12]. The slight

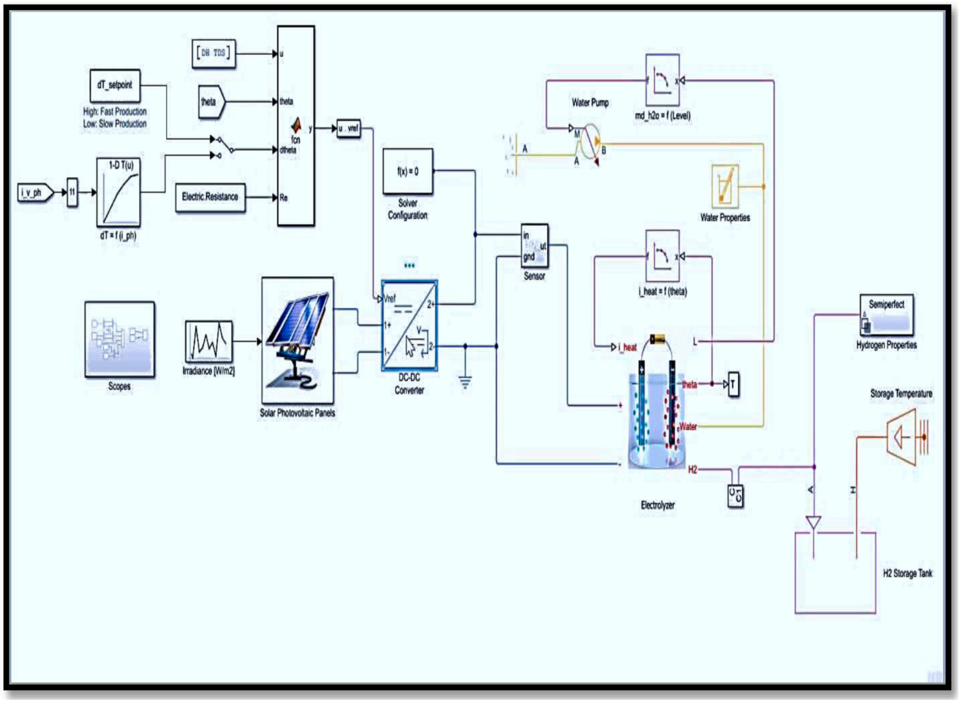

**Fig. 1.** of the Electrolyzer Matlab Model.

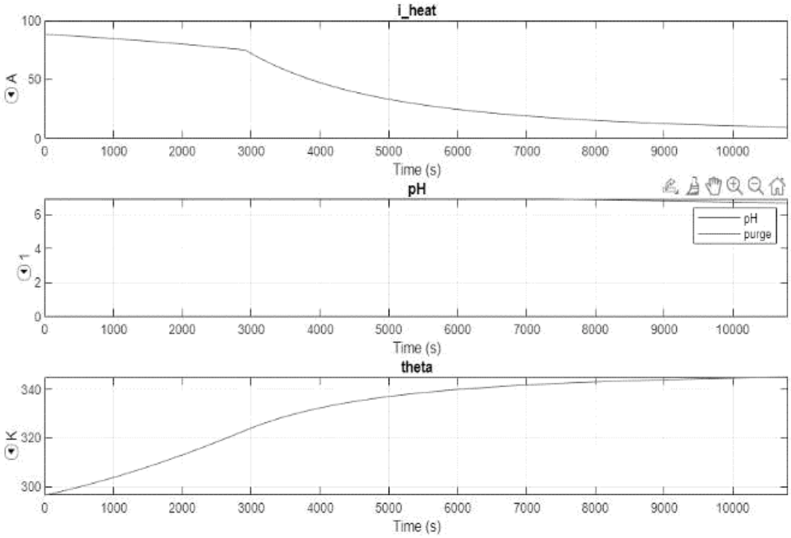

**Fig. 2.** Hydrogen collection.

alkalinity observed in the graph suggests that the electrolyte solution is within an optimal range for efficient hydrogen production, minimizing energy losses and maximizing output. The temperature gradually increases from approximately 300K to 340K. This increase in temperature is expected, as the electrolysis process generates heat [24]. The gradual temperature rise can enhance the efficiency of the hydrogen production process, as higher temperatures typically improve the reaction kinetics, leading to faster hydrogen generation. However, it is crucial to manage the temperature to prevent overheating, which could damage the electrolyzer components or reduce the lifespan of the system. Temperature management is critical in small-scale electrolyzer systems, as it directly influences reaction kinetics and component durability. In this study, an operating temperature range of 300K to 340K was found to be optimal, enhancing the hydrogen production rate without compromising the system's stability. While higher temperatures can accelerate hydrogen generation by improving reaction kinetics, exceeding 340K may lead to material degradation, especially in the PEM and catalyst layers. Therefore, maintaining temperatures within this range ensures sustained efficiency and prolongs the electrolyzer's operational lifespan. The observed temperature increase suggests that the electrolyzer is operating within a safe range, as the temperature rise is steady and does not exhibit any abrupt spikes. This steady increase indicates effective thermal management within the system, possibly through cooling mechanisms or thermal regulation strategies.

### *3.3. Hydrogen production*

Table 2 shows the data on hydrogen production. These results show the production of hydrogen possessed by all parameters mentioned above in the methodology. The above figure shows two different graphs with two different outputs, which are known as Hydrogen Volumetric Rate and Hydrogen Mass Rate. The reading of the Hydrogen Volumetric rate is taken in $m^3$/hr, whereas the reading of the Hydrogen Mass Rate is taken in kg/hr. Both readings are conducted in different aspects. At the beginning, the hydrogen mass rate starts at approximately 1.5 kg/hr. This initial production rate establishes the baseline efficiency of the electrolyzer system. The step-like pattern suggests that the system experiences periodic improvements or optimizations, possibly due to adjustments in operating