Doi: 10.61435/jbes.2025.19985

Research Article

Model and Simulation of Solar-Powered PEM Water Electrolysis for Green Hydrogen and Environmental Assessment in the Ibukota Nusantara

Parluhutan Siahaan[1], Sulistyo[2,*], Endang Kusdiyantini [3]

[1] Master Program of Energy, School of Postgraduate Studies, Diponegoro University, Semarang, Indonesia 50241;
[2] Department of Mechanical Engineering, Faculty of Engineering, Diponegoro University, Semarang, Indonesia 50275;
[3] Department of Biology Faculty of Science and Mathematics, Diponegoro University, Semarang, Indonesia 50275.

* Correspondence: sulistyo@lecturer.undip.ac.id;

Received: November 27th, 2025
Accepted: December 1st, 2025
Published: April 1st, 2026

Copyright: © 2026 by the authors. This work is under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Abstract. Energy demand in Indonesia continues to rise in line with population and economic growth. Using Jakarta city of Indonesia, as a representative case, energy consumption in the transportation sector has risen significantly from year to year. This escalation contributes to deteriorating air quality and poses adverse impacts on public health. To prevent similar condition in the new capital city (Ibukota Nusantara - IKN), this study examines green hydrogen production to support Fuel Cell Electrical Vehicle (FCEV)-based transportation. The objective of this research is to evaluate the technical, economic feasibility and environmental benefit of a solar PV -power-driven Proton Exchange Membrane Water Electrolyzer (PEMWE) system for large-scale hydrogen generation in IKN. A dynamic PEMWE model was developed and simulated using MATLAB/Simulink/Simscape under operating temperatures of 60 °C, 80 °C and 100 °C at a current density of 1.2 A/cm^2. Key performance indicators evaluated include membrane water diffusion flux, electro-osmotic drag, hydrogen production rate and system efficiency. Result show that operation 80 °C achieves the optimal performance. Scaled-up calculations indicate a hydrogen output of 3,006.62 kg/day with an electricity demand of 143,617 kWh, resulting in specific energy consumption of 47.9 kWh/kg outperforming the commercial PEMWE range 51-55 kWh/kg. This production capacity can fuel approximately 1,500 FCEVs corresponding to a potential CO_2 emission reduction of 13,112.7 kg CO_2-eq/day. Economic analysis using the Levelized Cost of Hydrogen (LCOH), with a 6% WACC and 20-years project life, yields an annualized CAPEX of roughly MUSD 31 and electricity dominated OPEX of KUSD 577 per year. The resulting LCOH od USD 3.0/kg H_2 aligns with projected 2030 green hydrogen cost target. In conclusion, Solar PV -powered PEMWE development in IKN is demonstrates holistic feasibility in term of technical viable, economically competitive and environment impactful.

Keywords: PEMWE, Solar PV, Hydrogen, FCEV, LCOH, CO_2-Emision

1. Introduction

Indonesia is experiencing rapid growth in energy demand driven by population expansion and economic development (Putri et al., 2022), energy demand projections until 2060 per sector and the form or type of energy needed. Recent projections indicate that Indonesia's total final energy demand is expected to rise from 195 million tons of oil equivalent (Mtoe) in 2020 to approximately 556.5 Mtoe by 2060. Transportation sector which accounted for 19% of national energy demand in 2020, is projected to increase to 22% by 2060 which driven by mobility need, expanding vehicle ownership and gradual penetration of electric and hydrogen-based transport system (Liun et al., 2022). This escalation energy demand particular evident in Jakarta electrical energy supply in 2023 amount 36,992,354,101 kWh used by 5,225,077 of customers (Triana et al., 2024). Final energy consumption in 2025 estimate 8.66 Mtoe, part of that transportation sector is largest contributing at 40,4% following fuel (BBM) consumption at 38.2% (RUED Jakarta, 2022.). This escalation energy demand creating complex environment challenging, one of the most critical is deterioration of air quality which the concentration of fine particular matter (PM_{2-5}) average above 50µg/m^3, far surpassing the safety

threshold at 15μg/m3 (Teresia et al., 2025.). The big impact is occurring risk particularly of respiratory and cardiovascular diseases. To mitigate and protecting human healthy quality, Government regulation number 3, 2022 is issued for development and management of new capital city called Nusantara, a sustainable world city that provides comfort, harmony with nature, resilience through efficient resource use and low-carbon development (UU No. 3, 2022.). Lesson learn from Jakarta city which deteriorating air quality particularly contribute from transportation sector, this research investigates using MATLAB/Simulink/Simscape the integration of PEM water electrolysis (PEMWE) power with Solar photovoltaic in IKN Penajam Paser Utara, East Kalimantan to produce green hydrogen particularly as fuel for fuel cell electrical vehicles (FCEV). The objective is to minimize CO_2 emission within the new capital city and contribute to Indonesia's national target of achieving net-zero emissions by 2060 or earlier through increased utilization of renewable energy, as mandated in ESDM regulation No. 10/2025. The novelty of this research lies in the development of a fully integrated modelling and simulation framework that evaluates the holistic techno-economic-environmental performance. Unlike previous studies that looked at PEMWE or Solar PV or environment in isolation.

To safeguard future urban livability and ecological health, the Indonesia Government enacted law No. 3/2022 to guide the development of Nusantara as a sustainable capital city, emphasizing harmony with nature, resilience, resource efficiency, and a low-carbon pathway. Learning from Jakarta's deteriorating air quality, where transportation emissions are major contributor. The development of IKN provides an opportunity to implement forward-looking technology that avoid repeating past environmental failures. In alignment with Indonesia's national commitment to net-zero emissions by 2060 or sooner and renewable energy mandates under ESDM Regulation No. 10/2025, green hydrogen emerges as a strategic fuel alternative. As a clean energy carrier compatible with fuel cell electrical vehicles (FCEV), hydrogen offers zero tailpipe emissions and substantial decarbonization potential for the transportation sector in the new capital.

Modeling and simulation of Solar PV powered PEMWE generation to assess its feasibility for large-scale hydrogen production in the new capital city, Nusantara. Utilize MATLAB/Simulink/Simscape (Brezak et al., 2023), to analyzes the system's dynamic behavior, electrical to chemical energy conversion into green hydrogen and operational interactions under variable solar irradiance condition typical site location in Penajam, Paser Utara, East Kalimantan. The objective is to determine optimal configuration in term of input power, electrolyzer capacity, and output green hydrogen which suitable for fueling FCEVs within the city and being contributor to environmental clean air quality. This research indeed requires further technology development to get optimal efficiency

The Solar PV powered to PEMWE system is expected to enable policymakers to integrate green hydrogen into Nusantara's energy and transportation ecosystem by providing a technically validated production pathway, a quantifiable environmental benefit and a clear investment signal (Concept IKN,). The key aspect to attract the investors mainly to formulation of regulatory frameworks with financial incentives such as capital subsidies, carbon credit and partial tax-free import duties. Through a combination of technical validation, environmental benefits, and alignment with regulatory directive, this green hydrogen position may take attention and being a cornerstone of Nusantara's transition toward a resilient and low-carbon urban ecosystem.

Carbon emissions intensity of transportation sector in Jakarta require proper action to mitigation the environmental impact. The number and type of vehicles are growth yearly and big contribute to escalate the CO_2 emission of 24.64 % only from transportation sector (Nasional, n.d.), number and type of Jakarta's vehicles shown Table 1 and Table 2 fossil fuel consumption.

