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Original Article

Green Electricity Generation from Domestic Wastewater Using an Integrated PV-PEMEC-PEMFC System

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Abstract *- The swift exhaustion of fossil fuels, alongside increasing worldwide water scarcity, is hastening the transition to sustainable energy options and advanced wastewater recycling methods. A Proton Exchange Membrane Electrolysis Cell (PEMEC) has become essential for producing green hydrogen through water electrolysis because of its high energy efficiency and rapid dynamic response. This study investigates the generation of green hydrogen from Photovoltaic (PV) electricity via PEMEC, which is subsequently converted into green electricity with a Proton Exchange Membrane Fuel Cell (PEMFC). An integrated PV-PEMEC-PEMFC system was experimentally evaluated using tap water and 1% and 2% dishwashing solutions, as simulated domestic wastewater electrolytes, under different solar irradiance conditions. Experimental results showed a significant linear correlation between solar irradiance and PEMEC current, with the highest current and hydrogen production obtained using the 2% dishwashing solution. The measured hydrogen generation closely matched theoretical predictions. PEMFC performance showed a nonlinear relationship with irradiance, achieving an electrical output of about 2.4 kWh/day·m^2 under optimal conditions. The integrated system attained a maximum. PEMEC-PEMFC efficiency of 42%, with the 2% electrolyte consistently outperforming the other concentrations. The overall system efficiency peaked at approximately 5%. In addition to energy generation, the system produced about 1.2-1.4 L/day of clean water as a byproduct of fuel cell operation, demonstrating potential for co-production of potable water. Surplus hydrogen generated during the day was enough to maintain the electricity supply at night, ensuring continuous operation. Monthly estimations confirmed stable performance throughout the year.*

Keywords *- Green Electricity, Photovoltaic (PV), Proton Exchange Membrane Electrolysis Cell (PEMEC), Proton Exchange Membrane Fuel Cell (PEMFC), Domestic wastewater.*

1. Introduction

The shift towards sustainable energy systems is a global necessity motivated by concerns about climate change, exhaustion of fossil fuels, and ecological deterioration [1]. Solar Photovoltaic (PV) technology is regarded as one of the most environmentally friendly ways to produce electricity, providing a viable option for addressing climate change and enhancing energy security [2]. Nonetheless, the fluctuating nature of solar energy generation necessitates the integration of energy storage solutions to ensure a reliable power source. Although batteries are frequently used for short-term energy storage, their restricted capacity renders them unsuitable for extended or seasonal storage needs [3]. As an alternative, hydrogen energy storage offers a viable option for both daily and seasonal energy demands [4]. Hydrogen is anticipated to be crucial for sustainable development since it can be generated in nearly limitless amounts utilizing renewable energy sources [5]. Although various hydrogen production methods utilizing renewable energy sources are under development, water electrolysis stands out as the most feasible option at present [6-9]. Water electrolysis involves the breakdown of water into hydrogen and oxygen through electricity with an electrolyzer. This approach is considered "green" since it harnesses clean, renewable energy and produces no greenhouse gas emissions in the purest form of hydrogen production [1, 10, 11]. Proton Exchange Membrane Electrolysis Cell (PEMEC) is a favored approach for sustainably transforming renewable energy into high-purity hydrogen, providing high current densities, great efficiency, quick response, compact design, and operation at low temperatures [12, 13]. Green hydrogen serves as a clean energy carrier, capable of being transformed back into green electricity through the use of a Proton Exchange Membrane Fuel Cell (PEMFC) [14]. PEMFC converts the chemical energy of hydrogen supplied to the anode and air or oxygen supplied to the cathode directly into electrical energy without combustion. Fuel cells represent a highly promising energy technology for various uses, including transportation, portable

devices, and residential power generation. PV-electrolysis-fuel cell hybrid systems have attracted considerable attention due to their potential to produce green electricity and high-purity hydrogen by coupling solar power with electrochemical conversion. One of the early efforts was by Lehman and Chamberlin [15], who designed a solar fuel cell system integrating PV panels with a high-pressure bipolar alkaline electrolyzer for hydrogen production and a PEMFC for electricity generation. In addition, numerous studies have concentrated on the dynamic modeling and optimal design of the PV-electrolysis-fuel cell systems [4, 16-24]. Kim et al. [4] conducted a numerical simulation to assess the feasibility of a PV-electrolysis-PEMFC hybrid system incorporated into the electric grid network throughout the Korean Peninsula.

Hwang et al. [16] created a mathematical model of a standalone PV-fuel cell hybrid system, demonstrating effective energy management in which solar energy meets load demands, surplus energy generates hydrogen, and the PEMFC provides reliability during periods of low solar radiation. Devrim and Pehlivanoğlu [17] developed an off-grid PV panel/PEMEC/high-temperature PEMFC hybrid system based on a solar radiation model for Ankara. The PV/PEMFC hybrid system was designed and simulated in MATLAB/Simulink to estimate the daily energy output from the PV array for the electrolyzer, along with the hydrogen produced and stored for constant hydrogen consumption of the PEMFC [18].

The simulation also evaluated the power delivered by the PEMFC to the DC bus under varying solar irradiation over time [19]. A numerical simulation of a three-dimensional model integrating a PEMEC and a PEMFC was performed to evaluate power production, efficiency, and the levelized cost of electricity [20]. Shboul et al. [21] also developed an optimized hybrid PV-fuel cell system for generating green hydrogen and electricity through numerical modeling to evaluate its energy, economic, and environmental effectiveness. HOMER software was also employed to analyze monthly electricity production from PV array and PEMFC, as well as hourly data for electrolyzer power input and PEMFC power output, and stored hydrogen in May and September in NEOM, Saudi Arabia [22]. Ganguly et al. [23] designed a model of a PV-electrolyzer-PEMFC system and found that 51 PV modules rated at 75 W each, combined with a 3.3 kW electrolyzer and two PEMFC stacks of 480 W, could adequately satisfy the energy requirements of a 90 m^2 floriculture greenhouse. Zhang et al. [24] modeled a PV-electrolyzer-fuel cell process to simulate the effects of solar irradiance and ambient temperature on system efficiency and performance, and estimated that a system with a 28 m^2 PV array could fulfill 70% of a household's annual power needs. Despite the limited experimental data on the integrated PV-PEMEC-PEMFC system, several studies have experimentally investigated hydrogen production using standalone PV-PEMEC configurations [25-31]. As previously noted, fresh water is commonly used in the electrolysis process for hydrogen production; however, it remains a scarce resource in many regions, with over 80% of the global population facing significant water security risks [32]. In contrast, using wastewater as a feedstock conserves freshwater resources and enables concurrent pollutant removal, presenting a dual-benefit strategy for integrated energy and environmental management. In recent years, wastewater has increasingly been recognized as a valuable and sustainable resource for cost-effective energy generation [33, 34]. Among various energy recovery methods, wastewater electrolysis has become a notably encouraging approach for hydrogen generation [6, 35-40]. Most existing studies have primarily focused on hydrogen production, while limited attention has been given to testing hydrogen derived from wastewater for electricity generation using fuel cells.

For instance, Al-Maghalseh [41] proposed a power management strategy, implemented using a MATLAB function, for a combined PV-fuel cell system created for domestic wastewater treatment, wherein a Microbial Fuel Cell (MFC) prototype was experimentally tested for the wastewater pre-treatment prior to electrolysis. Nevertheless, experimental studies demonstrating the effectiveness of PV-PEMEC-PEMFC integration, especially when utilizing domestic wastewater as an electrolyte, remain limited.

