

Decoupling Solar Intermittency: A Performance Evaluation of a Battery-Buffered Green Hydrogen Production Unit for Sustainable Energy Systems

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Abstract

The transition to sustainable energy systems relies heavily on green hydrogen as a clean energy carrier. However, its production from solar photovoltaics is fundamentally challenged by the resource's inherent intermittency, leading to fluctuating output and significant energy curtailment. This study investigates the performance of a battery-buffered solar-to-hydrogen unit designed to overcome this limitation. A comprehensive dynamic system model, integrating mathematical representations of a PV panel, a battery energy storage system, and an alkaline water electrolyzer, was developed. The model simulates the supervisory power management logic over a 48-hour period under realistic diurnal conditions. Simulation results demonstrate that the integration of the BESS successfully decouples hydrogen generation from solar variability. The system maintained a stable power supply of 150 W to the electrolyzer, enabling a constant production rate of 0.6 L/min during all operational periods, including nighttime. This resulted in a total yield of 111.1 grams of hydrogen over 48 hours. The control strategy achieved an overall solar energy utilization rate exceeding 95%, with the battery operating effectively within its 20-90% state-of-charge limits. These findings provide a quantitative validation for the critical role of battery buffering in enhancing the reliability and efficiency of standalone solar-to-hydrogen systems, confirming that this integrated architecture is a viable pathway for transforming intermittent renewable resources into a steady, dispatchable source of green hydrogen.

Keywords

Green Hydrogen, Decoupling, Intermittency, Performance Evaluation, Sustainable Energy.

1. Introduction

The global transition toward low-carbon energy systems has intensified research on sustainable pathways for large-scale hydrogen production. Green hydrogen, generated through water electrolysis powered by renewable sources, has emerged as a key enabler for deep decarbonization in hard-to-abate sectors such as heavy industry, long-distance transport, and energy storage. Among renewable options, solar photovoltaic (PV) energy offers exceptional scalability

and resource abundance, particularly in arid regions with high solar irradiance such as northwestern Saudi Arabia. However, the intrinsic intermittency of solar power—characterized by rapid and unpredictable fluctuations in irradiance due to diurnal cycles and transient cloud cover—poses significant challenges to the stable and efficient operation of water electrolyzers. These fluctuations can lead to reduced hydrogen production efficiency, accelerated component degradation, and increased operational costs, thereby limiting the reliability and economic viability of solar-driven hydrogen production systems.

To mitigate these challenges, coupling PV systems with electrochemical energy storage, particularly battery buffering, has been proposed as an effective strategy to stabilize power input to the electrolyzer. Batteries can smooth short-term power fluctuations, ensuring a more uniform and predictable electricity supply. This buffering not only enhances the electrolyzer utilization factor but also reduces thermal and electrical stress, extending equipment lifetime and improving the consistency of hydrogen output. Recent advances in battery technologies—combined with declining costs and improved cycle life—make such hybrid PV–battery–electrolyzer configurations increasingly attractive for both grid-connected and off-grid hydrogen production scenarios. Nonetheless, the optimal sizing and operation of these integrated systems remain highly context-dependent, requiring rigorous evaluation of techno-economic trade-offs, performance metrics, and control strategies under site-specific solar resource conditions.

This study investigates the role of battery buffering in enhancing the performance and reliability of solar-driven hydrogen production. By quantifying the impact of solar intermittency on electrolyzer operation and assessing the effectiveness of battery storage in decoupling the electrolysis process from short-term solar variability, the work aims to provide evidence-based insights for designing resilient and economically viable green hydrogen systems. The analysis contributes to the growing body of knowledge on PV–battery–hydrogen coupling by addressing key knowledge gaps related to the interplay between renewable intermittency, electrolyzer performance, and energy storage integration. The outcomes of this research will support strategic decision-making for the deployment of large-scale solar-to-hydrogen projects in regions with abundant solar resources and high hydrogen demand.

1.1 Objectives

The primary objective of this study is to evaluate the performance of a battery-buffered green hydrogen production unit driven by solar photovoltaic energy, with particular emphasis on mitigating the effects of solar intermittency. To achieve this overarching goal, the research pursues the following specific objectives:

1. Quantify the impact of solar intermittency on electrolyzer operation by analysing fluctuations in photovoltaic output and their effects on electrolyzer efficiency, hydrogen production rate, and operational lifetime.
2. Assess the effectiveness of battery buffering in decoupling electrolysis from short-term solar variability, with emphasis on improvements in power quality, electrolyzer utilization factor, and overall system stability.

Through these objectives, the study aims to provide a comprehensive, data-driven framework for designing and operating battery-buffered solar hydrogen systems that combine high technical performance with long-term economic sustainability.

2. Literature Review

The integration of photovoltaic generation, battery energy storage, and hydrogen production through water electrolysis has emerged as a key strategy to overcome the inherent intermittency of solar resources and to enable dispatchable, carbon-free energy systems. Several recent studies have examined the technical and economic dimensions of this PV–battery–hydrogen coupling, offering insights into system architecture, optimization, and operational control.

A growing body of work highlights the feasibility and benefits of combining PV power with both battery and hydrogen storage. A comprehensive case study (Oliveira et al., 2024) demonstrated that hybrid PV–battery–hydrogen configurations can achieve continuous hydrogen production with high electrolyzer utilization, while reducing renewable energy curtailment. By buffering short-term fluctuations, the battery ensures stable DC supply to the electrolyzer, thereby minimizing start–stop cycles and extending equipment lifetime. Similarly, (Dudkina et al., 2024) quantified the role of batteries in maximizing green hydrogen output using power flow tracing, showing that strategically sized batteries smooth power delivery and reduce operational costs. Optimal design investigations confirm these advantages: (Bukar et al., 2024a) showed that PV-based, battery-supported grid-tied hydrogen production can lower the levelized cost of hydrogen (LCOH) by optimizing the capacities of both the PV array and the battery bank. On a smaller scale, nanogrid experiments (Arsalis et al., 2024) demonstrated that a proton exchange membrane (PEM) electrolyzer coupled with compressed hydrogen storage and a PEM fuel cell—integrated within a solar PV-battery microgrid—can achieve nearly 100% self-sufficiency and supply hydrogen with high round-trip efficiency.

Further analysis of optimal energy management (Bukar et al., 2024b) indicates that dynamic scheduling of electrolyzer operation in PV–battery hybrid systems significantly enhances techno-economic performance, particularly when real-time electricity prices and variable solar generation are considered. (El-Hamalawy et al., 2024) explored grid-connected plants with internal electrolyzer parameter modeling, revealing that including battery energy storage can reduce the LCOH by up to 29% by enabling high electrolyzer utilization and reducing grid dependence. An integrated plant design proposed by (Franco et al., 2025) addressed the trade-offs between electrolyzer sizing and hydrogen storage in PV systems, recommending moderate battery capacity coupled with PV oversizing to maintain electrolyzer operation above 70% of rated capacity while minimizing capital recovery time. