Hydrogen Production Rate of Temperature Controlled Proton Exchange Membrane Electrolyzer

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***Abstract*—This study investigates the hydrogen production through the Proton exchange membrane electrolyzer. It focuses on the hydrogen production rates, power, voltage and stack temperature to elaborate the operating dynamic behavior and efficiency of the system. The simulation reveals the characteristically behavior of these parameters including the activation phases, peak performances and stabilization trends. This study provides a framework for designing and optimization the system which contribute in the advancement of renewable hydrogen production technologies.**

Keywords—Hydrogen production, Proton exchange membrane electrolyzer, Electrolysis, Renewable energy

I. INTRODUCTION

Due to rapid industrialization and population growth, the global energy consumption is soaring. Massive amounts of fossil fuels are burned today to fulfil energy needs, which causes the release of dangerous gases into the atmosphere [1]. The higher gas emissions caused by conventional energy production technologies hasten global warming. Both humans and other species are at risk of being extinct due to the big issue of global warming [2]. It is necessary to employ alternative renewable energy sources, like wind, solar and geothermal energy. One of the best ways to address these issues is to use more renewable energy instead of fossil fuels. The global shift towards renewable energy focuses to reduce the greenhouse gas emission, carbon and climate change mitigation and efficient energy source.

Hydrogen appears to be a crucial component in green economy, offering a clean and efficient solution in transportation, energy storage, industry and power generation sectors. In transportation, it appears as zero carbon emission fuel and can particularly use in heavy transport where battery system is not efficient. Furthermore, hydrogen labels the intermittency of renewable technology especially solar, wind by storing excess energy and balancing the grid, ensuring reliable energy supply [3]. Future energy systems are expected to heavily depend on hydrogen, particularly in the aspect of storing and transferring energy from renewable sources. The proton exchange membrane (PEM) electrolyzer emerges as a encouraging method for hydrogen production due to its high efficiency, rapid reaction times, and adjustable power output [4][5].

Although production thorough PEM Electrolyzer faces many challenges like inefficiency, high operational cost, durability and scalability. PEM require substantial energy input to produce hydrogen and this results in higher operational cost [6]. Furthermore, durability is also often compromised due to certain operating conditions like higher temperature, high pressure in the PEME and this leads to degradation of certain components like catalyst and liquid channels [7]. So, this study addresses these challenges by using temperature-controlled system to optimize the operating temperatures to enhance the efficiency [8], reduce energy consumption, and lower cost [9]. Improved temperature-controlled system also minimizes the component degradation and results in increasing life spawn and offering the insights into scalable and cost-effective hydrogen production.

Focusing on these critical aspects, the objective of this study is to setup a reliable and efficient hydrogen production system by using temperature-controlled PEM electrolyzer that addresses key challenges and facilitates the wider adoption of renewable energy technologies. The discoveries from this study will significantly contribute to progressing sustainable hydrogen production and facilitating the transition towards a cleaner energy future [10].

II. LITERATURE REVIEW

A. Electrolysis System

Electrolysis systems are the primary source of hydrogen production, utilizing electric energy to split water into hydrogen and oxygen. Various methods exist within this system, each with distinct efficiencies, operating conditions, and characteristics. Alkaline water electrolysis employs an alkaline electrolyte, typically 20-30% potassium hydroxide (KOH) or sodium hydroxide (NaOH) solutions. This technology achieves efficiency ranges of 65-70% [11]. However, it suffers from high ohmic losses and diaphragm design challenges compared to other electrolysis technologies [12].

Solid Oxide Electrolysis produces hydrogen at high temperatures, generally 800°C to 1000°C, using a solid oxide electrolyte to conduct oxygen ions. It can achieve efficiencies over 80% due to favorable thermodynamic considerations at high temperatures [13]. Drawbacks include degradation factors, high ohmic resistance [14][15], and the requirement for high steam temperatures.

High-temperature steam electrolysis utilizes solid oxide electrolytes like yttria-stabilized zirconia (YSZ) to conduct oxygen ions at elevated temperatures. Its efficiency is temperature-dependent and typically exceeds 80% [16]. Major challenges include high temperature demands, high costs, and the need for precise control [17]. Photoelectrochemical (PEC) water splitting electrolysis integrates photovoltaic and chemical technologies, using semiconductor materials such as titanium dioxide or bismuth vanadium. It operates on an electron-hole mechanism in the presence of sunlight. Current PEC systems achieve efficiencies of 5-15% [18], determined by light absorbance, charge carrier separation, and catalytic activity. The main challenges are the stability and durability of photoelectrode materials. Improvements in materials and system design are necessary for PEC water splitting to become a potentially low-cost, large-scale hydrogen production option [19].