conditions, such as temperature, pressure, or current. These increments could also result from the stabilization of the electrolysis process as the system warms up and reaches optimal operating conditions [25]. Towards the end of the simulation period, the hydrogen mass rate stabilizes around 2.5 to 3 kg/hr. This indicates that the electrolyzer system reaches a steady-state operation, maintaining a consistent production rate.

**Table 2**
Hydrogen production data.

| Time (s) | Hydrogen Volumetric Rate ($m^3$/h) | Hydrogen Mass Rate (kg/h) | System Efficiency (%) |
|---|---|---|---|
| 1000 | 20 | 1.5 | 70 |
| 5000 | 10 | 2.0 | 80 |
| 8000 | 1–2 | 2.5 | 86.4 |

The gradual and consistent increase in the hydrogen mass rate over time is a positive indicator of the electrolyzer's efficiency. The stabilization at a higher production rate suggests that the system's performance improves as it runs, likely due to optimal electrochemical reactions and efficient energy use [26]. Fig. 3 illustrates the Hydrogen Volumetric Rate over time, measured in cubic meters per hour ($m^3$/hr). The graph shows a sharp decline initially, followed by a more gradual decrease that levels off as time progresses. At the start, the volumetric rate is very high, around 20 $m^3$/hr. This peak can be attributed to the initial surge in hydrogen production when the electrolyzer is first activated [27]. The high initial rate indicates that the system is capable of producing a large volume of hydrogen quickly. Following the initial peak, the volumetric rate rapidly decreases within the first 2000 s. This decline suggests that the initial high production rate is not sustainable, possibly due to the depletion of readily available reactants or the system adjusting to a more stable and efficient operating state [28]. After the rapid decline, the volumetric rate levels off and continues to decrease gradually, eventually stabilizing at around 1 to 2 $m^3$/hr. This indicates that the system finds a balance between production rate and resource consumption, achieving a steady-state operation. The initial high volumetric rate indicates a strong start, but the rapid decline and subsequent stabilization suggest that the system undergoes a settling phase where it optimizes resource use and energy consumption [29]. The incremental increases in the mass rate graph imply that, over time, the system becomes more efficient in converting energy into hydrogen, leading to higher mass production rates. The final stabilization of both rates reflects the electrolyzer's ability to maintain consistent performance once optimal operating conditions are achieved.