Table 1. Number of registered motor vehicles by Regian and Type (Units), 2022

Region	Passenger Cars	Buses	Goods Vehicles	Motorcycles	Special Vehicles	Total
Central Jakarta	467,194	52,475	135,684	1,331,878	12,083	1,999,314
North Jakarta	397,568	27,757	73,179	1,410,480	40,873	1,949,857
West Jakarta	849,328	87,268	159,996	2,506,546	113,781	3,666,919
South Jakarta	746,004	97,826	126,459	1,978,001	12,977	2,962,067
East Jakarta	471,899	27,916	83,693	2,149,741	16,028	2,749,277
Bodetabek	1,278,397	51,115	270,121	7,934,827	58,139	9,592,599
Total	**4,210,390**	**344,357**	**849,132**	**17,062,273**	**153,881**	**22,620,033**

Note: Excluding military (TNI), police (Polri) and diplomatic vehicles

@The Author(s). 2026. Published by CBIORE

Table 2. Fuel Consumption in Vehicles Transportation Sector

Year	Oil Fuel (kL)	
2023	Gasoline RON 92	BioGasoil
	5,438,351	31,181,237

The register motor vehicle population in Jakarta and Bodetabek region reached 22.62 million units in 2022, dominated overwhelmingly by motorcycles (17.06 million units) and follow by passenger cars (4.21 million units). This massive and growing fleet is a major contributor to urban CO_2 emission, air pollution and environmental degradation. Using average emission factors for internal combustion engines (ICE) 2.3 kg CO_2/L for gasoline and 2.7 kg CO_2/L for diesel, the transportation sector in Jakarta is estimate to radiate tens of millions of CO2 annually. Mitigation strategies require a systemic and multi-layered approach. Key solutions include transitioning from fossil fuel-based transport to zero emission mobility, expanding FCEVs and establish supporting infrastructure such as green hydrogen refueling stations. For Nusantara (IKN), Jakarta 's experience provides critical lessons. Without proactive intervention, rapid population growth and rising vehicle ownership could replicate Jakarta severe air quality. Thus, the data from Jakarta highlight the urgency of adopting clean mobility solution in IKN to prevent future pollution crises and support Indonesia's long-term climate goals. The fuel consumption data both gasoline and diesel type for vehicles transportation as per shown in table 1 is estimated allocation for Indonesia, therefore to get precisely estimate approximately CO_2 emission from vehicle transportation in Jakarta not available

2. Method

2.1. Research framework and system boundary

The research objective is to develops a modeling and simulation the integration solar photovoltaic power generation (Solar PV) with a Proton Exchange Membrane Water Electrolyzer (PEMWE) for green hydrogen production. The operational assessment evaluates the influence of elevated electrolyzer cell temperatures on hydrogen output, while electrical current, voltage, water consumption, and power input are assumed to remain stable during PEMWE operation. The water-splitting mechanism focuses on three key reaction transport phenomena such as following: (1). Diffusion, (2). Electro-osmotic drag, and (3). Membrane conductivity, to ensure reliable and efficient hydrogen generation. The Solar PV system is driven by average solar irradiance and ambient temperature condition of average 30 °C based on regional datasets for January 2021 to December 2022 in IKN Penajam Paser Utara area, East Kalimantan. All computational analyses and system level simulation were conducted using MATLAB/Simulink/Simscape.

2.2. Solar PV power generation

The first stage consists of parameter engineering, which includes acquiring and analyzing site specific environmental data particularly hourly solar irradiance (Figure 1 and Table 3) and ambient temperature (Figure 2 and Table 4) at the target area solar PV site installation in IKN. The datasets both solar irradiance and temperature has taken from NASA archive (power. larc.nasa.gov/data-access-viewer). The selection of solar photovoltaic module materials and execution of performance calculation based on manufacturer specifications and standard condition. Second stage, the electrical energy generation capacity and the required energy storage configuration are designed to ensure stable and continuous power supply for hydrogen production through PEMWE. The third stage involves constructing a dynamic simulation model using MATLAB/Simulink (R2022a) to evaluate the operational behavior of the solar PV -PEMWE system.

@The Author(s). 2026. Published by CBIORE

Table 3. Temperature (°C) period Jan 2021-Dec 2022

Year / Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Des	Average (°C)
2021	30.41	30.87	30.15	30.04	30.34	30.03	29.44	30.41	30.46	30.59	30.35	30.51	30.31
2022	30.3	29.89	30.99	30.18	31.15	29.59	29.63	29.83	30.47	30.69	30.87	30.41	30.33

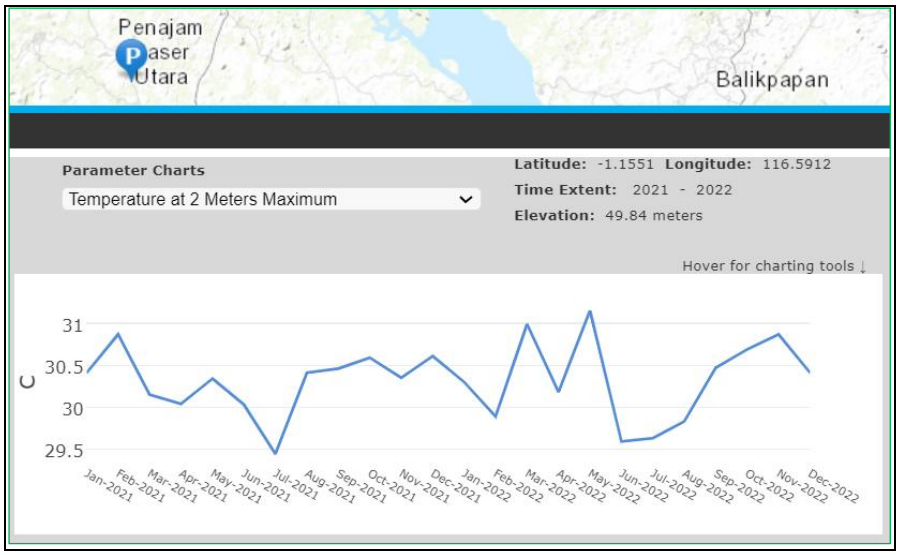


Figure 1. at the PEMWE location, Penajam East Kalimantan period Jan 2021-Dec 2022

Table 4. Solar irradiance period Jan 2021-Dec 2022

Year / Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Des	Average (kWh/m²)
2021	6.79	6.97	7.07	6.71	6.29	6.05	6.13	6.50	6.87	6.96	6.77	6.65	6.65
2022	6.79	7.01	7.07	6.74	6.31	6.05	6.07	6.49	6.88	6.93	6.78	6.65	6.65

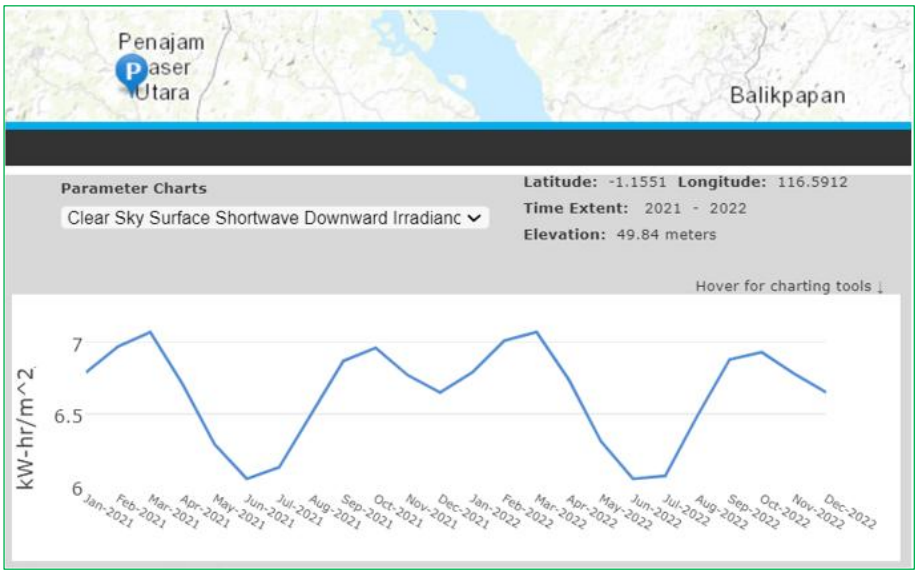


Figure 2. Solar irradiance at the PEMWE location, Penajam, East Kalimantan Period Jan 2021-2022