Anion exchange membrane electrolysis operates at mild temperatures between 60°C to 80°C and uses metal catalysts like nickel or iron at the cathode and anode for H_2 and O_2 production, respectively. Challenges include membrane stability [20], lower lifetime [21], and material compatibility in alkaline environments. In Proton Exchange Membrane (PEM) electrolysis, water molecules are separated into hydrogen and oxygen gases. Protons pass through the membrane to one side of the cell, while electrons flow to the other side and recombine with protons on the electrode surface. The critical component is the membrane, which conducts protons while blocking electron flow, operating at 60-80°C. PEM electrolysis is characterized by fast dynamics and high efficiency. However, current drawbacks include the cost of platinum group metals and operation at high contamination and degradation temperatures [22]. PEM electrolysis is preferred for high-purity hydrogen applications, such as fuel cells and industrial processes. Ongoing research aims to increase efficiency and reduce costs through material innovations and system optimization.

B. Hydrogen Production through Electrolysis

A system integrating photovoltaics (PV) with electrolysis has been developed to meet high energy and hydrogen demands. The study investigates variations in solar intensity and temperature, revealing that system efficiency increases linearly with growing solar radiation intensity until reaching a maximum point, after which it declines. Higher temperatures consistently cause system inefficiency. The calculated system efficiency ranges from 6% to 7% [23].

Another system has been designed to simultaneously produce hydrogen gas and cooling. This setup comprises a concentrated photovoltaic thermal (CPVT) system, an absorption chiller, and a PEM electrolyzer. The CPVT generates electric energy to power the PEM electrolyzer for hydrogen production, while excess heat from the CPVT is utilized by the chiller for cooling and overall performance enhancement. Energy and exergy analysis reveal that the CPVT contributes most to exergy destruction in the system, followed by the absorption chiller, with the PEM electrolyzer contributing the least. However, exergoeconomic analysis shows that the CPVT is most economical, with a capital cost of 0.08946$/h and 28.82% exergoeconomic factor [24].

A simulation model study presents a PV panel coupled with an electrolyzer to enhance hydrogen production. To improve PV power utilization, a maximum power point tracking (MPPT) system is employed. Results demonstrate that using both a buck converter and MPPT leads to improvements in both photovoltaic and electrolysis processes. Furthermore, the system's application to a 0.5 MW PV array showcases its capability to produce approximately 20 million litres of hydrogen within a month [25].

C. Photovoltaic Technology coupled with PEM Electrolyzer

Integrating photovoltaic (PV) systems with electrolysis enables direct hydrogen production from solar energy. In China, studies show that using a Maximum Power Point Tracking (MPPT) system yields higher efficiency for PV-electrolysis (PVE) systems compared to direct coupling or P&O Algorithm [26]. An experiment investigating the dependency of irradiance and temperature on hydrogen production by a PEM electrolyzer (HG60) demonstrates high hydrogen production of 284L per day, with PEM electrolyzer and PV system efficiencies of 18-40% and PV efficiency alone at 9-12% [27].

A comparative study of PV and PV-thermal (PVT) systems reveals PV efficiency around 9% and PVT efficiency around 50%, attributed to the cooling mechanism in PVT [28]. Under identical power conditions, concentrated PV achieves solar-to-hydrogen (STH) conversion efficiency of 18-21% with hydrogen production rates of 0.8-1L, while conventional PV modules average 9.4% STH efficiency and 0.3L hydrogen production rate [29]. Caglar proposed an integrated PVT and PEM electrolyzer system, demonstrating energy efficiencies of 40% and 56%, and exergy efficiencies of 13.8% and 14.1% [30]. To enhance cooling, an improved thermal system with semi-length fins was developed. Longitudinal and wavy fins provide more cooling, increasing electric supply to the electrolysis unit. Hydrogen production rates for longitudinal fins, wavy fins, simple PVT, and PV are 13.5, 12.1, 9.5, and 7.8 ml/min respectively [31].