This study aims to demonstrate that hydrogen produced by a PEMEC using dishwashing wastewater as the electrolyte can be directly fed into a PEMFC for electricity generation without any purification process. Accordingly, a novel self-sustainable green energy system is proposed by directly integrating a PV-powered PEMEC with a PEMFC, using dishwashing wastewater as the hydrogen source. In this study, the influences of solar irradiance on hydrogen production from wastewater through combined PV-PEMEC and the electricity generation via PEMFC using the produced hydrogen are experimentally investigated. Key performance indicators are examined, including Solar-to-Hydrogen (STH) and PEMEC-PEMFC efficiency. In addition, monthly estimates of energy generation, wastewater utilization, and freshwater recovery are provided based on solar irradiance profiles across different months-an aspect that has not been addressed in previous studies.

2. Literature Review

Numerous studies have explored methods to integrate PV and electrolysis to generate green hydrogen. The main concept is to harness sunlight for electricity generation while simultaneously producing hydrogen that can be stored and utilized later. This enhances the overall flexibility and efficiency of the system. Among the different types, PEMEC is highly favored. The reason is their high efficiency, quick response to changes, and compact size [16, 25]. Various approaches for connecting PV with electrolysis have been tested. The most straightforward method is direct coupling. It

is inexpensive and simple, yet demands precise tuning, as the electrolyzer must align with the PV array's Maximum Power Point (MPP) [27].

In a study, Atlam [25] demonstrated that the operating point of a PEMEC could be predicted with a minimal relative error of 0.1-0.8% over irradiance levels from 18% to 100%, confirming the model's reliability in comparison to actual data. The PV module showed peak efficiencies of 11-12%, while coupling with the PEM electrolyzer yielded 7.5% because of mismatches at the operating point. Nonetheless, the PEM electrolyzer attained an efficiency of 70% and a utilization efficiency between 64% and 70%, resulting in overall STH efficiencies ranging from 5.1% to 5.4% under varying irradiance.

Moreover, Stansberry et al. [26] investigated the integration of a PEMEC with a PV system using MPPT-based power electronics in both direct DC and grid-connected AC configurations. The direct DC setup attained 7-8% greater energy transfer efficiency than the AC setup and maintained consistent hydrogen generation under rapid PV power variations, with ramp rates reaching up to 1270 W/s and part-load operation down to 7.6% of rated power. Performance improved even more at higher stack and ambient temperatures, showcasing the reliability of direct coupling for dynamic STH applications.

Similarly, Mraoui et al. [27] optimized the system operation using a mathematical model to simulate the operation. The pure water electrolysis using PEMEC is directly connected to a PV to supply electric power for the operating system. The system underwent simulation to assess the accuracy of the model for enhancement purposes. The optimization procedure enables the retrieval of the highest power from the photovoltaic panel without the need for a DC-DC MPPT controller. Although the models demonstrated strong accuracy for PV and PEMEC elements (RMSE ≈ 2%), differences from experimental outcomes in the direct-coupling setup (RMSE ≈ 7%) underscore the necessity for enhanced modeling approaches for effective STH conversion.

In another case, Khelfaoui et al. [28] investigated the influences of ambient temperature and solar radiation on the performance characteristics of solar PV/PEM electrolyzer through modeling, simulation analysis, and experimental research. Experiments conducted with the PEM electrolyzer HG60 demonstrated a substantial hydrogen yield of 284 L during 8 hours of operation, with PEM efficiency ranging between 18%-40% when powered by the PV system. The PV panels exhibited 9-12% efficiencies under the tested conditions. A major issue hindering electrolysis, however, is water. The majority of systems require fresh water, which is increasingly becoming limited worldwide [31]. Certain research efforts are now utilizing wastewater as an alternative resource to overcome this. This concept is interesting because it addresses two problems simultaneously: conserving fresh water and generating clean energy. It also relates to the idea of a circular economy—waste flows transforming into resources.

Several kinds of wastewater have been tested. For instance, Cuesta-Mota et al. [38] examined the combined advantages of concurrent dye effluent discolouration and hydrogen production in the textile industry through electrochemical methods. Dissolutions of four widely utilized azoic reactive dyes were examined as synthetic textile wastewater, evaluating hydrogen production efficiency and quality in comparison to traditional Alkaline Water Electrolysis (AEL). Electrochemical experiments were carried out using two 1 cm^2 Platinum (Pt) sheets as electrodes, positioned with an interelectrode gap of 8 cm.

Results demonstrate that contaminants in wastewater and salts affect hydrogen production while successfully eliminating colors from various textile dyes. NaCl and NaOH were included as chemical aids. The hydrogen purity generated during the electrochemical processing of effluents from textile reactive dyeing was approximately 95-96% at the highest current densities. They achieved faradaic efficiency between 80% and 95% for hydrogen production, and at the same time, the process removed more than 90% of the color from the wastewater. The results also showed the hydrogen generation of 1.5-2 mL/min/cm^2 at a current density of 212-244 mA/cm^2.

Marques et al. [39] tested hydrogen production by integrating a PV-driven electrochemical system with alternative electrolytes derived from ornamental stone industry residues. The electrolysis system used 304 stainless steel for the electrodes. A specially designed cylindrical electrolytic cell showed that traditional loom granite electrolyte yielded the most hydrogen (329 mL in 2 h at 1332 W/m^2 irradiance), while diamond multiwire granite waste generated 54% less because of reduced conductivity. While NaOH demonstrated greater efficiency, the granite-based electrolytes offer a more sustainable and economical option by lessening corrosivity and minimizing environmental effects.

Orosa et al. [40] also presented a self-made single cavity electrolyzer without a membrane for hydrogen generation in atmospheric conditions, using olive mill and biodiesel wastewaters in KOH medium. Graphite was identified as the most suitable electrode for the process among the tested materials. Hydrogen produced from olive mill wastewater can be regarded as very pure. The low current readings (1-2 A) suggest a restricted gas flow, which fell from 1.54 L/h initially to 0.52 L/h by the end of the process. The electrolytic experiments were conducted at a constant voltage of 3 V using electrodes with a surface area of 100 cm^2 and thicknesses of 8 mm and 16 mm. For the 8 mm electrodes, hydrogen flow rates decreased from 1.54 L/h at the start to 0.55 L/h at the end of

the process, whereas the 16 mm electrodes delivered higher flows throughout, from 2.83 L/h initially to 1.40 L/h at the end. These studies demonstrate that wastewater electrolysis can simultaneously achieve two objectives: generating energy and treating wastewater. However, most of the work conducted to date has focused on industrial effluents. Research on hydrogen production from wastewater using PEMEC systems remains limited [6]. Moreover, few studies have investigated the use of domestic wastewater in integrated PV-PEMEC-PEMFC systems [41]. That leaves a gap and an opportunity for decentralized solutions that can generate renewable energy while facilitating the management of local water resources.

Al-Maghalseh [41] carried out a hybrid PV-PEMFC system in MATLAB for treating domestic wastewater. The system integrated an MFC for wastewater pre-treatment before electrolysis, allowing simultaneous provision of household energy and wastewater treatment. The sizing of the PV generator, PEMFC, and electrolyzer was designed based on regular daily energy usage for home utilization. Results indicated that, at this scale, the system required 18 PV panels of 260 W each, three PEM fuel cells rated at 500 W, a 1500 W electrolyzer, and a 5 kW hybrid inverter.

In addition, the majority of studies on PV-electrolyzer-PEMFC system integration have been conducted through modeling rather than experimental validation, typically assuming pure water as the electrolyte [22-23]. Most research has focused on system sizing to meet energy consumption requirements, as illustrated in the studies by Ghoniem et al. [22] and Ganguly et al. [23].

Ghoniem et al. [22] analyzed three PEMFC capacities (30, 40, and 50 kW) to identify the optimal PV/PEMFC configuration, finding that a 30 kW PEMFC combined with a 201 kW Trina Solar module provided the lowest net present cost and cost of energy, with a levelized hydrogen cost of USD 15.9-23.4/kg. Replacing the PV module with a 50 kW Tindo system reduced costs by 32%.