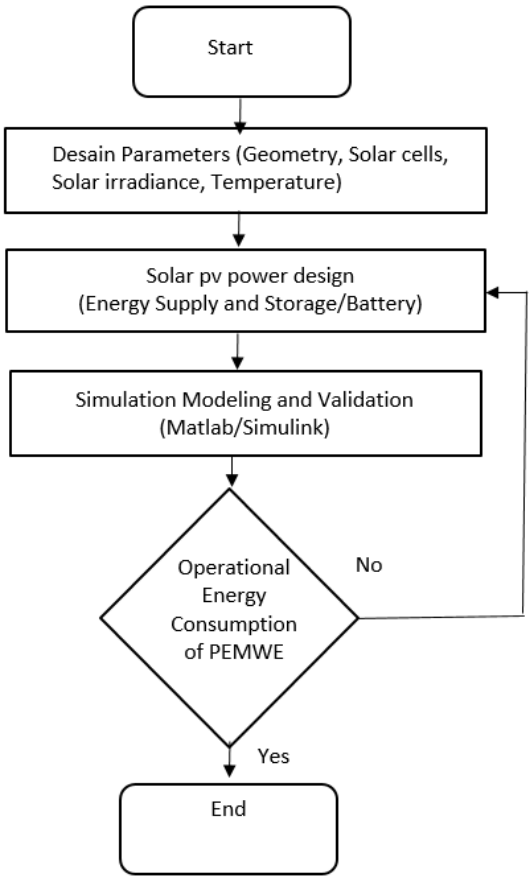
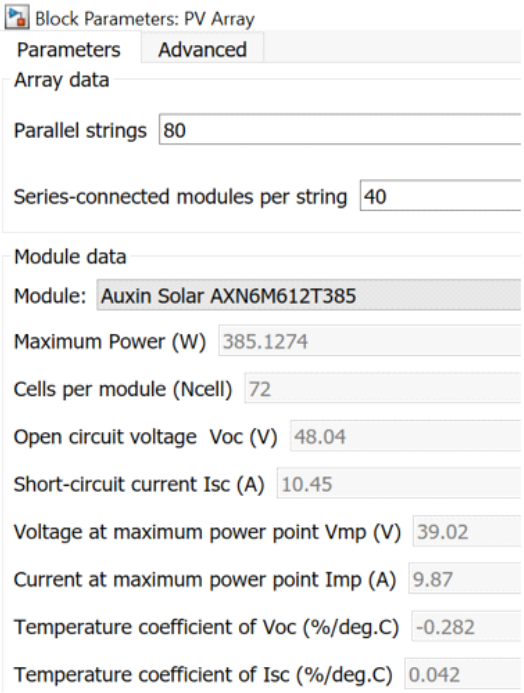


Figure 3. Flow diagram of Solar PV power system

Figure 4. Perovskite tandem solar cell parameters



@The Author(s). 2026. Published by CBIORE

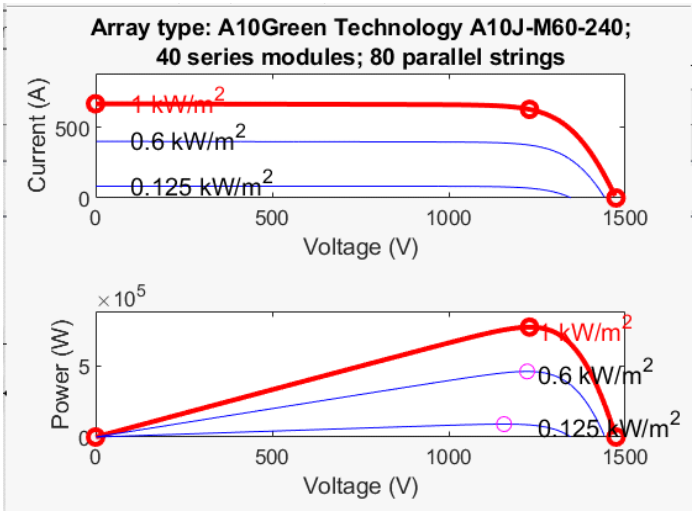


Figure 5. Current-Voltage curve of Solar Cell

The Figure 3 illustrates the methodological workflow of solar PV power system. The process begins defining key design parameter. The system model is then constructed and validated using MATLAB/Simulink to ensure accurate representation of real operational behavior. Figure 4 is PV array block parameter used in the simulation. The array configuration consists of 80 parallel strings and 40 series connected modules per string, representing a large-scale PV field capable of supplying the substation electrical demand of PEMWE. The Figure 5 shows the performance characteristic (i-v and p-v curves) of PV array at irradiance result.

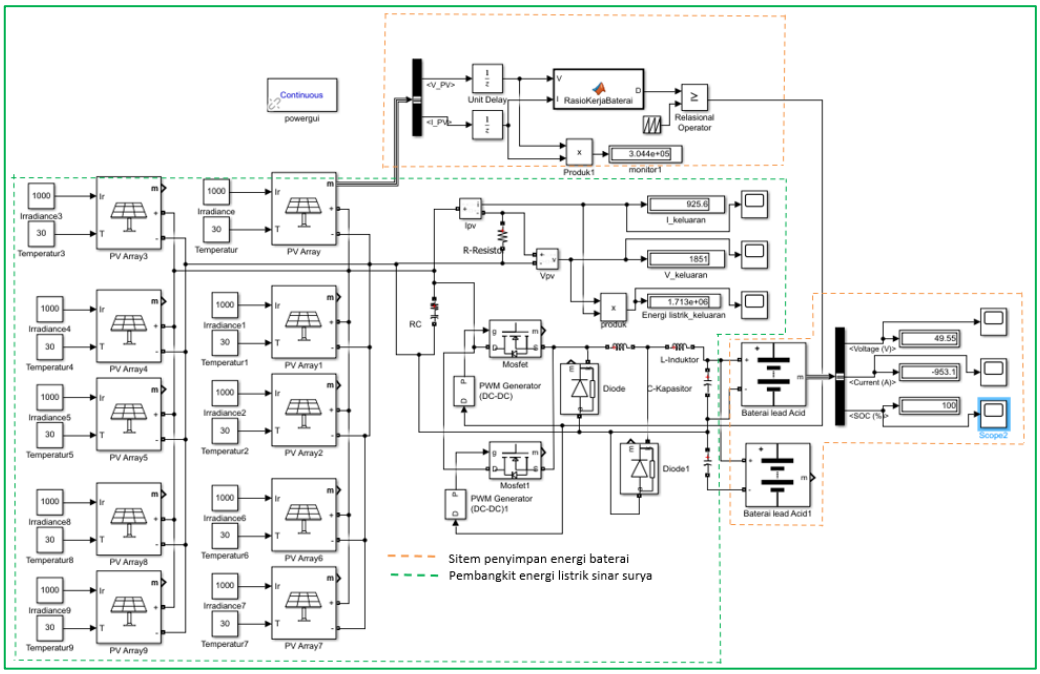


Figure 6. Block diagram of Solar PV power system

The solar PV power generation model is design to supply sufficient electrical power to meet the operational requirement of PEMWE in producing hydrogen (Figure 6). The model simulates the performance of the solar PV system to optimize electrical output by considering the following aspect such as: (i) The selected solar cell technology, implemented in Matlab/Simulink, utilize tandem perovskite materials specification (Karmaker et al., 2023). This technology offers high power conversion efficiency (PCE) due to its multilayer semiconductor structure with varying bandgaps, enabling enhanced absorption of solar irradiance and more effective conversion of photons into electrical energy. (ii) Key performance parameters of perovskite-based solar cells namely short-circuit current density ((Jsc), open-circuit voltage (Voc), Fill factor (FF), and overall power conversion capability are standardized within the model to accurately represent solar PV performance under solar irradiation. (iii) Lead-acid battery storage is incorporated to function as back up energy source, ensuring continuity of PEMWE operation during period low solar availability. (iv) Direct current

(DC) output from solar PV system is utilized, eliminate the need for converting DC to Alternating Current (AC). The DC/DC converter may require only to regulate the voltage and current levels to ensure matching the specific operational requirements of PEMWE. (v)Additional factors, such as solar panel tilt orientation and shading effects are not considered within the scope of this model.