To mitigate heat on PV, flow rates are increased from 5g/s to 50g/s. As flow rates change, exergetic performance decreases while energetic performance increases. PV-T exergetic efficiencies range from 15.40% to 16.99%, with energetic efficiencies between 60.55% and 67.27%. PEM hydrogen production varies from 144.1g to 335.4g [32]. Concentrated PV-thermal (CPVT) systems generate both high-efficiency electricity and thermal energy. The electrical output powers the PEM electrolyzer, while thermal energy maintains optimal operating temperatures, enhancing electrolyzer performance and longevity. CPV module area and concentrating ratio affect energy/exergy efficiency and hydrogen production. Increasing solar irradiation on the PV leads to higher hydrogen production rates and efficiency [33].

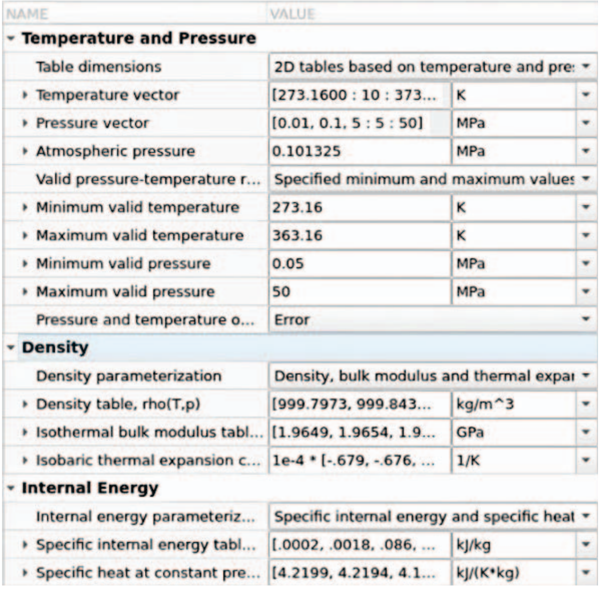
III. MODEL DEVELOPMENT

The typical electrolysis system breaks down into different subsystems/modules like heat exchanger, proton exchange membrane, cathode gas channels and anode fluid channels, and these all modules are linked with each other. Also, to make the simulation to run efficiently and precisely, the possibility of changing functional inputs like temperature, irradiation level of sun, current and pressure should be applied.

A. *MATLAB Simulation of PEME*

A typical electrolysis system comprises various subsystems/modules, including heat exchangers, proton exchange membranes, cathode gas channels, and anode fluid channels, all interconnected. To ensure efficient and precise simulation, the system should allow for adjustable functional inputs such as temperature, solar irradiation level, current, and pressure.

The PEM Electrolyzer, the primary source of hydrogen production, consists of several subsystems working in tandem for efficient hydrogen generation. Water supply to the proton membrane is the initial step, ensuring a constant and sufficient flow of water to the anode and cathode channels for the electrolysis process.



NAME	VALUE	
Temperature and Pressure		
Table dimensions	2D tables based on temperature and pre:	
Temperature vector	[273.1600 : 10 : 373...	K
Pressure vector	[0.01, 0.1, 5 : 5 : 50]	MPa
Atmospheric pressure	0.101325	MPa
Valid pressure-temperature r...	Specified minimum and maximum values	
Minimum valid temperature	273.16	K
Maximum valid temperature	363.16	K
Minimum valid pressure	0.05	MPa
Maximum valid pressure	50	MPa
Pressure and temperature o...	Error	
Density		
Density parameterization	Density, bulk modulus and thermal expai	
Density table, rho(T,p)	[999.7973, 999.843...	kg/m^3
Isothermal bulk modulus tabl...	[1.9649, 1.9654, 1.9...	GPa
Isobaric thermal expansion c...	1e-4 * [-.679, -.676, ...	1/K
Internal Energy		
Internal energy parameteriz...	Specific internal energy and specific heat	
Specific internal energy tabl...	[.0002, .0018, .086, ...	kJ/kg
Specific heat at constant pre...	[4.2199, 4.2194, 4.1...	kJ/(K*kg)