Furthermore, a greenhouse-integrated power system with PV-PEMEC-PEMFC was modeled and analyzed by Ganguly et al. [23]. PEMFCs utilize the hydrogen generated by the electrolyzer from surplus solar energy captured during peak hours to satisfy energy demands during low-availability times. A 90 m^2 fan-pad ventilated floriculture greenhouse showed that an optimal setup of 51 PV modules (each 75 Wp), a 3.3 kW electrolyzer, and two 480 W PEMFC stacks can function entirely independently and sustainably. The above-mentioned studies highlight the lack of experimental investigations on PV-PEMEC-PEMFC systems using domestic wastewater. Furthermore, the impact of solar irradiance on the efficiency of PV–PEMEC systems and hydrogen production from domestic wastewater has not been previously investigated. The objective of this study is to evaluate system performance, including energy production, wastewater utilization, and water output, throughout the year based on monthly solar irradiance data.

3. Materials and Methods

3.1. PV-PEMEC-PEMFC System

Figure 1 illustrates the proposed PV-PEMEC-PEMFC system, which utilizes domestic wastewater to generate green electricity, freshwater, and surplus hydrogen for nighttime operation. Hydrogen production using a PV-PEMEC system involves two primary steps. Initially, solar energy is captured by a PV panel and transformed into electrical energy. On-site solar irradiance was measured using a TES 1333R Datalogging solar power meter. The generated electrical energy is then used to drive the electrolysis of dishwasher wastewater in a PEMEC, producing hydrogen through an electrochemical process. In this study, a PV panel with an active surface area of 64 cm^2 was directly coupled to a single PEMEC with an electrode area of 6.25 cm^2.

The direct connection permitted the PEMEC to operate under fluctuating solar irradiance conditions without requiring intermediate power conditioning, thus facilitating real-time assessment of the PV-PEMEC integration for hydrogen production. The PEMEC consists of a membrane electrolyte positioned between an anode and a cathode. Domestic wastewater was fed into the anode side of the PEMEC, while the hydrogen produced at the cathode side was directly transported to the anode of the PEMFC. The cathode of the PEMFC was exposed to ambient air without forced airflow. Water generated as a byproduct of the PEMFC electrochemical reaction was collected. The PEMEC and the PEMFC used in the experiments were made by Horizon Fuel Cell Technologies. A renewable energy monitoring system, also provided by Horizon Fuel Cell Technologies, was used to measure and record the voltage, current, and power associated with the electrical input to the PEMEC and the power output from the PEMFC.

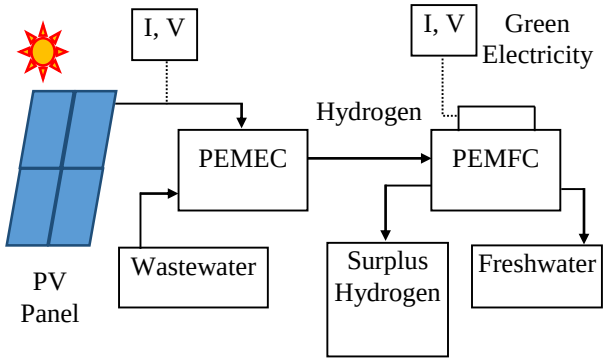

Fig. 1 Proposed PV-PEMEC-PEMFC system

In the PEMEC, water is oxidized at the anode to generate oxygen gas, protons, and electrons. Protons merge with electrons at the cathode, resulting in hydrogen gas formation.

The electrochemical half-reactions occurring at the anode and cathode are as follows:

$$\text{Anode: } H_2O \rightarrow \tfrac{1}{2}O_2 + 2H^+ + 2e^- \quad (1)$$

$$\text{Cathode: } 2H^+ + 2e^- \rightarrow H_2 \quad (2)$$

$$\text{Overall: } H_2O \rightarrow H_2 + \tfrac{1}{2}O_2 \quad (3)$$

In the PEMFC, hydrogen undergoes oxidation at the anode, generating electrons and protons. The electrons travel through an external circuit to the cathode, producing electrical energy, while the protons move through the PEM.

At the cathode, incoming protons and electrons react with oxygen to produce water as a byproduct. The electrochemical half-reactions taking place at the anode and cathode are as defined:

$$\text{Anode: } H_2 \rightarrow 2H^+ + 2e^- \quad (4)$$

$$\text{Cathode: } \tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (5)$$

$$\text{Overall: } H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \quad (6)$$

In this study, dishwashing wastewater, a type of domestic wastewater, was used as the hydrogen source. The concentration of dishwashing wastewater, defined as the volume ratio of dishwashing liquid to water, was varied at 1% and 2%, and the results were compared with those obtained using tap water (0%). The dishwashing liquid used contains 8.850% sodium lauryl ether sulfate and 1.495% cocamidopropyl betaine as the main ingredients.

The impact of these concentrations on PEMEC performance was evaluated. For dishwashing wastewater concentrations of 0%, 1%, and 2%, the measured pH values were 7.08, 7.07, and 7.10; the electrical conductivities were 151.9, 674.5, and 1348 µS/cm; and the resistivities were 6.59, 1.48, and 0.75 kΩ·cm, respectively. For comparison, deionized water exhibited a pH of 8.11, an electrical conductivity of 0.74 µS/cm, and a 265 kΩ·cm resistivity.

3.2. Theoretical Produced Hydrogen and Consumed Hydrogen

The theoretical hydrogen formation as a function of the consumed current in the PEMEC was calculated to enable comparison with the experimental results. The produced hydrogen, $v_{H_2,PEMEC}$ (mL/min), is given by Equation 7 as a function of the current utilized by the PEMEC, I_{EC} (A), and the molar volume, v_M (L/mol), calculated using Equation 8 [20, 42]:

$$v_{H_2,PEMEC} = v_M \left(\frac{L}{mol}\right)\left(\frac{10^3\ mL}{L}\right)\left(\frac{60\ s}{min}\right)\left(\frac{I_{EC}\left(\frac{C}{s}\right)}{2F\left(\frac{C}{mol}\right)}\right) \quad (7)$$

$$v_M = \frac{RT}{p} \quad (8)$$

Where F is the Faraday constant (96,485 C/mol), T is the working temperature (K), p is the working pressure (atm), and R is the ideal gas constant (0.082 L atm K^{-1} mol^{-1}).

As the current, I_{FC} (A), is generated by the PEMFC, the amount of consumed hydrogen, $v_{H_2,PEMFC}$ (mL/min), is obtained as follows:

$$v_{H_2,PEMFC} = v_M \left(\frac{L}{mol}\right)\left(\frac{10^3\ mL}{L}\right)\left(\frac{60\ s}{min}\right)\left(\frac{I_{FC}\left(\frac{C}{s}\right)}{2F\left(\frac{C}{mol}\right)}\right) \quad (9)$$

Since the active area of the PEMEC is larger than that of the PEMFC, the quantity of hydrogen generated by electrolysis exceeds the hydrogen consumed by the fuel cell. Therefore, the surplus hydrogen can be calculated as follows:

$$\text{Surplus } H_2 = v_{H_2,PEMEC} - v_{H_2,PEMFC} \quad (10)$$

3.3. Wastewater Utilization and Water Production

The wastewater utilization by the PEMEC is calculated based on the stoichiometric relationship in which one mole of water produces one mole of hydrogen, as shown in Equation 3. Accordingly, the water utilization by the PEMEC, $v_{H_2O,PEMEC}$ (mL/min), can be calculated as follows:

$$v_{H_2O,PEMEC} = \frac{I_{EC}\left(\frac{C}{s}\right)M_{H_2O}\left(\frac{g}{mol}\right)}{2F\left(\frac{C}{mol}\right)\rho_{H_2O}\left(\frac{g}{mL}\right)}\left(\frac{60\ s}{min}\right) \quad (11)$$

Where M_{H_2O} is the molar mass of water (18 g/mol) and ρ_{H_2O} Is the water density (1 g/mL)?