The increase in hydrogen production in the 1kW electrolyzer model was closely related to changes in three key operational parameters: temperature, pressure, and current. In the simulation, the temperature of the system was observed to rise from an initial value of 300K to a final value of 340K. This increase in temperature enhanced the

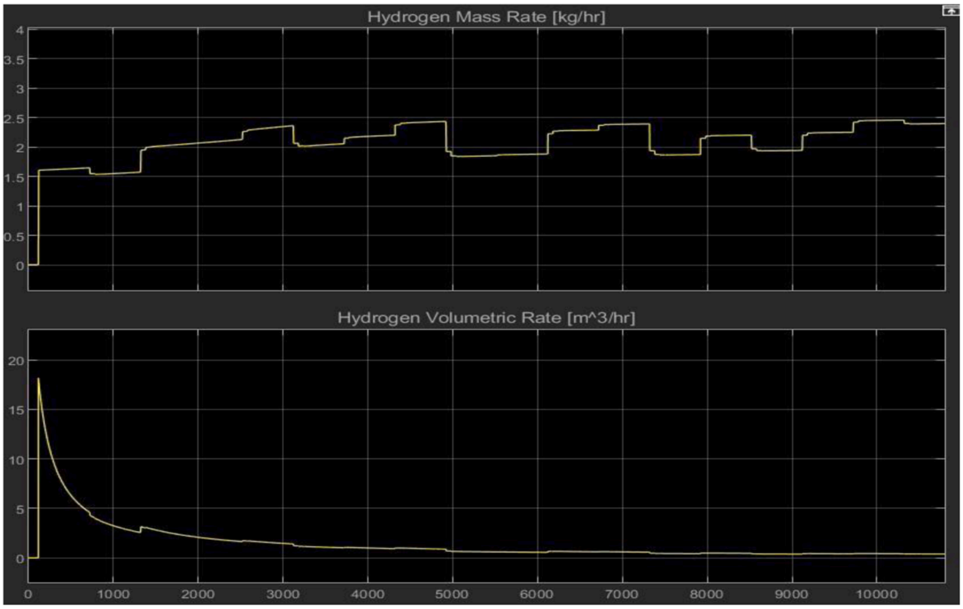

**Fig. 3.** Hydrogen Rate of Production.

electrochemical reaction kinetics, leading to more efficient hydrogen production [30]. Higher temperatures typically lower the activation energy for electrolysis, resulting in faster hydrogen generation [31]. Similarly, the current supplied to the electrolyzer initially spiked before stabilizing as the system reached a steady operational state. The initial current was high, indicating that significant electrical energy was being supplied to the electrolyzer [32]. As the current decreased and stabilized over time, the system became more efficient in utilizing this energy for hydrogen production. In the simulation, the final current value that led to steady hydrogen production was approximately 82 % of the initial current. While the simulation was conducted under a standard atmospheric pressure of 1 atm, the results suggest that varying the pressure could further influence hydrogen production rates. Higher pressures typically increase the solubility of hydrogen in water, which could result in higher production rates, although this was not varied in our model [33]. The steady-state operation observed at approximately 340K and a stable current allowed the electrolyzer to achieve a hydrogen production rate of up to 2.5 kg/h.