2.3. *PEMWE System*

The first stage to provide parameter engineering by defining the material specification of electrolyzer cells, including the number of cell stack, active cell area and system operating condition such as temperature, voltage, current density and electrical power input. Second stage, maximum capacity hydrogen production, electrical energy and water consumption. The third stage, to perform a dynamic PEMWE model and simulating using MATLAB/Simulink/Simscape under temperature of 60 °C, 80 °C and 100 °C and current density 1,2 A/cm^2. The fundamental operating principle of PEMWE system involves the electrochemical dissociation of water (H_2O) into hydrogen (H_2) and oxygen (O_2) driven by electrical input from solar PV. This process is governed by three key transport and reaction mechanisms following: (i) molecular diffusion, (ii) electro-osmotic drag, (iii) proton-conductive transport across proton exchange membrane. Fundamental electrochemical reactions related to water splitting are expressed shown following thermodynamic equation: (i) Anode reaction (oxygen evolution reaction, OER) $H_2O \rightarrow 2H^+ + \frac{1}{2} O_2 + 2e^-$, (ii) Cathode reaction (hydrogen evolution reaction, HER) $2H^+ + 2e^- \rightarrow H_2$, (iii) The overall water splitting reaction, $H_2O_{(l)} + 237.2\ mol^{-1} + 48.6kJ\ mol^{-1} \rightarrow H_2 + \frac{1}{2}O_2$. PEMWE offers significant advantages compared to others electrolysis technology, particularly due its capability to operate efficiently at industrial scale using intermittent renewable electricity such as solar PV (Brezak et al., 2023). The thermodynamic principle of water electrolysis requires an electrical energy input equal to standard Gibbs free energy change (237.2 kJ mol^{-1} and thermal energy equal to standard molar enthalpy change (48.6 kJ mol^{-1}). The efficient conversion of electrical and thermal energy into hydrogen is strongly influenced by membrane material properties. High performance PEMWE must exhibit: (i) high thermal stability and mechanical robustness, (ii) excellent ions conductivity for proton transport, (iii) strong oxidative and hydrolytic stability, (iv) high chemical and electrochemical durability (Kamaroddin et al., 2021). The electrical energy demand of PEMWE stack is defined by equation (1) (Hancke et al., 2022): $W_{stack} = \frac{2.F.U_{stack}}{\mu F} \int_{lost}$, where F is Friday' s constant, U_stack is voltage, μF is Faradaic efficiency, and $\int_{lost}$ represents hydrogen losses associated with increasing current density.

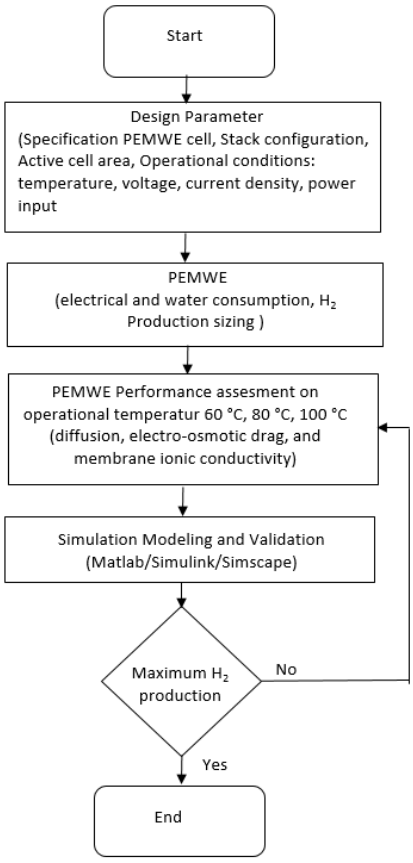


Figure 7. Flow diagram PEMWE Hydrogen production

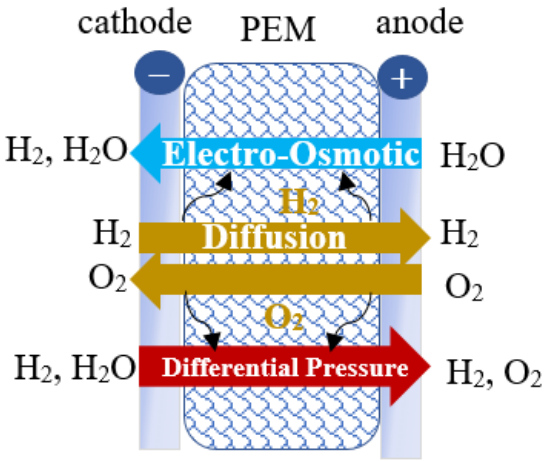


Figure 8. Hydrogen-Oxygen separation method: diffusion, electro-osmotic drag and differential pressure

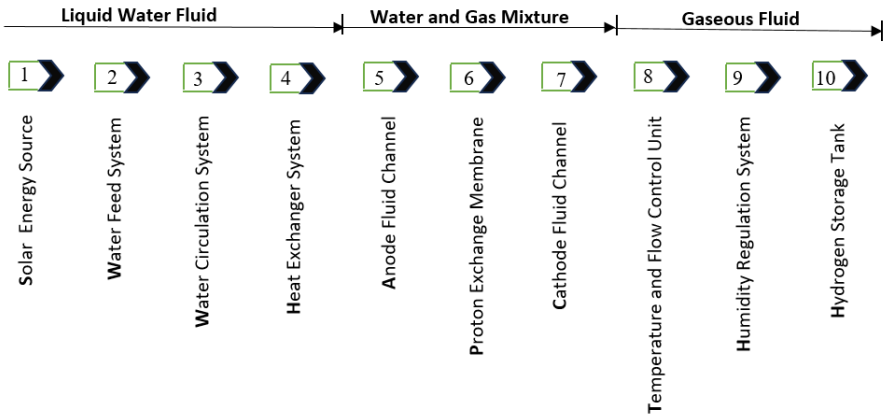


Figure 9. The 10 primary PEMWE process system

The electrical energy generated by solar PV power system is sufficient to meet the operational requirements of the pressure vessel (cell stack) which responsible for splitting water (H_2O) into hydrogen (H_2) and Oxygen (O_2). The performance of cell stack is strongly influenced by operating temperature and current density. This research examines the hydrogen production process with specific emphasis on diffusion and electro-osmotic drag phenomena occurring inside the cell stack, as illustrated in Figure 7 and Figure 8 Water molecule transported from the anode to cathode experience both diffusion-driven permeation and electro-osmotic drag. The movement of water molecules is driven by ionic species (H^+, H_2, and O_2) and is governed by the concentration gradients between the anode and cathode. The diffusion-driven permeation process follows Fick's law, where the mass flow rate of water (Ṁ_H_2O,diff) is proportional to the membrane diffusion coefficient (N117) and concentration difference of water (ΔK_([H_2O]) between both sides of the membrane. The water flow rate (Shin et al., 2020) is expressed as equation (3): Ṁ_H_2O,diff = -N117 $\frac{\Delta K_{H2O}}{t_{mem}}$ [mol/m².s]. The Nafion N117 membrane is employ due to its high monovalent ion conductivity, particularly for proton (H^+), while effectively blocking divalent ions (Ca^{2+}, Mg^{2+}), thus enhancing hydrogen production efficiency. The water concentration (ΔK_[H_2O]) on the cathode side transitions from the liquid phase to saturated vapor depending on local thermodynamic conditions. Electro-osmotic drag (Ṁ_[H_2O,drag]) refer to the electrochemical process by which water molecules (H_2O) are transported along with migrating hydrogen ions during the electrolysis reaction that separates water into hydrogen and oxygen. The electro-osmotic drag coefficient represents the ratio of water molecules moving in forward direction relative to the number of transported hydrogen ions. The water transport rate (Ṁ_[H_2O,drag]) toward the cathode at a constant temperature is proportional to the number of cells (N_[cell]), current density (J), and the hydrogen production rate (Shin et al., 2020) as shown in equation (4): = ηdrag = $\frac{\dot{M}_{H2O,drag}}{\dot{M}H^{2+}}$. The 10 primary PEMWE process system can be shown in Figure 9.

2.4. CO_2 measurement-based vehicles transportation

Framework for quantifying transportation related CO_2 emissions in Jakarta based on established international guideline, particularly the Intergovernmental Panel on Climate Change (IPCC) Tier 1 fuel-combustion approach. Ideally, emission is quantified through the Vehicle-Kilometer-Travel (VKT) framework, which links transportation activity, fuel economy, and engine characteristic to total Fuel-Consumption (FC). Under this method, annual FC is derived from the equation (5) FC = VKT x (1/fuel-economy) for each vehicle category, enabling accurate bottom-up estimation when detailed traffic data are available. Emission is the calculate using the standard IPCC relation CO2 = FC x EF, where EF is the fuel-specific emission factor of 2.3 kg CO_2/L for gasoline and 2.7 kg CO_2/L for diesel (Mofolasayo, 2023). These factors represent the complete stoichiometric oxidation of fuel carbon content and widely used in national greenhouse gas inventory. However, Jakarta lacks publicly accessible, high resolution fuel consumption datasets, particularly disaggregate by vehicle class. As a result, application of full VKT-based accounting is constrained, making bottom-up FC estimation impractical. This limitation necessitates and alternative methodology that remain scientifically consistent but adapted to Indonesia's data environment.