The water production from the PEMFC, $v_{H_2O,PEMFC}$ (mL/min) can be determined as follows:

$$v_{H_2O,PEMFC} = \frac{I_{FC}\left(\frac{C}{s}\right)M_{H_2O}\left(\frac{g}{mol}\right)}{2F\left(\frac{C}{mol}\right)\rho_{H_2O}\left(\frac{g}{mL}\right)}\left(\frac{60\ s}{min}\right) \quad (12)$$

3.4. Efficiency Calculation

Solar-To-Hydrogen (STH) efficiency represents the overall efficiency of converting sunlight into hydrogen through electrochemical water splitting. It is influenced by the combination of two essential elements: the efficiency of the PV system (η_{PV}) in converting solar energy into electricity and the efficiency of PEMEC (η_{PEMEC}) in turning that electricity into hydrogen. This relationship is described by Equation 13 [43].

$$\text{STH Efficiency} = \eta_{PV} \times \eta_{PEMEC} \quad (13)$$

Consequently, the Solar-To-Hydrogen (STH) efficiency is determined based on the experimentally measured flow rate

of hydrogen and the solar energy input used for hydrogen generation, as shown in Equation 14 [43]:

$$\text{STH Efficiency} = \frac{v_{H_2,PEMEC}\left(\frac{mL}{min}\right)\left(\frac{L}{10^3 mL}\right)\left(\frac{60\,min}{h}\right)\times H_2 LHV \times H_2 density}{PV\ area\ (m^2)\times Solar\ irradiance\left(\frac{W}{m^2}\right)} \times 100 \quad (14)$$

Where H_2 LHV (hydrogen low heating value) is 33.35 kWh/kg at 1 and 298 K, the H2 density is 0.000082 kg/L at 1 and 298 K.

Under standard conditions of 25°C and 1 atm, a minimum voltage of 1.48 V (thermal-neutral voltage, V_{TN}) is necessary for water electrolysis. The efficiency of conversion is determined as the ratio of the thermal-neutral voltage to the electrolysis cell voltage (V_{EC}), representing the effectiveness of converting electrical energy into chemical energy. Typically, water electrolysis efficiency is evaluated based on hydrogen's higher heating value (HHV) since water is delivered to the cell in its liquid state. Accordingly, the efficiency of the PEMEC (η_{PEMEC}) can be determined using Equation 15 [44].

$$\eta_{PEMEC} = \frac{V_{TN}}{V_{EC}} \quad (15)$$

The PEMFC efficiency is characterized by the proportion of the electrical power output (W_{FC}) to the chemical power of the consumed hydrogen (W_{H_2}), as expressed in Equation 16 [45].

$$\eta_{PEMFC} = \frac{W_{FC}}{W_{H_2}} \quad (16)$$

The electrical power produced by the PEMFC is determined by multiplying the output voltage (V_{FC}) with the current (I_{FC}), as indicated in Equation 17. The value of chemical energy from hydrogen consumed, expressed in Joules per second (Watts), is calculated using Equation 18. The consumed hydrogen flow rate, $v_{H_2,PEMFC}$ Was converted from mL/min to L/h by multiplying the measured values by a factor of 0.06.

$$W_{FC} = I_{FC} V_{FC} \quad (17)$$

$$W_{H_2} = v_{H_2,PEMFC} \times H_2 LHV \times H_2 density \quad (18)$$

The effectiveness of the PEMEC combined with the PEMFC system for energy production is determined as the multiplication of the PEMEC efficiency and the PEMFC efficiency, as illustrated in Equation 19.

$$\text{PEMEC-PEMFC Efficiency} = \eta_{PEMEC} \times \eta_{PEMFC} \quad (19)$$

The overall system efficiency can be evaluated using Equation 20.

$$\text{Overall system efficiency} = STH \times \eta_{PEMFC} \quad (20)$$

4. Results and Discussion

4.1. Green Hydrogen Production

In the experimental study, the PV panel transforms solar irradiance into electrical energy, which is directly provided to the PEMEC for hydrogen production. Figure 2 shows how the PEMEC current changes based on solar irradiance at three different electrolyte concentrations of 0%, 1%, and 2% dishwashing solution. With increasing solar irradiance, the current in the PEMEC likewise rises. The relationship between PEMEC current and solar irradiance is well represented by linear regression. Similar slopes are observed for the 0% and 1% concentrations; however, at 2% concentration, a lower slope is observed, indicating reduced current response to increased solar irradiance. The slight decrease in slope observed at the 2% concentration may be attributed to increased viscosity, which can resist mass transport, along with the possible accumulation of surfactants on the membrane or electrodes. Additionally, tap water was used as the primary component of the electrolyte. Ion transport in this context is influenced by water hardness and the mobility of ions in the solution. Ion movement may be restricted by the passage of ions via water to the anode/PEM interface [46].

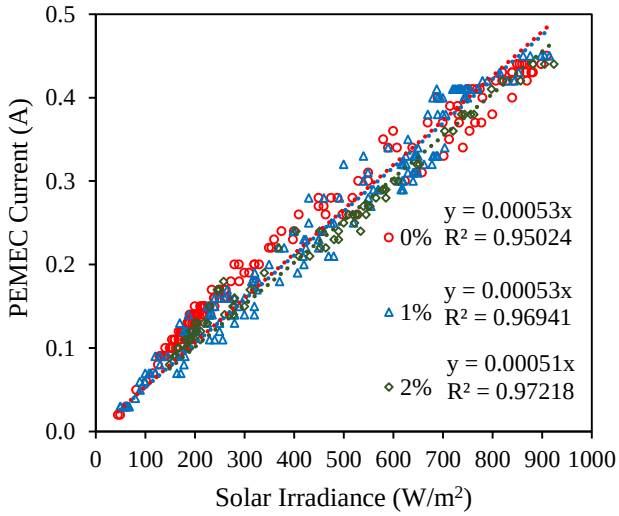

Fig. 2 PEMEC current at different solar irradiance

Figure 3 presents the experimental current-voltage (I-V) characteristics of the PEMEC with varying concentrations of dishwashing solution as the electrolyte. For all concentrations, the PEMEC voltage increases linearly with current due to the ohmic overpotential [16], and the experimental data are well approximated by linear fits. These results are consistent with previous studies on water electrolysis, which report current

ranges of 0-1 A and voltage values typically between 1.5 V and 1.8 V [25, 47]. These experimental I-V results are compared with a theoretical linear model described by Equation 21 [25].

$$I = \begin{bmatrix} 0 & V \leq 1.476 \\ 3.064(V - 1.476) & V > 1.476 \end{bmatrix} \quad (21)$$

This model can be rearranged to express voltage as a function of current when I > 0, as shown in Equation 22.

$$V = 0.3264I + 1.476 \quad (22)$$

The y-intercepts of the linear fits represent the theoretical equilibrium cell voltage (open-circuit voltage, V_{OCV}) under negligible load conditions [16]. Notably, all fitted lines lie above the theoretical model curve. In the case of electrochemical water splitting, the thermodynamic potential is 1.23 V under standard conditions (25 °C and 1 atm) [48]. However, in practice, the actual voltage required for electrolysis exceeds this theoretical value due to kinetic barriers at both the anode and cathode.

The slope of the I-V characteristic represents the internal electrical resistance of the PEMEC during operation [25]. At 2% electrolyte concentration, the slightly higher V_{OCV} may suggest increased electrode polarization or interference from surfactants, which can hinder hydrogen evolution kinetics.