### 3.4. *Efficiency of electrolyzer*

Fig. 4 shows the working efficiency of the electrolyzer. The efficiency reading is based on the production of the hydrogen. The hydrogen production efficiency keeps on increasing from 1000s to 10,771.9s which shows the effectiveness of hydrogen production is very high. The provided graph illustrates the efficiency of an electrolyzer over time, measured in seconds (s). At the start of the recorded period (around 1000 s), the electrolyzer's efficiency is approximately 0.70, or 70 %. This initial efficiency indicates the electrolyzer's baseline performance when it begins operating [34]. Several factors can influence this initial efficiency, including the system's initial setup, the temperature of the electrolyte, and the current supplied to the electrolyzer [35].

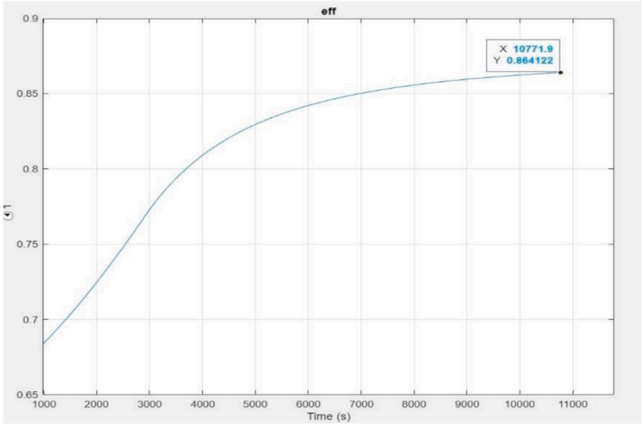

**Fig. 4.** Efficiency of the Electrolyzer.

As time progresses, there is a noticeable and steady increase in efficiency. This upward trend suggests that the electrolyzer becomes more efficient as it continues to operate [36]. The efficiency improvement can be attributed to several factors such as the electrolyzer operation, the system stabilizes, and various parameters such as temperature, pressure, and electrolyte concentration reach optimal levels, enhancing the efficiency of the electrolysis process. Initial losses due to start-up conditions, such as lower temperatures or suboptimal reactant distribution, are minimized over time, leading to higher efficiency. The electrochemical reactions within the electrolyzer may become more favorable over time, especially as the temperature increases, improving hydrogen production's kinetics [37]. After about 8000 s, the rate of increase in efficiency begins to slow down, eventually reaching a plateau. By the end of the recorded period (around 10,771.9 s), the efficiency reaches approximately 0.864, or 86.4 %. This plateau indicates that the electrolyzer has reached a near-optimal operating efficiency, where further improvements are marginal [38]. The final efficiency of 86.4 % is a significant improvement from the initial 70 %. This high level of efficiency suggests that the electrolyzer is well-optimized for hydrogen production, making effective use of the electrical energy supplied to it.

The accuracy of the MATLAB Simulink model used in this study was evaluated through a multi-step validation process. First, the mathematical equations governing the electrolysis process, such as those for Gibbs free energy, enthalpy, and Faraday efficiency, were cross-checked against established theoretical values from the literature. The results from the simulation were then compared to data reported in previous studies on hydrogen production using electrolyzers of similar scale and design. Specifically, the hydrogen production rates and system efficiency values obtained from the model aligned well with those observed in experimental studies conducted by Bessarabov and Millet [10] and Bernt et al. [11], which demonstrated similar trends in membrane area optimization and its impact on hydrogen output.

## 4. Conclusions

This study explored the optimization of hydrogen production using a 1kW electrolyzer powered by renewable solar energy, with a specific focus on enhancing efficiency through the manipulation of membrane area. Through detailed simulations using MATLAB Simulink, we demonstrated that varying the membrane area has a significant impact on the overall hydrogen production rate. Specifically, by optimizing the membrane area, the system was able to achieve a hydrogen production rate of up to 2.5 kg/h, which represents a notable improvement over the traditional method. The findings from this study highlight the importance of membrane optimization in small-scale electrolyzers, especially when integrated with renewable energy sources. The use of solar energy as the primary power source not only aligns with global efforts to reduce carbon emissions but also enhances the sustainability of hydrogen production systems. This research provides practical insights into how renewable energy can be effectively utilized in hydrogen production, contributing to the development of more efficient, eco-friendly energy systems.