To overcome scarcity while maintaining methodology integrity, this research employs an alternative hydrogen-substitution emission estimation framework widely used in low carbon transition analyses. Instead of relying on unavailable FC data, total avoidable emission is computed based on amount of green hydrogen produced and the corresponding displacement factor of fossil fuel emission. Following recent literature and national assessments, the mitigation potential of hydrogen in transportation is approximately using an emission-displacement coefficient of 4.37 kg CO_2-eq per kg of H_2, representing the average life-cycle emission avoided when replacing gasoline/diesel usage in internal combustion vehicles. Thus, daily avoided emission is estimate as CO_2 avoided = H_2 production (kg/day) x 4.37 kg CO_2-eq/kg H_2 (Liu et al., 2022). This approach enables a robust assessment of climate benefit event without Jakarta specific FC value and reflects a lesson learn from Jakarta's deteriorating air quality, where transport remains the dominant pollution source. Apply to IKN's planning context, the methodology demonstrates how FCEVs powered by solar-derived green hydrogen can substantially reduce future emission, preserve air quality and avoid replicating Jakarta environment degradation.

2.5. Economic analysis of PEMWE power by solar PV

A comprehensive analysis of major cost components is conducted to assess the financial viability and long-term sustainability of hydrogen production. The primary cost elements include the initial capital investment (CAPEX) and annual operational expenditure (OPEX) (Shin et al., 2023). A detailed assessment of CAPEX and OPEX enables the calculation of the average hydrogen production cost, expressed as Levelized Cost of Hydrogen (LCOH) in USD per kilogram of H_2. The conceptual framework illustrating the interrelationship among this cost parameter is presented in Figure 10 and mathematically formulated in equation (5).

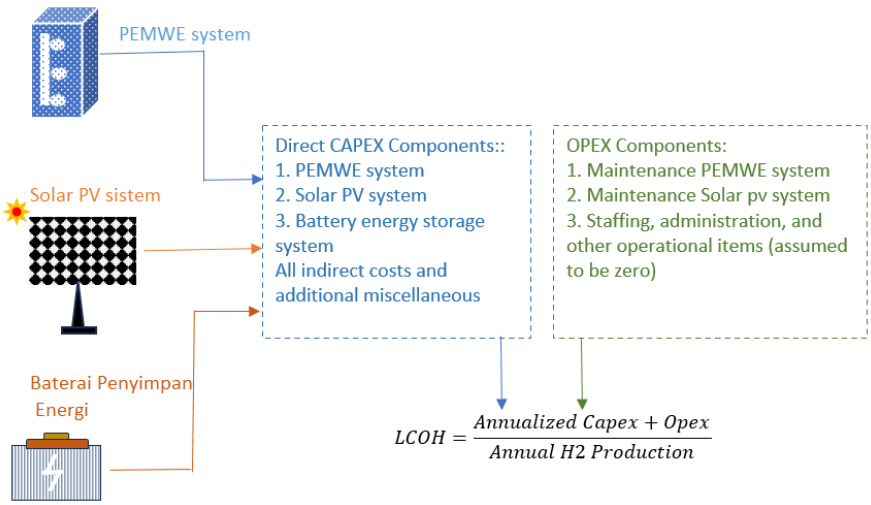


Figure 10. Framework calculation of CAPEX and OPEX

Technical data were derived from PEMWE and Solar PV simulation performed using MATLAB/Simulink/Simscape. System capacity and technical performance parameters serve as fundamental inputs for economic evaluation to determine the levelized cost of hydrogen (LCOH) expressed in USD per kilogram of hydrogen (USD/kg H_2) with equation (5) (Prasetyo et al., 2025).

$$LCOH = \frac{Annualized\ Capex+Opex}{Annual\ H2\ Production}, \quad (5)$$

Indirect cost such as operating staffing, water supply, land acquisition, engineering design and site installation is excluded because these components vary depending on technology maturity, site location, policy. Financial parameter such as discount rate, represent as Weighted Average Cost of Capital (WACC) is set at 6% reflecting a conservative mid-range value commonly apply to international analysis. In Indonesia, WACC typically range 4-8% depending on financial structure, project risk profile and policy support (Saphira et al., 2025). WACC represents the opportunity cost of capital, combining the cost of equity and cost of debt. This research does not consider external loan financing in evaluating the economic performance of the integrated PEMWE, Solar PV and Battery storage system. The initial CAPEX is annualized using a constant annual payment approach, represented by the Capital Recovery Factor (CRF) shown in equation 6 (Ariyadi et al., 2024).

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n-1} \quad (6)$$

where I is discount rate/WACC; n is operational project lifetime, The annualized CAPEX is defined as = CAPEX x CRF

3. Result and Discussion

The integrated PEMWE-Solar PV system designed in this research is positioning as a strategic reference for policymaker and industry stake holders to accelerate sustainable energy transition efforts. It supports Indonesia's goal of achieving net zero emission by 2060 or early. At present, green hydrogen development in Indonesia remains at pilot scale and has not reached commercial maturity. For this reason, the government is encouraged to initiate the first large scale green hydrogen project in IKN, East Kalimantan. Research location selected IKN based on following considerations: (i) Infrastructure development is relatively easy due to abundance of available land, (ii) The region receives adequate solar irradiance for solar PV power generating, (iii) As the new capital city, IKN is projected to became a major hub for economic development, including transportation. In addition to national decarbonization targets, this research PEMWE-Solar PV system is expected may contributes significantly to Indonesia's environmental and sustainability objectives under the United Nations Sustainable Development Goals (SDGs) (Gebara et al., 2023). Specifically, the system advances SDG 7 by promoting clean and renewable energy adoption, support to SDG 11 by enabling low emission urban development within the IKN, strengthen SDG 13 through substantial reduction CO_2 emissions, and contributes to SDG 9 via the integration of advance, innovative hydrogen technology.

The continuous rise transportation related to CO_2 emissions in Jakarta has contributed significantly to environmental degradation, primarily manifested through deteriorating air quality and elevated concentrations of particulate matter (PM_{2-5}). With more than 22.6 million registered vehicles in 2022, dominated by motorcycles and passenger cars, combustion of fossil fuel releases substantial quantities of CO_2, NOx, SO_2, and ultrafine particulates that accumulate within the urban corridor. Thereby intensifying public health risk such as respiratory, asthma, cardiovascular disease, and premature mortality. If unmitigated, these conditions present a clear warning sign for the newly established the IKN, indicating that the replication of Jakarta's high carbon mobility patterns would undermine the city's vision as a sustainable, low-emission and resilient urban center. To mitigate the impact, stakeholders-including central government, regional authorities, and energy planners must implement a multi-layered decarbonization strategy that prioritizes structure transition from fossil fuel-based mobility to clean energy system. This includes the development of green hydrogen production through Solar PV powered PEMWE, which purpose to supply fuel to FCEV based transportation.

3.1. Solar PV power system

The simulation result indicate that solar PV power system generates a total electrical output of 1,713,290 kWh as illustrate in figure 11a. The energy output is sufficient to supply power to PEMWE system, which produce 3,000.62 kg of hydrogen with an electrical consumption requirement 143,617 kWh. In addition to supplying electricity to PEMWE, a portion of the generated energy is allocated to Balance of Plant (BOP) components, including Battery Energy Storage Systems (BESS), compressor and other auxiliary equipment required for continuous operation. BESS shall be utilize as back up energy supply to enable continuous PEMWE operation during period with insufficient solar irradiance. Charging electrical energy into the BSS is illustrate in figure 11b.