Figure 1 Inlet water characteristics

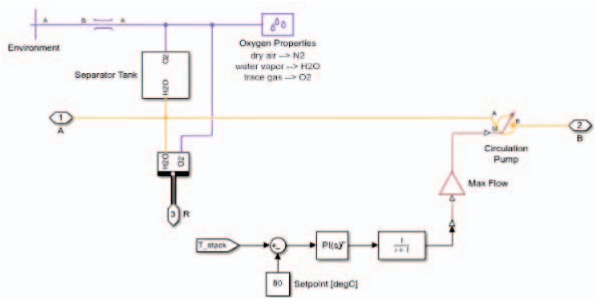


Figure 2 Recirculation system Simulation

Based on inlet water characteristics as shown in Fig. 1, water is directed to the recirculation system and then to the heat exchanger. Excess water or unconverted water in the anode channel is recycled back to the recirculation system (as shown in Fig 2) to maximize the resource efficiency. The circulation not only conserve the water but also help to maintain the concentration of electrolyzer fluids and constant temperature.

The heat exchanger plays a critical role in operational efficiency which is to regulate the operating temperature within the electrolyzer, maintaining optimal conditions for the electrolysis reaction. Moreover, the heat exchanger enables the recovery and utilization of waste heat generated during the electrolysis process. By capturing this heat and recirculating it back into the system, such as preheating reactants or maintaining the operating temperature, the heat exchanger improves the overall energy efficiency of the system. This lowers the operational costs, making the hydrogen production process more economically viable. As illustrated in Fig. 3, it extracts heat from the environment or an attached system like CPVT, transferring thermal energy to the water before it enters the membrane. This process maintains the optimal operating temperature of 20-80°C for the water, which is then directed to the anode channels.

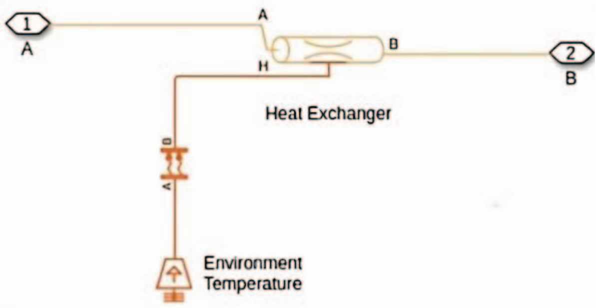


Figure 3 Heat Exchanger Simulation

Anode channels play a vital role in the initial PEM process, distributing water efficiently to the anode side where the electrochemical process begins. Water is evenly distributed across the anode layers' surface, ensuring optimal contact with catalyst sites. The electrochemical reaction starts and splits water into hydrogen and oxygen ions, with excess water returning to the recirculation system as shown in Fig. 4.

The anode reaction is shown in Eq. 1:

$$H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^- \qquad (1)$$

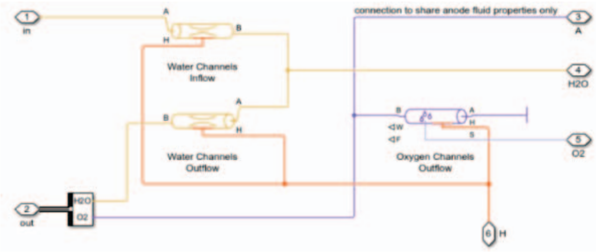


Figure 4 Anode Liquid Channels simulation

From the anode channels protons are transported through PEM membrane assembly which is specially designed to allow only protons to pass through it and blocks the gases. This separation maintains the high efficiency and purity of hydrogen.

Once the proton exits from the membrane it is transferred to cathode channels where they interact with the electrons returning from the external circuit to form hydrogen gas as shown in Fig 5. Waste heat dissipates to the connected thermal mass. The cathode reaction is as shown in Eq. 2:

$$2H^+ + 2e^- \rightarrow H_2 \qquad (2)$$

The overall reaction is:

$$2H_2O \rightarrow H_2 + \frac{1}{2}O_2 \qquad (3)$$

Following this, there is a dehumidifier as shown in Fig. 6, which manages the moisture content in the hydrogen gas stream exiting the electrolyzer membrane, making it suitable for storage. Dehumidification prevents corrosion and degradation in storage units or pipes. Finally, the hydrogen output system ensures the purification, collection, and measurement of produced hydrogen gas. This system incorporates sensors and flow meters to measure the flow rate, production rate, and pressure of the hydrogen gas.