Moreover, the application of MATLAB Simulink for modeling and simulating the electrolysis process offers a flexible and precise tool for further experimentation and system optimization. The approach presented in this study can be adapted to various scales and conditions, making it a valuable resource for future research in the field of hydrogen production. While the results of this study are promising, further research is needed to explore additional variables, such as pressure and temperature, that could further improve the efficiency of electrolyzers. Additionally, experimental validation of the simulation results would provide a deeper understanding of the practical applications of the optimized system. Future work could also explore the scalability of these findings for larger electrolyzer systems and investigate the integration of other renewable energy sources.

In conclusion, this research has made significant strides in improving the efficiency of small-scale electrolyzers through membrane optimization, contributing to the broader goal of developing sustainable hydrogen production systems powered by renewable energy. The insights gained from this study have the potential to influence future innovations in the field, advancing the global transition to clean energy.

## CRediT authorship contribution statement

**Yaw Chong Tak:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Johnny Koh Siaw Paw:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **K. Kadirgama:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **D. Ramasamy:** Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Oday A. Ahmed:** Writing – review & editing, Validation, Project administration, Methodology, Investigation, Formal analysis. **Jagadeesh Pasupuleti:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Investigation, Funding acquisition, Data curation. **F. Benedict:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **L. Samylingam:** Writing – review & editing, Visualization, Methodology, Data curation. **Chee Kuang Kok:** Writing – review & editing, Validation, Software, Resources, Investigation.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Johnny Koh Siaw Paw reports financial support was provided by National Energy University Institute of Sustainable Energy. Johnny Koh Siaw Paw reports a relationship with National Energy University Institute of Sustainable Energy that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

This work was supported by the Ministry of Higher Education of Malaysia through the HICoE grant (2022001HICOE), Dato' Low Tuck Kwong International Energy Transition Grant (202203004ETG), AAIBE Chair of Renewable Energy grant (202202KETTHA), BOLD HICOE grant (J510050002/HICOE01), as well as Tenaga Nasional Berhad (TNB) and UNITEN through the BOLD Refresh Publication Fund under the project code of J510050002-IC-6 BOLDREFRESH2025-Centre of Excellence and Universiti Malaysia Pahang for the international collaboration research grant [RDU223307].

## Data availability

Data will be made available on request.

## References

[1] M.H.A. Khan, R. Daiyan, Z. Han, M. Hablutzel, N. Haque, R. Amal, I. MacGill, Designing optimal integrated electricity supply configurations for renewable hydrogen generation in Australia, iScience 24 (6) (2021).

[2] T.T. Le, P. Sharma, B.J. Bora, V.D. Tran, T.H. Truong, H.C. Le, P.Q.P. Nguyen, Fueling the future: a comprehensive review of hydrogen energy systems and their challenges, Int. J. Hydrogen. Energy 54 (2024) 791–816.

[3] C. Haoran, Y. Xia, W. Wei, Z. Yongzhi, Z. Bo, Z. Leiqi, Safety and efficiency problems of hydrogen production from alkaline water electrolyzers driven by renewable energy sources, Int. J. Hydrogen. Energy 54 (2024) 700–712.

[4] J. Mao, Z. Li, J. Xuan, X. Du, M. Ni, L. Xing, A review of control strategies for proton exchange membrane (PEM) fuel cells and water electrolyzer: from automation to autonomy, Energy and AI (2024) 100406.

[5] H. Husin, M. Zaki, A critical review of the integration of renewable energy sources with various technologies, Protect. Control Modern Pow. Syst. 6 (1) (2021) 1–18.

[6] L. Samylingam, N. Aslfattahi, C.K. Kok, K. Kadirgama, M. Schmirler, T. Yusaf, D. Ramasamy, M. Ghazali, Underlying developments in hydrogen production technologies: economic aspects and existent challenges, Korean J. Chem. Eng. (2024) 1–24.