Furthermore, the slope increases with concentration (from 0.4191 to 0.4833), indicating greater membrane resistance, likely resulting from additive accumulation on the membrane surface. Although increased electrolyte concentration would generally enhance ionic conductivity, the presence of non-ionic surfactants or fillers in the dishwashing liquid appears to dominate the transport behavior, ultimately reducing overall performance. Figure 4 illustrates the correlation between PEMEC current and the measured hydrogen production rate.

A strong linear relationship is observed for all electrolyte concentrations, indicating highly stable PEMEC performance across varying current loads and concentrations. Minor deviations from the theoretical line are noted.

Since hydrogen production is a direct function of PEMEC current, as defined in Equation 7, the experimental data are compared against the theoretical hydrogen production rates. Electrolyte concentrations of 1% and 2% dishwashing solution yield hydrogen production rates that closely match theoretical values, confirming the practical reliability and efficiency of the system. At a fixed current of 0.24 A, the hydrogen production rates for tap water containing 0%, 1%, and 2% dishwashing solution were 1.73, 1.74, and 1.78 mL/min, respectively. In contrast, distilled water under the same current conditions produced 1.9 mL/min of hydrogen [27].

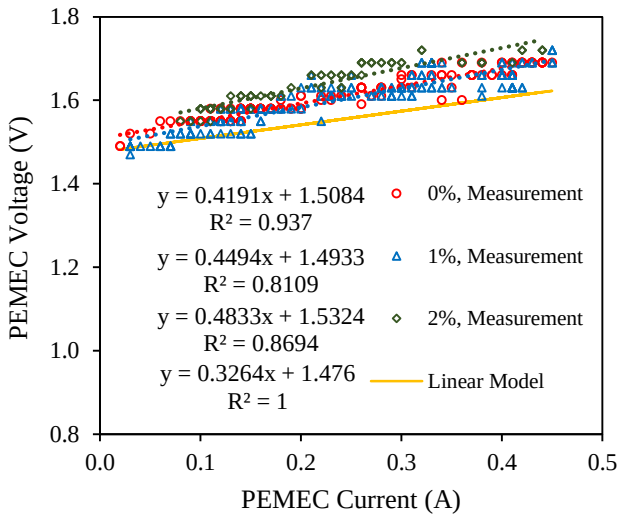

Fig. 3 Current-Voltage characteristics of PEMEC for measurement and linear model

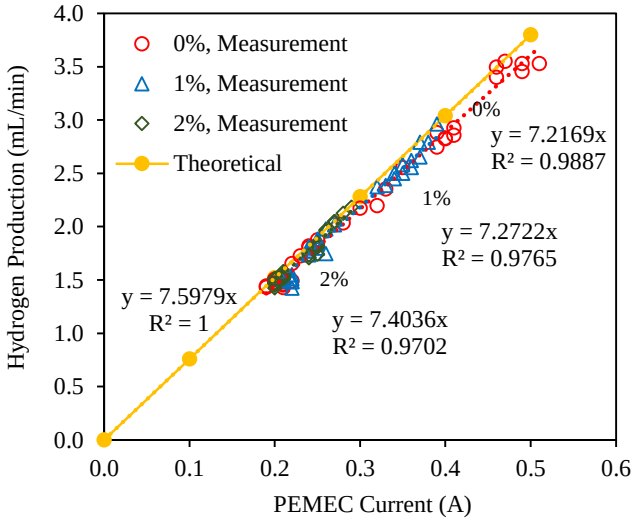

Fig. 4 Hydrogen production at different PEMEC currents

Figure 5 shows the direct relationship between solar irradiance and the hydrogen production rate. A rise in solar irradiance increases hydrogen production. At the highest tested solar irradiance of 900 W/m^2, the hydrogen production rates for tap water with 0%, 1%, and 2% dishwashing solution were 3.27, 3.38, and 3.35 mL/min, respectively. In comparison, the use of distilled water under the same irradiance yielded a significantly lower hydrogen production rate of 1.98 mL/min [27]. Across the tested electrolyte concentrations of 0-2% dishwashing solution, the overall hydrogen production did not vary significantly. An increase in the electrolyte concentration of 1% of dishwashing liquid, corresponding to increased electrolyte conductivity, resulted in a slight improvement in hydrogen production. However, at a 2% concentration, hydrogen production declined. This reduction is likely due to the presence of non-conductive substances such as surfactants, which may interfere with the

PEMEC membrane or electrode surfaces. This interpretation corresponds with the noted decline in current at higher concentrations, as shown in Figure 2.

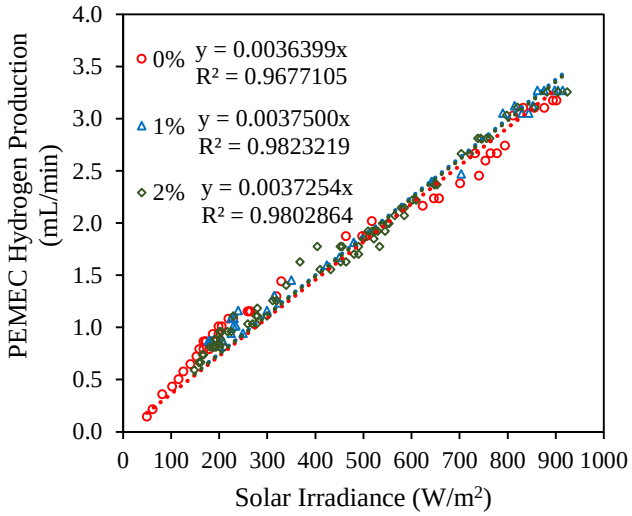

Fig. 5 Hydrogen production at different solar irradiance

4.2. Green Electricity Production

To evaluate the potential of using dishwashing solution as a surrogate for domestic wastewater in hydrogen production, the hydrogen generated by the PEMEC was directly fed into the PEMFC without intermediate storage. Figure 6 demonstrates the measured electrical power output of the PEMFC in relation to solar irradiance for different electrolyte concentrations. For all concentrations, an increase in solar irradiance corresponds to an increase in PEMFC power output.

Replacing plain tap water with a 1-2% concentration of dishwashing wastewater markedly enhances power generation, particularly under medium to high irradiance conditions. At solar irradiance in the range of 500-900 W/m^2, the 1-2% concentration yields the high power output, reaching approximately 0.12-0.16 W. Furthermore, while the performance of the 1% concentration slightly surpasses that of the 2% solution, both significantly outperform the tap water, indicating the practical benefits of household wastewater utilization in decentralized hydrogen-powered energy systems.

The consumed hydrogen is estimated based on the current generated by the PEMFC. The effect of hydrogen utilization in the electrochemical reaction is reflected in the power output. As solar irradiance increases, hydrogen utilization also rises, leading to greater electricity production, as illustrated in Figure 7. However, despite additional increases in solar irradiance, hydrogen consumption plateaus at irradiance levels exceeding 700 W/m^2. This shows that the hydrogen generated by the PEMEC surpasses the consumption ability of the PEMFC in these conditions.