@The Author(s). 2026. Published by CBIORE

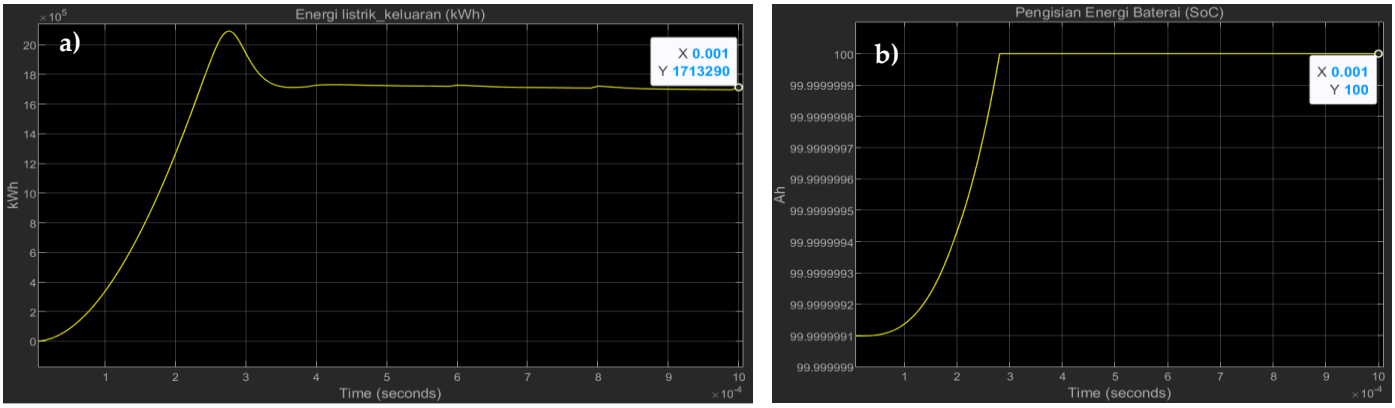


Figure 11. a) Total energy output of Solar PV power; b) BSS charging electrical energy

3.2. *PEMWE system*

The simulation results for each operational condition at temperatures of 60 °C, 80 °C and 100 °C ware evaluated to compare the impact of temperature increase on hydrogen production. This comparation serve as basis for estimating large scale hydrogen production capacity. Due to limitations in Simulink/Simscape block-based modelling, the detailed calculations ware performed separately using MATLAB. The comparative impact of temperature variation on hydrogen production is presented in Table 5 and 6.

Table 5. Comparison of the impact of temperature increased on hydrogen production rate

No	Parameter	Unit	Operating Temperature		
			60 °C	70 °C	80 °C
1	Electrolysis Temperature	°C	60	80	97.5
2	Current Density	A/cm^2	1.4	1.2	1.2
3	Voltage	Volt	92.7	111	92.7
4	Electrolysis Pressure	Pa	3 x 10^6	3 x 10^6	3 x 10^6
5	Electrolysis Electrical Power	kW	129.3	129.2	128.9
6	H_2O Transport	1/s	5	5	5
7	Hydrogen Production	g/s	0.1	0.5	0.7
8	Electrical Energy Consumption	W/s	1.6	22.5	30.6
9	Average H_2O Consumption	l/s	1	1	1
10	Thermal Energy Efficiency	-	0.999998	0.999987	0.999976

Result on model and simulation as illustrate operating temperature in Table 5 and Table 6 PEMWE parameters indicate a substantial increase in hydrogen production at 80 °C, corresponding to a 20 °C escalation from baseline conditions. Therefore, the operating temperature 80 °C has adopted as a basis for estimating large scale hydrogen production. Estimating result is illustrate in figure 12a which significant achievement of hydrogen production approximately 3,000.62 kg/day which consider a big impact to supply hydrogen fuel for the transportation FCEV basis in IKN and to keep environment clean from CO_2 emission.

The hydrogen production performance relative to electrical energy consumption indicates that PEMWE achieves an average specific electrical consumption of 47.9 kWh/kg H_2 (143,617/3,000.62) (Figure 12a-c). This value demonstrates an improvement compared to the typical electrical consumption of commercial PEM water electrolysis such as HyLYZER series by Cummins, which range between 51-55 kWh/kg H_2 (Makhsoos et al., 2023). The calculated electrical energy efficiency of 44 % (Figure 12d) does not yet account for the thermal management requirements of the system. Additional cooling capacity is necessary to handle the heat generated during operation, which is expected for further enhance hydrogen production performance and improve overall system efficiency.

@The Author(s). 2026. Published by CBIORE

Table 6. Parameters and Constants of PEMWE

Description	Value	Unit
Parameter:	8750	cell
Number of cells in pressurized vessel (N cell)	314	cm^2
Active cell area (Area_cell)	150	µm
PEM thickness (t membrane)	80	°C
Operational temperature (T_stack)	25	°C
Initial temperature (T_0)	1200	kg/m^3
Dry membrane density	1.21	A/cm^2
Current density (i_cell)	1.8	v
Cell voltage (v cell)	1.18E+0.3	J/(kg*k)
Specific heat capacity of water (Cp water)		
Constants:		
Faraday constant	96485	C/mol
Molar mass of H_2 (MW H_2)	2.01588	g/mol
Molar mass of H_2O (MW_H_2O)	18.01528	g/mol
Higher Heating Value of H_2 (HHV H_2)	2.86E+0.5	J/mol

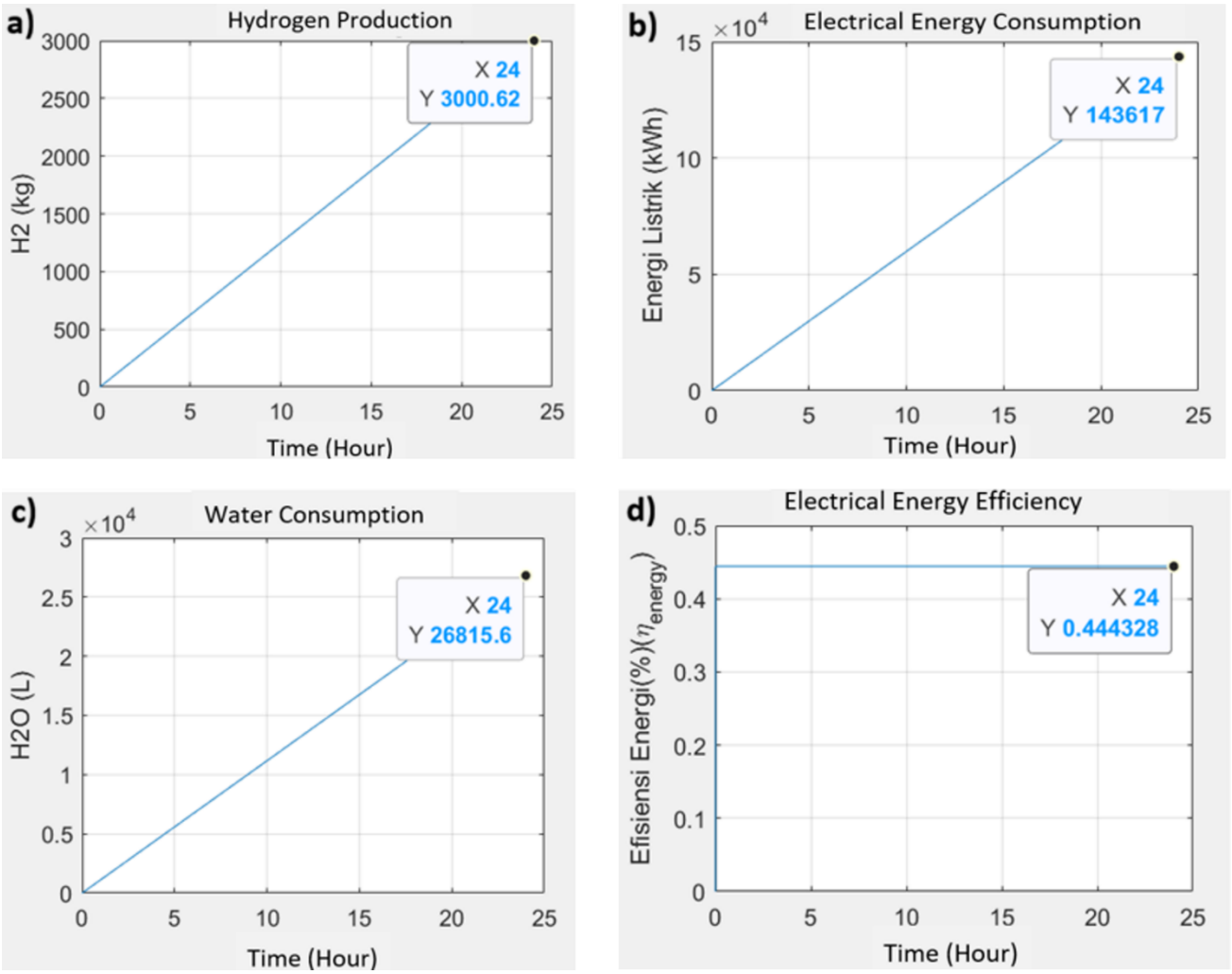


Figure 12. a) Total Production of H_2 3,000.62 kg/d; b) Energy Consumption 143,617 kWh/d; c) Water Consumption 26,815.6 L/d; d) Energy efficiency 44%.