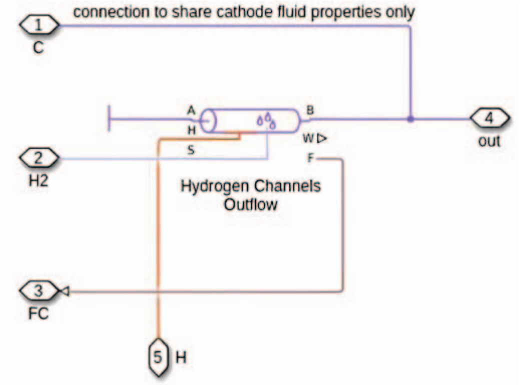


Figure 5 Cathode Gas Channels simulation

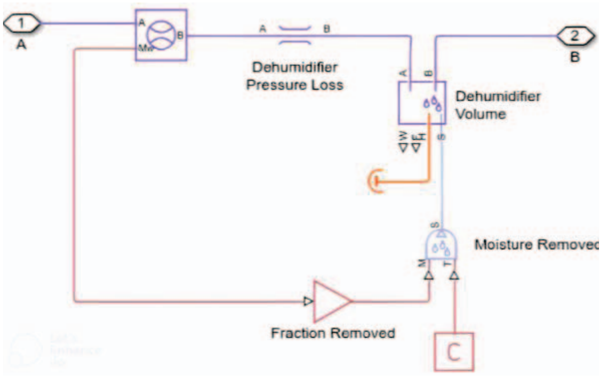


Figure 6 Dehumidifier simulation

B. Mathematical Simulation of PEME

Electrical energy is essential in electrolysis to split water molecules. However, during the electrolysis process, the voltage requirement increases due to activation and ohmic overvoltage [34]. To accurately determine the cell overpotential, it is necessary to calculate the various losses within the electrolyzer system. The total cell voltage comprises the sum of all possible overpotentials, including ohmic and activation losses, among others [35]. This comprehensive approach to voltage calculation ensures a more precise understanding of the electrolyzer's energy requirements and overall efficiency.

$$V = V_0 + V_{\mathrm{ohm}} + V_{\mathrm{activation}} \qquad (4)$$

where V_o describes the minimal voltage required for electrolysis to operate [36].

$$V_0 = 1.229 - 8.5 \times 10^{-4}(T_{PEM} - 298) \qquad (5)$$

$$V_{ohm} = \mathrm{I} \,.\, R_{ohmic} \qquad (6)$$

$$V_{activation} = \frac{RT}{\propto F}\left(ln\frac{I}{I_o}\right) \qquad (7)$$

where R is the universal gas constant (8.314 (J/mol.K)), α is the charge transfer coefficient and Io is exchange current density.

To calculate the efficiency of electrolyzer we have to compare the actual energy with the experimental ones.

$$\eta = \frac{\Delta H_{H2O}}{E_{cell} \cdot I} \qquad (8)$$

The ΔH_{H2O} shows the enthalpy change in the electrolysis reaction and E_{cell} is the actual cell voltage. The enthalpy is defined as energy needed for breaking up the chemical bond and entropy quantifies the irreversibilities within thermodynamic systems and Gibbs free energy of reaction. Therefore, enthalpy is prescribed as [37]:

$$\Delta H = \Delta G + T.\Delta S \qquad (9)$$

The Hydrogen production rate can be calculated by two ways:

$$\dot{V}_{H_2} = \frac{I \cdot M_{H_2}}{2F \cdot \rho_{H_2}} \qquad (10)$$

where V_{H2} is the volumetric hydrogen production rate and M_{H2} is the molar mass of hydrogen and ρ is the density of hydrogen.

Another method to calculate hydrogen production is:

$$H_{2-production} = \frac{N_{cell}.MW_{H2}.Cell\ Area.i\_cell}{2F} \tag{11}$$

where N_{cell} is the number of cells used in electrolyzer, MW_{H2} the molar mass of hydrogen, i_cell is the cell current density and F is Faraday constant which is 96485 (C/mol).

IV. RESULTS AND DISCUSSION

This section will analyze the performance of the PEM electrolyzer system focusing on crucial parameters including hydrogen production, voltage, power, and stack temperature. The graphical representations offer valuable insights into the system's behavior over its operational hours, particularly emphasizing the initial start-up phase and the cycle completion.