[7] J. Bisquert, The Physics of Solar Energy Conversion, CRC Press, 2020.

[8] A. Pareek, R. Dom, J. Gupta, J. Chandran, V. Adepu, P.H. Borse, Insights into renewable hydrogen energy: recent advances and prospects, Mater. Sci. Energy Technol. 3 (2020) 319–327.

[9] P.K. Seelam, B. Rathnayake, S. Pitkäaho, E. Turpeinen, R.L. Keiski, Overview on recent developments on hydrogen energy: production, catalysis, and sustainability, Current trends and future developments on (bio-) membranes (2020) 3–32.

[10] D. Bessarabov, P. Millet, PEM Water Electrolysis, 1, Academic Press, 2018.

[11] M. Bernt, J. Schröter, M. Möckl, H. Gasteiger, Analysis of gas permeation phenomena in a PEM water electrolyzer operated at high pressure and high current density, J. Electrochem. Soc. 167 (12) (2020) 124502.

[12] J. Brauns, T. Turek, Alkaline water electrolysis powered by renewable energy: a review, Processes 8 (2) (2020) 248.

[13] R. Daneshpour, M. Mehrpooya, Design and optimization of a combined solar thermophotovoltaic power generation and solid oxide electrolyzer for hydrogen production, Energy Convers. Manage 176 (2018) 274–286.

[14] G.C. Mazumder, S.N. Shams, M.H. Rahman, S. Huque, Development and performance analysis of a low-cost hydrogen generation system using locally available materials, Dhaka Uni. J. Sci. 68 (1) (2020) 49–56.

[15] S. Biswas, A.P. Kulkarni, S. Giddey, S. Bhattacharya, A review on synthesis of methane as a pathway for renewable energy storage with a focus on solid oxide electrolytic cell-based processes, Front. Energy Res. 8 (2020) 570112.

[16] D. Çelik, M. Yıldız, Investigation of hydrogen production methods in accordance with green chemistry principles, Int. J. Hydrogen. Energy 42 (36) (2017) 23395–23401.

[17] P.J. McHugh, A.D. Stergiou, M.D. Symes, Decoupled electrochemical water splitting: from fundamentals to applications, Adv. Energy Mater. 10 (44) (2020) 2002453.

[18] A. Alzahrani, S.K. Ramu, G. Devarajan, I. Vairavasundaram, S. Vairavasundaram, A review on hydrogen-based hybrid microgrid system: topologies for hydrogen energy storage, integration, and energy management with solar and wind energy, Energies. (Basel) 15 (21) (2022) 7979.