3.3. CO_2 emission evaluation

Based on the hydrogen substitution methodology, the total CO_2-equivalent emissions avoided from the production and utilization of green hydrogen in the modeled system can be quantified by multiplying the daily hydrogen output by displacement coefficient of 4.37 kg CO_2-eg per kg of H_2 (Liu et al., 2022) . For a calculate generation capacity of 3,000.62 kg H_2 per day, resulting mitigation potential reaches 13,112.71 kg CO_2-eq/ day, equivalent to 13.11 tons of CO_2-eq per day. This value reflects the amount of fossil fuel related emissions that would otherwise be generate by gasoline and diesel combustion in conventional internal combustion vehicles. The magnitude of this avoided emission demonstrates that even amid scale green hydrogen facility can deliver substantial climate benefits, especially when urban or newly development region such as IKN. The results confirm that hydrogen produced from solar PV-powered PEMWE provides a high impact decarbonization pathway; the displacement of fossil fuels directly translates into measurable reduction in vehicles transportation sector carbon intensity (Gebara & Laurent, 2023). Furthermore, the daily mitigation potential, when scaled annually, correspond to more than 4,783 tones CO_2-eq/year, reinforcing the strategic justification for integrating hydrogen infrastructure in long-term planning to maintain regional air quality and prevent the recurrence of pollution patterns currently observed in Jakarta.

3.4. Technical-Economic evaluation

The integrated hydrogen production system comprising PEMWE-Solar PV-Battery Energy Storage System (BESS) yields a Levelized Cost of Hydrogen (LCOH) of 3.0 USD/kg H_2. This value is obtained by incorporating the major economic elements, including capital expenditure (CAPEX), Operational expenditure (OPEX), and the cost of BESS. The economic components and calculation parameters used to determine the LCOH are summarized on Table 7. The integrated hydrogen production system combining Solar PV-power PEMWE and Battery Energy Storage System (BESS) demonstrate a Levelized Cost of Hydrogen (LCOH) of 3.0 USD/kg H_2 under the specific technical and financial assumption. This value is derived through a rigorous cost breakdown incorporating capital expenditure (CAPEX), system lifetime, and discount rate consistent with contemporary technic-economic assessment methodologies. The CAPEX of the system reaches 30.92 million USD which is primarily dominated by the Solar PV and balance of system (BOS) components (17.29 million USD), followed by PEMWE stack and BOP requirements (7.78 million USD), and the BES investment (5.85 million USD). The sizing of these components is technically justified: the PEMWE capacity of 5,984 kW is scaled to meet a daily hydrogen production of 3,000.62 kg H_2/day, while the solar PV array is upscaled to 17,952 kWp to ensure continuous electrolyzer operation and accommodate BESS charging requirements. The financial evaluation applies a 20-year project life time and a 6% discount rate, consistent with recent literature (Steffen, 2020) , (Xia et al., 2022) and (Bhandari & Shah, 2021). Following annualization via the Capital Recovery Factor (CRF=0.08781), the system yields an annualized CAPEX of 2.70 million USD, forming the core basis for the LCOH calculation.

Operational expenditure contributes an additional 576,772 USD per year, which includes PEMWE O&M at 4% of its CAPEX (311,170 USD/y), Solar PV O&M equal to 1.5% of its CAPEX (259,318 USD/y) and BESS O&M at 0.35 USD/kWh (6,283 USD/y). These cost assumptions follow recent benchmark data from (Pettinau et al., 2024), (Windarta et al., 2021), and (Fagerström et al., 2024), ensuring methodological reliability. When combined, the total annual cost comprising annualized CAPEX and OPEX reaches 3.27 million USD. Given the annual hydrogen production capacity of 1,095,226 kg H_2 per year, the LCOH is calculated as (annualized CAPEX + OPEX) / Annualized H_2 production, resulting in 3.0 USD/kg H_2. This result indicates that, under Indonesia's renewable resource potential and cost structure, solar PV-powered PEMWE integrated BESS is approaching cost competitiveness relative to global green hydrogen benchmark while delivering fully decarbonized hydrogen production. The analysis confirms that that largest economic leverage point remains PEMWE CAPEX and Solar PV cost reduction, while BESS contributes stability but represents a smaller share cost. Consequently, this techno-economic framework establishes a robust basis for scaling hydrogen production in emerging development such as IKN, where renewable integration and emissions reduction are national priority.

@The Author(s). 2026. Published by CBIORE

Table 7. Technical-Economic evaluation of PEMWE-Solar PV-Battery Energy Storage System (BESS)

Description	Value	Unit	Data source
System Capacity:			
1. PEMWE	3,000.62	kg H_2	
2. Solar PV Power system	143,617	kWh	
Major Components:			
3. Life cycle PEMWE and Solar PV	20	year	Layer et al., 2024
4. Discount rate/WACC	6%	percent	Steffen, 2020
5. CAPEX unit cost PEMWE Stack + Balance of Plant (BOP) Stack (membrane, electrode, bipolar plate), BOP (Power Supply / Rectifier, cooler (heat exchanger, pump, water tank deionization), Drying H_2 , Instrument & Control, Mechanical items)	1300	USD/kW	Alex Budgett et al.,2024
6. CAPEX unit cost Solar PV + Balance of System (BOS) "Modules/panel, Inverter, Structure and Mounting, Cable DC/DC, Protection, fuse, switchgear, System control"	963	USD/kWp	Langer et al., 2023
7. CAPEX unit cost BESS	326	USD/kWh	Fagerström et al., 2024
8. OPEX PEMWE Stack + BOP (2.5% Capex)	311,170	USD/kW/year	Pettinau et al., 2024
9. OPEX Solar PV (1.5% Capex)	259,318	USD/kWp/year	Windarta et al., 2021
10. OPEX BESS	0.35	USD/kWh/year	Fagerström et al., 2024
CAPEX:			
11. PEMWE Stack + BOP			
143,617 / day	5,984	kW	
(5,984 x 2) x 1,300 (markup allocation BOP)	7,779,254	USD	
12. Solar PV + BOS			
5,984 x 3 (mark up for energy supply BESS and Operational support equipment	17,952	kWp	
17,952 x 963	7,287,896	USD	
13. Battery Energy Storage System (BESS)			
326 x 17,952	5,852,393		
TOTAL Capex	30,919,543	USD	
OPEX:			
14. PEMWE Stack + BOP			
4 % Capex (Pettinau et al., 2024)	311,170	USD/y	
15. Solar PV + BOS			
1.5 % Capex (Windarta et al., 2021)	259,318	USD/y	
16. Battery Energy Storage System (BESS)			
USD 0.35 x 17,952 kWh (Fagerström et al., 2024)	6,283	USD/y	
TOTAL OPEX	576,772	USD/y	
LCOH:			
$Capital\ Recovery\ Factor\ (CRF) = \frac{i(1+i)^n}{(1+i)^n - 1}$	0.087184557		
PEMWE hydrogen production per year 3000,62 x 365 day	1,095,226	kg H_2/y	
Annualized Capex = Capex x CRF	2,695,707	USD	
LCOH = (Annualized Capex + OPEX)/H_2 per year	3.0	USD/kg H_2	

4. Conclusion

Green hydrogen represents a promising future energy carrier capable of reducing CO_2 emission and decreasing reliance on fossil fuels. The PEMWE-Solar PV, still requires significant technology improvement to enhance durability, performance and overall efficiency. The result of hydrogen production of 3,000.62 kg/day, sufficient to fuel

@The Author(s). 2026. Published by CBIORE

approximately 1,500 FCEVs-corresponding to a potential CO2 emission reduction of about 13,112.7 kg CO2-eq per day. This substantial reduction directly supports United Nations Sustainable Development Goal-SDG-7 (affordable and clean energy) by promoting clean energy adoption and SDG-13 (Climate Action) through measurable mitigation of green gas emission. Furthermore, by replacing internal combustion vehicle with FCEVs, the system contributes to improved urban air quality, lower particulate matter (PM_{2-5}) and reduction in nitrogen and sulfur oxides (NO_x and SO_x), ultimately enhance public health and supporting SDG 3 (Good Health and Well Being). Cleaner air and reduced urban pollution also align with sustainable living environment envisioned for IKN, reinforcement long term environmental resilience and promoting a higher quality of life for the community.