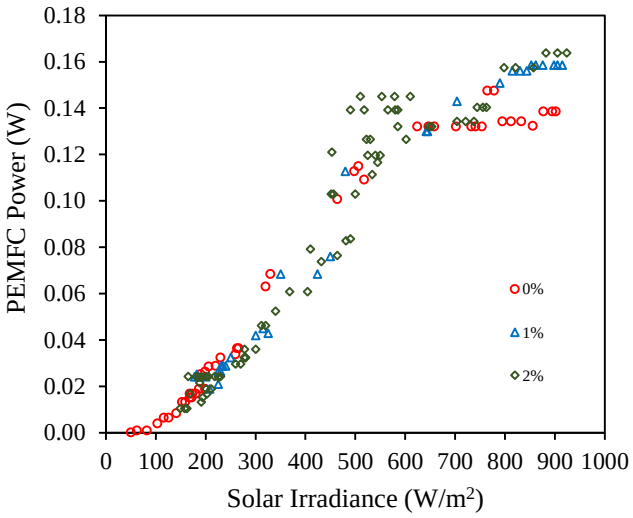

Fig. 6 PEMFC power generation at different solar irradiance

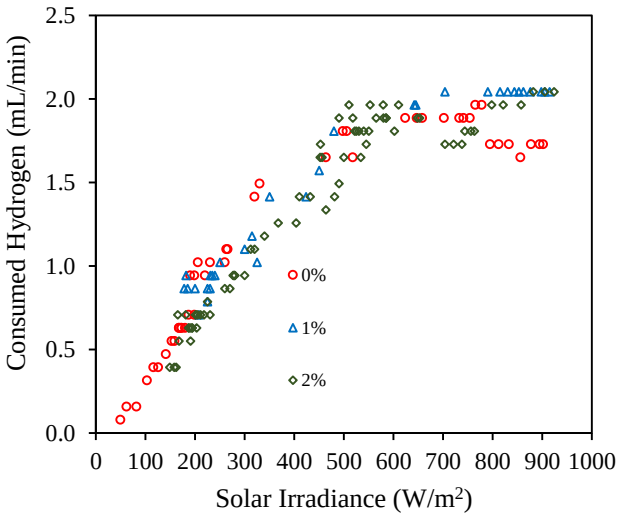

Fig. 7 Consumed hydrogen in PEMFC at different solar irradiance

4.3. Efficiency Analysis

Figure 8 shows the STH efficiency of the PV-powered PEMEC system based on solar irradiance for three electrolyte concentrations. At solar irradiance levels of approximately 200 W/m^2, all concentrations exhibit higher STH efficiencies, ranging from 10-14%. This trend is typical in PV-PEMEC systems, where the voltage and current output from the PV panel more closely align with the electrolyzer's optimal operating point under reduced irradiance. As irradiance increases beyond approximately 400 W/m^2, the STH efficiency in this study gradually declines and stabilizes in the range of 8-12%, depending on the electrolyte concentration. This decrease is primarily attributed to increased ohmic losses associated with higher current levels [49]. Arunachalam and Han [50] found an efficiency ranging from 7.78 to 8.81% in the low current density area and 6.6% in the high current density when converting solar energy into hydrogen. The STH

efficiencies in the 10-15% range are respectable for the PV-PEMEC system using household dishwashing solution as electrolyte. Comparable performance has been reported by Calnan et al. [51], who developed integrated PV-alkaline electrolysis prototypes with solar collection areas ranging from 64 cm^2 to 2600 cm^2, achieving STH efficiencies between 4% and 13%.

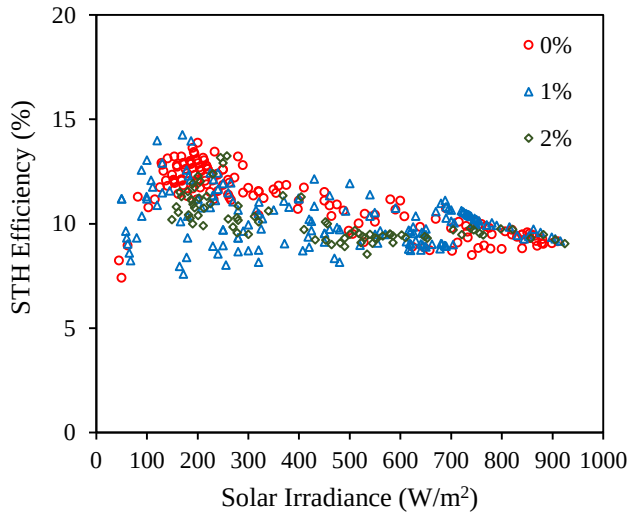

Fig. 8 STH efficiency at different solar irradiance

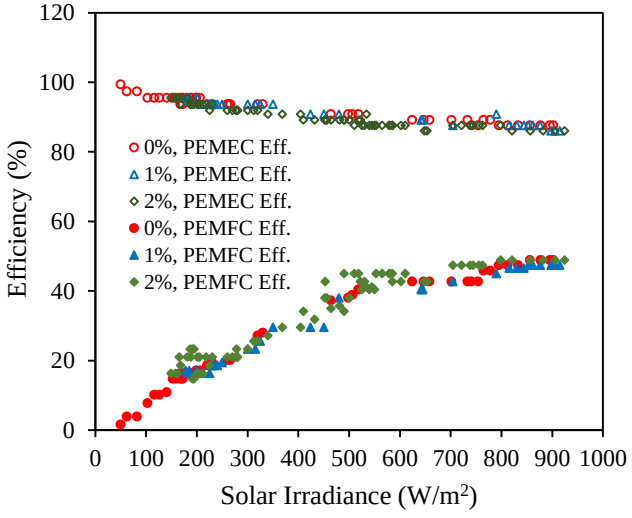

Fig. 9 PEMEC efficiency and PEMFC efficiency at different solar irradiance

Figure 9 presents a comparative efficiency analysis of the PEMEC and PEMFC under varying solar irradiance levels, using three different electrolyte concentrations. The PEMEC efficiency remains consistently high (> 85%) across the entire irradiance range for all concentrations. Peak efficiency approaches ~98-100% under low irradiance (< 200 W/m^2), indicating optimal electrolysis performance at lower current densities. At higher irradiance (> 600 W/m^2), a slight decrease in PEMEC efficiency is observed, which aligns with the earlier noted increase in PEMEC operating voltage and current, leading to greater energy losses. Nevertheless, the impact of electrolyte concentration on efficiency remains minimal. In contrast, the PEMFC efficiency, which reflects the conversion of hydrogen back into electricity, shows an increasing trend with solar irradiance. At low irradiance levels (<200 W/m^2), efficiency remains below 20%. As solar irradiance increases (300-600 W/m^2), efficiency rises significantly, reaching values between 30-50%, depending on the electrolyte concentration. However, similar to the PEMEC, the effect of different concentrations on PEMFC efficiency was not notably significant.

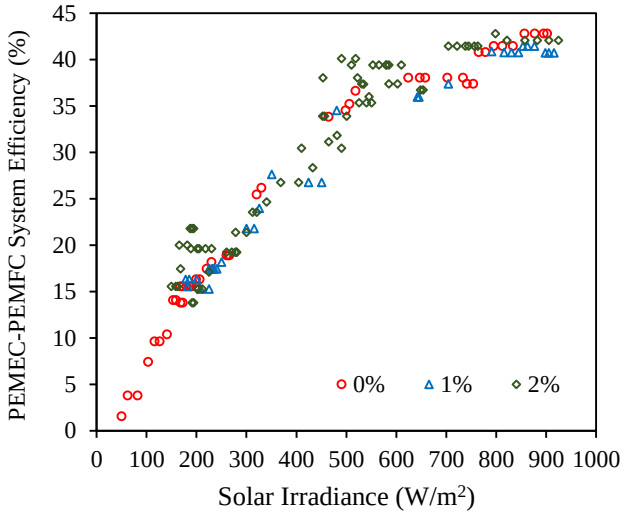

Fig. 10 PEMEC-PEMFC system at different solar irradiance

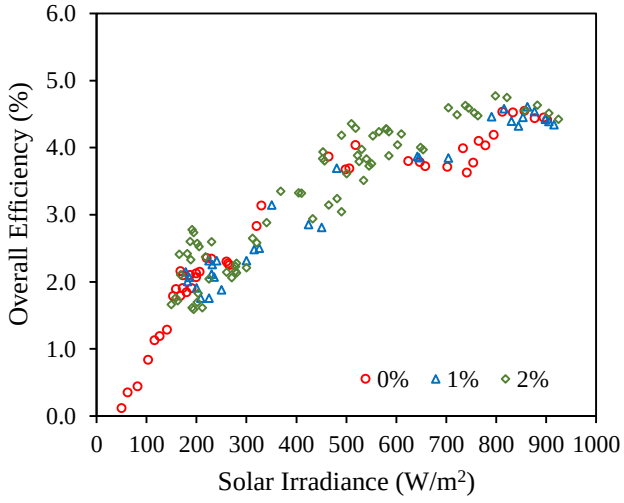

Fig. 11 Overall efficiency at different solar irradiance

Figure 11 illustrates the total efficiency of the entire solar-to-electricity system within the PV-PEMEC-PEMFC integrated configuration, evaluated under varying solar irradiance levels and electrolyte concentrations. The system achieved a maximum overall efficiency of approximately 5%

at around 800 W/m^2, with a slight decline observed at higher irradiance levels. These experimental results align well with earlier simulation studies involving PV-electrolyzer-fuel cell systems, which reported system efficiencies in the range of 6 - 7% under various operating conditions [24].