[19] M.S. Balogun, W. Qiu, Y. Huang, H. Yang, R. Xu, W. Zhao, G.R. Li, H. Ji, Y. Tong, Cost-effective alkaline water electrolysis based on nitrogen-and phosphorus-doped self-supportive electrocatalysts, Adv. Mater. 29 (34) (2017) 1702095.
[20] L. Samylingam, N. Aslfattahi, C.K. Kok, K. Kadirgama, N. Sazali, M. Schmirler, D. Ramasamy, W.S.W. Harun, M. Samykano, A. Veerendra, Green engineering with nanofluids: elevating energy efficiency and sustainability, J. Adv. Res. Micro Nano Eng. 16 (1) (2024) 19–34.
[21] Q. Ye, X. Zhao, R. Jin, F. Dong, H. Xie, B. Deng, Advances and challenges in membrane electrode assembly electrolyzers for CO2 reduction, J. Mater. Chem. A (2023).
[22] C. Acar, I. Dincer, Review and evaluation of hydrogen production options for better environment, J. Clean. Prod. 218 (2019) 835–849.
[23] R. Jain, N.L. Panwar, S.K. Jain, T. Gupta, C. Agarwal, S.S. Meena, Bio-hydrogen production through dark fermentation: an overview, BioMass Convers. Biorefin. 14 (12) (2024) 12699–12724.
[24] O. Posdziech, K. Schwarze, J. Brabandt, Efficient hydrogen production for industry and electricity storage via high-temperature electrolysis, Int. J. Hydrogen. Energy 44 (35) (2019) 19089–19101.
[25] A. Sojoudi, A.M. Sefidan, K. Alam, S.C. Saha, Hydrogen production via electrolysis: mathematical modeling approach. Bioenergy Resources and Technologies, Elsevier, 2021, pp. 157–193.
[26] C. Zhang, Y.-L. Wei, P.-F. Cao, M.-C. Lin, Energy storage system: current studies on batteries and power condition system, Renew. Sustain. Energy Rev. 82 (2018) 3091–3106.
[27] Z. Shafiee, B. Hosseinzadeh Samani, K. Taki, Simulation of a combined solar-wind-hydrogen system for energy supply to a dried fruit factory in Iran, J. Renew. Energy Environ. (2024).
[28] P. Seferlis, P.S. Varbanov, A.I. Papadopoulos, H.H. Chin, J.J. Klemeš, Sustainable design, integration, and operation for energy high-performance process systems, Energy 224 (2021) 120158.
[29] C.-S. Liew, W. Kiatkittipong, J.-W. Lim, M.-K. Lam, Y.-C. Ho, C.-D. Ho, S. K. Ntwampe, M. Mohamad, A. Usman, Stabilization of heavy metals loaded sewage sludge: reviewing conventional to state-of-the-art thermal treatments in achieving energy sustainability, Chemosphere 277 (2021) 130310.
[30] K. Tan, L. Samylingam, N. Aslfattahi, M.R. Johan, R. Saidur, Investigation of improved optical and conductivity properties of poly (methyl methacrylate)–MXenes (PMMA–MXenes) nanocomposite thin films for optoelectronic applications, Open. Chem. 20 (1) (2022) 1416–1431.
[31] W. Zhang, M. Liu, X. Gu, Y. Shi, Z. Deng, N. Cai, Water electrolysis toward elevated temperature: advances, challenges and frontiers, Chem. Rev. 123 (11) (2023) 7119–7192.
[32] C. Zhang, J. Wang, Z. Ren, Z. Yu, P. Wang, Wind-powered 250 kW electrolyzer for dynamic hydrogen production: a pilot study, Int. J. Hydrogen. Energy 46 (70) (2021) 34550–34564.
[33] P. Haug, B. Kreitz, M. Koj, T. Turek, Process modelling of an alkaline water electrolyzer, Int. J. Hydrogen. Energy 42 (24) (2017) 15689–15707.
[34] G. Sakas, A. Ibáñez-Rioja, V. Ruuskanen, A. Kosonen, J. Ahola, O. Bergmann, Dynamic energy and mass balance model for an industrial alkaline water electrolyzer plant process, Int. J. Hydrogen. Energy 47 (7) (2022) 4328–4345.
[35] F. Scheepers, M. Stähler, A. Stähler, E. Rauls, M. Müller, M. Carmo, W. Lehnert, Temperature optimization for improving polymer electrolyte membrane-water electrolysis system efficiency, Appl. Energy 283 (2021) 116270.
[36] E.S. Akyüz, E. Telli, M. Farsak, Hydrogen generation electrolyzers: paving the way for sustainable energy, Int. J. Hydrogen. Energy 81 (2024) 1338–1362.
[37] M. Younas, S. Shafique, A. Hafeez, F. Javed, F. Rehman, An overview of hydrogen production: current status, potential, and challenges, Fuel 316 (2022) 123317.
[38] Y. Zhao, X. Zheng, P. Gao, H. Li, Recent advances in defect-engineered molybdenum sulfides for catalytic applications, Mater. Horiz. 10 (10) (2023) 3948–3999.