References

Ariyadi, S.B., & Purwanto, W. W. (2024). Development Strategies for Grid-Connected Utility-Scale Solar Photovoltaic to Increase Renewable Energy Penetration. *CSID Journal of Infrastructure Development*, *7*(3), 478–495. https://doi.org/10.7454/jid.v7.i3.1164

Badgett, A., Brauch, J., Thatte, A., Rubin, R., Skangos, C., Wang, X., Ahluwalia, R., Pivovar, B., & Ruth M. (2024). Updated Manufactured Cost Analysis for Proton Exchange Membrane Water Electrolyzers. https://doi.org/10.2172/2311140

Bhandari, R., & Shah, R. R. (2021). Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany. *Renewable Energy*, *177*, 915–931. https://doi.org/10.1016/j.renene.2021.05.149

Brezak, D., Kovač, A., & Firak, M. (2023). MATLAB/Simulink simulation of low-pressure PEM electrolyzer stack. *International Journal of Hydrogen Energy*, *48*(16), 6158–6173. https://doi.org/10.1016/j.ijhydene.2022.03.092

Fagerström, J., Das, S., Klyve, Ø. S., Olkkonen, V., & Marstein, E. S. (2024). Profitability of battery storage in hybrid hydropower–solar photovoltaic plants. *Journal of Energy Storage*, *77*. https://doi.org/10.1016/j.est.2023.109827

Gebara, C. H., & Laurent, A. (2023). National SDG-7 performance assessment to support achieving sustainable energy for all within planetary limits. *Renewable and Sustainable Energy Reviews*, *173*. https://doi.org/10.1016/j.rser.2022.112934

Hancke, R., Holm, T., & Ulleberg, Ø. (2022). The case for high-pressure PEM water electrolysis. *Energy Conversion and Management*, *261*. https://doi.org/10.1016/j.enconman.2022.115642

Kamaroddin, M.F.A., Sabli, N., Tuan Abdullah, T. A., Siajam, S. I., Abdullah, L. C., Abdul Jalil, A., & Ahmad, A. (2021). Membrane-based electrolysis for hydrogen production: A review. In *Membranes* (Vol. 11, Issue 11). MDPI. https://doi.org/10.3390/membranes11110810

Karmaker, H., Siddique, A., & Das, B. K. (2023). Numerical investigation of lead free Cs2TiBr6 based perovskite solar cell with optimal selection of electron and hole transport layer through SCAPS-1D simulation. *Results in Optics*, *13*. https://doi.org/10.1016/j.rio.2023.100571

Konsep Pembangunan IKN. (n.d.).

Langer, J., Kwee, Z., Zhou, Y., Isabella, O., Ashqar, Z., Quist, J., Praktiknjo, A., & Blok, K. (2023). Geospatial analysis of Indonesia's bankable utility-scale solar PV potential using elements of project finance. *Energy*, 283, 128555. https://doi.org/10.1016/j.energy.2023.128555

Layer, R.K., Prosser, J.H., Kellu, J.C., James, B.D., & Elgowainy, A. (2024). Life-cycle Analysis of Hydrogen Production from Water Electrolyzers. *International Journal of Hydrogen Energy,* 81, 1467-1478. https://doi.org/10.1016/j.ijhydene.2024.06.355

Liu, W., Wan, Y., Xiong, Y., & Gao, P. (2022). Green hydrogen standard in China: Standard and evaluation of low-carbon hydrogen, clean hydrogen, and renewable hydrogen. *International Journal of Hydrogen Energy*, *47*(58), 24584–24591. https://doi.org/10.1016/j.ijhydene.2021.10.193

Liun, E., Suparman, Sriyana, Dewi, D., & Pane, J. S. (2022). Indonesia's Energy Demand Projection Until 2060. *International Journal of Energy Economics and Policy*, *12*(2), 467–473. https://doi.org/10.32479/ijeep.12794

@The Author(s). 2026. Published by CBIORE

Makhsoos, A., Kandidayeni, M., Pollet, B. G., & Boulon, L. (2023). A perspective on increasing the efficiency of proton exchange membrane water electrolyzers– a review. In *International Journal of Hydrogen Energy* (Vol. 48, Issue 41, pp. 15341–15370). Elsevier Ltd. https://doi.org/10.1016/j.ijhydene.2023.01.048

Memutusian. (n.d.). *Republik Indonesia-2 Mengingat Dengan Persetqjuan Bersama Dewan Perwakilan Rakyat Republik Indonesia dan Presiden Republik Indonesia*.

Mofolasayo, A. (2023). Assessing and Managing the Direct and Indirect Emissions from Electric and Fossil-Powered Vehicles. *Sustainability (Switzerland) , 15*(2). https://doi.org/10.3390/su15021138

Nasional, S. H. (n.d.). *Kementerian Energi dan Sumber Daya Mineral Republik Indonesia*. www.ebtke.esdm.go.id

Naskah Akademis Raperda Rencana Umum Energi Daerah (Rued) Provinsi Dki Jakarta. (2022).

Pettinau, A., Marotto, D., Dessì, F., & Ferrara, F. (2024). Techno-economic assessment of renewable hydrogen production for mobility: A case study. *Energy Conversion and Management*, *311*. https://doi.org/10.1016/j.enconman.2024.118513

Prasetyo, S. D., Trisnoaji, Y., Arifin, Z., & Mahadi, A. A. (2025). Harnessing unconventional resources for large-scale green hydrogen production: An economic and technological analysis in Indonesia. *Unconventional Resources*, *6*. https://doi.org/10.1016/j.uncres.2025.100174

Putri, A.R., Gunarto, T., Emalia, Z., & Murwiati, A. (2022). Pengaruh Pertumbuhan Ekonomi, Pertumbuhan Penduduk, dan Konsumsi Energi Terhadap Emisi CO2 di Indonesia. *BULLET: Jurnal Multidisiplin Ilmu*, 1(6), 1070-1080. https://journal.mediapublikasi.id/index.php/bullet

Saphira, D., & Sofyan, N. (2025). *Project Financing Strategy For On-Grid Solar PV Installation In The Cement & Construction Material Industry (Case Study: Pt Cibinong Bangun Sarana, West Java, Indonesia)*.

Shin, H. S., & Oh, B. S. (2020). Water transport according to temperature and current in PEM water electrolyzer. *International Journal of Hydrogen Energy*, *45*(1), 56–63. https://doi.org/10.1016/j.ijhydene.2019.10.209

Shin, H., Jang, D., Lee, S., Cho, H. S., Kim, K. H., & Kang, S. (2023). Techno-economic evaluation of green hydrogen production with low-temperature water electrolysis technologies directly coupled with renewable power sources. *Energy Conversion and Management*, *286*. https://doi.org/10.1016/j.enconman.2023.117083

Steffen, B. (2020). Estimating the cost of capital for renewable energy projects. *Energy Economics*, *88*. https://doi.org/10.1016/j.eneco.2020.104783

Teresia, K.F., Fahmi Muzakki, M., Mutiara Salsadila Sodik, V., & Hotimah, O. (2025). Dampak Polusi Udara Terhadap Kesehatan: Studi Komparatid Antara Kota Jakarta dan Kota Hanoi. *Jurnal Enviromental Science,* 8(1), 8-15. https://doi.org/10.35580/jes.v8i1.71956

Triana, D., Garniwa, I., Rosadi, A. H. Y., & Martono, D. N. (2024). Performance Analysis Simulation of Urban Rooftop Photovoltaic Potential in Jakarta City, Indonesia. *Environmental Research, Engineering and Management*, *80*(4), 21–38. https://doi.org/10.5755/j01.erem.80.4.34200

Windarta, J., Handoko, S., Sukmadi, T., Irfani, K. N., Masfuha, S. M., & Itsnareno, C. H. (2021). Technical and economic feasibility analysis of solar power plant design with off grid system for remote area MSME in Semarang City. *IOP Conference Series: Earth and Environmental Science*, *896*(1). https://doi.org/10.1088/1755-1315/896/1/012007

Xia, X., & Li, P. (2022). A review of the life cycle assessment of electric vehicles: Considering the influence of batteries. In *Science of the Total Environment* (Vol. 814). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2021.152870

@The Author(s). 2026. Published by CBIORE