4.4. PV-PEMEC-PEMFC System Estimation

To estimate monthly power generation, wastewater utilization, and water production, the hourly solar irradiance profiles for each month were analyzed, the hourly solar irradiance data for each month was evaluated based on measurements taken in Bangkok, Thailand (Latitude: 13° 41′ 37″ N, Longitude: 100° 36′ 48″ E) from 9.00 to 16.00 hours [52]. These profiles are illustrated in Figure 12. Across all months, the irradiance exhibits a bell-shaped diurnal pattern, consistently peaking between 12.00 and 13.00 hours. The highest irradiance values, typically ranging from 750 to 850 W/m^2, are observed in the summer months, especially in February, March, April, and May.

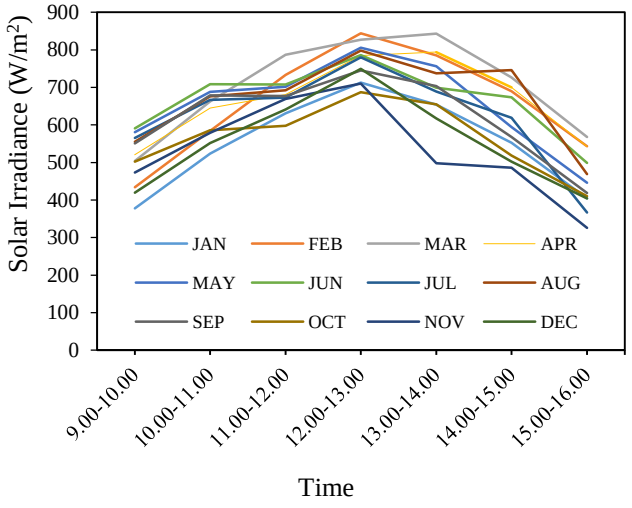

Fig. 12 Monthly solar irradiance at different times

Based on the experimental setup, the area ratio of the PV, PEMEC, and PEMFC components is 16:1.56:1. For system performance estimation, this ratio is used to model instantaneous power generation from a 1 m^2 PEMFC, powered by hydrogen produced from a 1.56 m^2 PEMEC, which is in turn supplied by 16 m^2 of PV panels.

Figure 13 presents the estimated daily wastewater consumption by the PEMEC throughout the year, using three different electrolyte concentrations. This data reflects the stoichiometric and operational water requirements necessary to sustain hydrogen production under varying solar irradiance conditions. Across all concentrations, monthly wastewater utilization ranges from 1.6 to 2.1 L/day, showing relative stability with seasonal fluctuations. The highest wastewater usage takes place in February, March, and April, aligning with the months of maximum solar radiation (refer to Figure 12) and elevated hydrogen production. In contrast, decreased consumption levels are noted from October to December, relating to lower irradiance and reduced electrolyzer performance. Electrolytes with 1% and 2% dishwashing solution show slightly higher water consumption throughout all months compared to tap water (0%). This is attributed to enhanced ionic conductivity, which improves electrolysis efficiency, resulting in greater hydrogen output and thus higher water usage. However, the difference in wastewater consumption between the 1% and 2% concentrations is minimal (approximately 0.05 L/day), suggesting diminishing returns at higher surfactant levels. This indicates that a 1% concentration may offer a practical balance between performance improvement, resource consumption, and membrane/electrode longevity. These findings support the feasibility of integrating greywater or domestic wastewater reuse in renewable hydrogen systems. Reusing dishwashing water reduces reliance on clean water sources and enhances the value of domestic waste, contributing to a circular resource model and more sustainable hydrogen production.

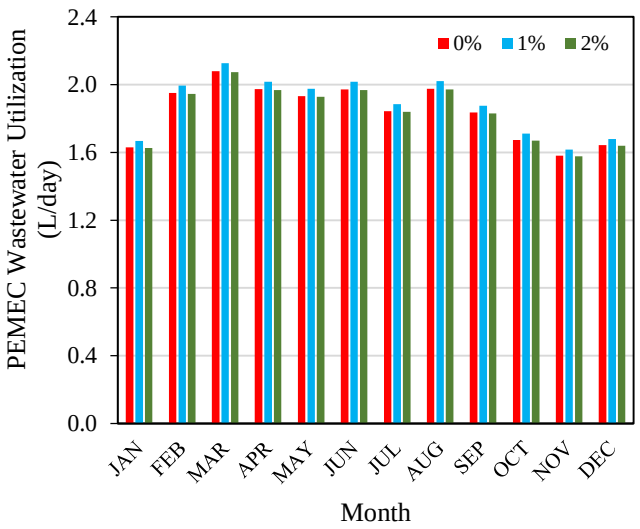

Fig. 13 Estimation of monthly PEMEC wastewater utilization

Figure 14 illustrates the estimated monthly electrical energy output from the PEMFC, measured in kWh/day, for each month at three different electrolyte concentrations. This experimental analysis aimed to confirm the feasibility of utilizing hydrogen produced from dishwashing wastewater and tap water via PEMEC as a feedstock for PEMFC-based electricity generation. The findings indicated that the 2% dishwashing solution consistently exceeds the performance of other concentrations each month, providing about 10-15% greater energy output in comparison to tap water (0%). The 1% solution also shows modest improvements over tap water, although less pronounced than the 2% case. These findings confirm that using household greywater, such as dishwashing wastewater, not only supports electrolysis but also enhances downstream fuel cell performance. Regarding seasonal variation, the monthly power output follows a clear seasonal

trend, reaching its highest values between March and May, and decreasing from November to January, in line with solar irradiance patterns. The highest energy production, around 2.4 kWh/day, takes place in March, aligning with optimal solar input.

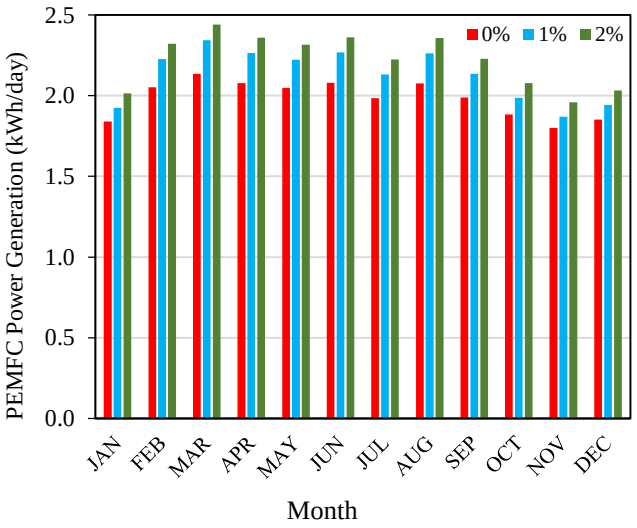

Fig. 14 Estimation of monthly PEMFC power generation

These results provide a valuable benchmark for assessing the energy yield of off-grid or hybrid renewable energy systems powered by solar-derived hydrogen. A daily energy output in the range of 1.8-2.4 kWh is sufficient to meet the demands of basic residential or microgrid applications, including lighting, refrigeration, and communication systems. This underscores the potential of the PV-PEMEC-PEMFC integrated system as a viable solution for decentralized and sustainable energy production, especially in areas with restricted access to traditional energy systems.