The hydrogen production graph, as illustrated in Fig. 7, depicts the production rate in gallons per second over time. A notable feature is the initial lag in hydrogen production. This delay is attributed to the system's start-up sequence, which involves energizing components, warming up the system, and establishing optimal operating conditions for water electrolysis. Once these conditions are met, hydrogen production commences, following a sinusoidal pattern. The production rate reaches a peak of 0.5 g/s before gradually declining as the cycle concludes. This pattern highlights the direct relationship between voltage input and hydrogen production rate, a critical aspect of PEM electrolyzer efficiency.

Voltage behavior exhibits a parallel sinusoidal trend. The initial voltage increase corresponds to the system's rising energy demands during start-up. Upon reaching its peak, the voltage follows a gradual degradation path as the cycle progresses. This voltage pattern directly influences the power production, highlighting the complex relationship between these parameters. The system achieves a maximum voltage of approximately 97V, corresponding to a peak power output of around 100KW. These figures provide benchmark data for assessing the electrolyzer's performance and efficiency.

Stack temperature is the temperature of electrolyzer membrane system where cell is stacked. Initially, as the system activates, the membrane temperature rises. However, the thermal management system, specifically the MEA thermal control, engages to regulate the temperature. It maintains a constant temperature of 80°C, which represents the optimal operating temperature for PEM systems. This temperature control is crucial for maintaining electrolyzer efficiency and longevity. The graph displays a constant temperature line until the cycle's conclusion, after which a temperature decline is observed as the system cools down.

The MATLAB-based analysis of the PEM electrolyzer reveals many insights on the operational dynamics and efficiency. The observed sinusoidal trends in hydrogen production, power output, and voltage illustrate the complex interplay between system activation, peak performance phases, and subsequent stabilization. These patterns provide valuable insights into system behavior, potentially guiding optimization strategies for future designs.

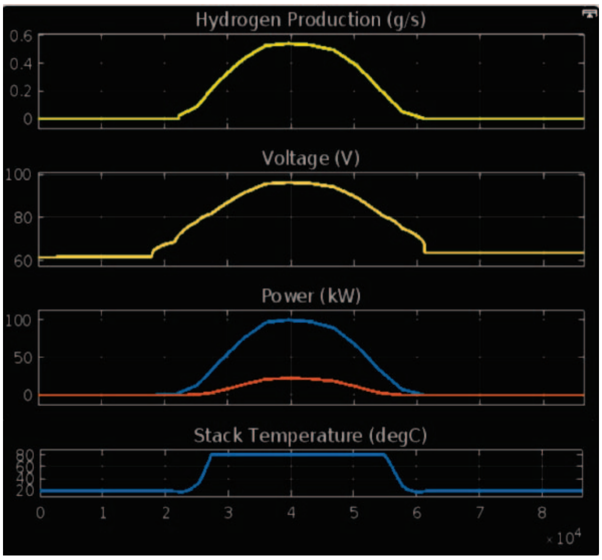


Figure 7 Simulation results of PEM Electrolyzer

V. CONCLUSION

This study provides the comprehensive analysis of MATLAB simulation of PEM electrolyzer. Different parameters including hydrogen production rate, power, voltage and stack temperature were analyzed to understand the nature, operating parameters and production rate of system. The hydrogen production rate, power and voltage show the sine curve which illustrates the interplay between system activation, peak performances and stabilization phases. It shows the maximum hydrogen production rate of 0.5g/s, voltage of 97V, power of 100W and stack temperature of the system during process remains constant at 80 C due to thermal mass MEA which extracts the excessive heat from the electrolyzer membrane. Overall, this system contributes in the advancements of the sustainable hydrogen production technologies.

During the simulation main challenge is the thermal behavior of the system. In real time PEM electrolyzer, heat generation and dissipation can be influenced by the several factors like specific design of electrolyzer, used materials and operating temperatures. To address this the simulation incorporated detailed thermal models that accounted for the heat generated by the electrolysis process and the heat capacity of the MEA. This approach has more accurate representation the system’s dynamics leading to more reliable simulation results.

This study highlighted the importance of thermal management in systems that combine PV technology with PEM electrolyzers demonstrating that with proper control and thermal management strategies, this combination can lead to efficient and sustainable hydrogen production. These insights are crucial for the future development of renewable energy systems that harness solar power for green hydrogen production, contributing to the broader goal of transitioning to a sustainable energy future.

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