It is crucial to highlight that the system configuration in this research features a direct combination of the PEMEC and PEMFC to assess the feasibility of generating green electricity using household wastewater as the feedstock. In typical applications, a hydrogen storage unit is positioned at the cathode outlet of the PEMEC to collect and store hydrogen, which can then be supplied to the PEMFC when electricity is needed. In this experimental setup, the PEMEC featured an active area 1.56 times larger than that of the PEMFC, resulting in the generation of surplus hydrogen beyond the immediate consumption needs of the fuel cell. This surplus hydrogen was calculated and is regarded as retained in a specific hydrogen storage tank for utilization during times without solar energy, like nighttime operation. This approach enhances system autonomy and supports continuous, off-grid power generation. Figure 15 demonstrates the estimated monthly surplus hydrogen production for three different electrolyte concentrations. The hydrogen utilized in the electrochemical reaction within the PEMFC is calculated based on the corresponding electricity output. Among the three cases, tap water exhibits the highest surplus hydrogen levels in most months. This is not a result of higher efficiency, but rather due to lower hydrogen consumption, as the PEMFC produces less power during daytime operation under this condition. In contrast, systems using 1% and 2% dishwashing solutions generate greater amounts of hydrogen overall due to improved electrolysis performance. However, they also consume more hydrogen during the day to facilitate higher power generation, leading to a lower net surplus in comparison to the tap water system. The peak surplus hydrogen production occurs in March, reaching approximately 800 L/day for the 0% concentration, with slightly lower values observed for the 1% and 2% concentrations.

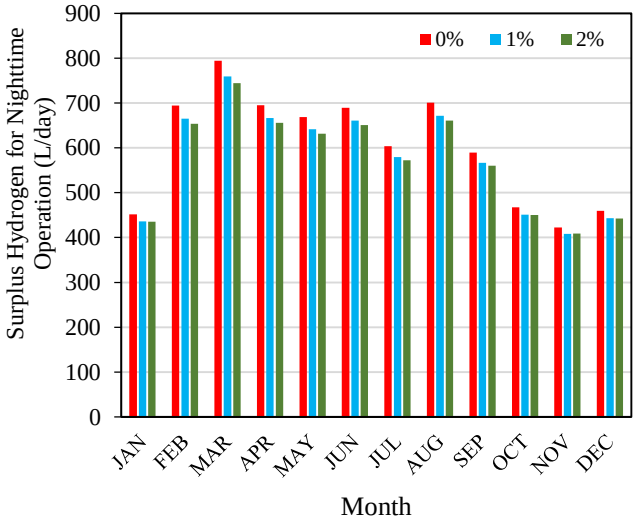

Fig. 15 Estimation of monthly surplus hydrogen for nighttime operation

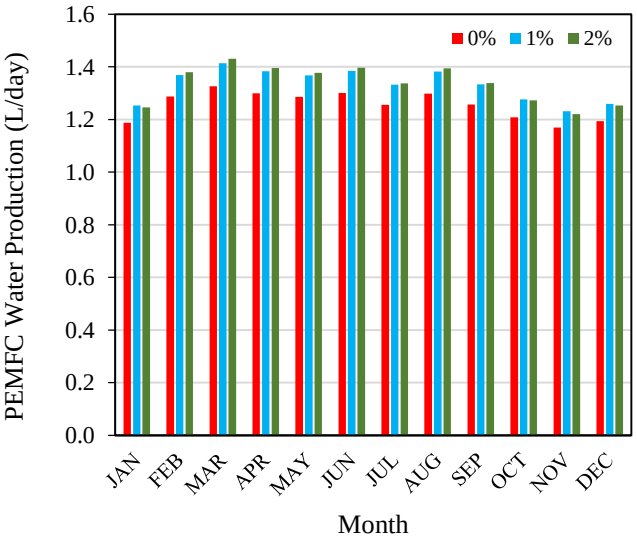

Fig. 16 Estimation of monthly PEMFC water production

Figure 16 illustrates the monthly water output from the PEMFC, generated as a byproduct of the hydrogen-oxygen electrochemical reaction within the fuel cell. The 0%

concentration (tap water) yields the lowest water production, consistent with its reduced hydrogen input and corresponding lower PEMFC power output. Peak water production is observed during the months of March to May, with average values reaching approximately 1.4 L/day, which is in line with increased hydrogen consumption driven by higher solar irradiance during this period. Overall, the system demonstrates an average daily water production of approximately 1.3 L/day, highlighting a significant potential for water recovery and reuse, particularly in off-grid or remote-area applications where access to clean water is limited. This study uniquely shows, for the first time, that simulated domestic wastewater (dishwashing solution) serves as a viable and efficient electrolyte for PEM electrolysis, while concurrently supporting elevated hydrogen production, electricity generation, and clean water recovery within an integrated PV-PEMEC-PEMFC system. In contrast to previous research that mainly employs ultra-pure water, such as distilled water [27, 31] and demineralized water [31] or deionized water [26] for electrolysis, this study offers experimental proof that dishwashing wastewater can substitute pure water with minimal efficiency reduction, thus decreasing operational expenses and facilitating decentralized implementation.

5. Conclusion

This study experimentally evaluated an integrated photovoltaic-powered hydrogen energy system, comprising a Proton Exchange Membrane Electrolysis Cell (PEMEC) for hydrogen production and a proton exchange membrane fuel cell (PEMFC) for electricity generation. Three concentrations of dishwashing solution, 0%, 1%, and 2%, were prepared as simulated domestic wastewater electrolyte and were tested to assess their effects on system performance under varying solar irradiance. The results showed that PEMEC current increased linearly with solar irradiance, with the highest current observed at the 2% dishwashing solution due to improved ionic conductivity. Voltage remained relatively stable across conditions, indicating stable electrochemical performance. The hydrogen production demonstrated a strong linear correlation with both PEMEC current and solar irradiance, with experimental values closely matching theoretical predictions, confirming efficient faradaic behavior. The Solar-to-Hydrogen (STH) efficiency reached up to 15% at low irradiance and remained above 12% even at higher irradiance levels.

The PEMFC subsystem exhibited a nonlinear response between solar irradiance and electrical power output, with peak energy generation exceeding 2.4 kWh/day·m^2 when operated with the 2% electrolyte. System efficiency increased with rising irradiance, reaching up to 42% under optimal conditions. The use of dishwashing solution further improved overall performance, with the highest overall system efficiency reaching approximately 5%. Water usage and recovery analysis revealed that the PEMEC consumed approximately 1.6 to 2.1 L/day of wastewater, while the PEMFC was capable of recovering 1.2-1.4 L/day of clean water as a byproduct, potentially reusable after minimal filtration. Additionally, the system produced surplus hydrogen during daylight hours, sufficient to support nighttime electricity generation, highlighting the system's capability for continuous off-grid operation.

Overall, the system demonstrated stable and efficient performance across seasonal and irradiance variations, as validated by monthly estimations of hydrogen production, water output, and energy yield. The findings confirm that a diluted dishwashing solution can serve as an effective, low-cost electrolyte for clean hydrogen generation without compromising performance. The integrated solar hydrogen fuel cell system simultaneously offers renewable electricity, storable hydrogen, and clean water, positioning it as a promising solution for energy self-sufficiency in remote, off-grid, or resource-constrained regions. The study highlights the potential for decentralized hydrogen-based energy systems that support environmental sustainability, economic affordability, and resilience to energy access challenges.

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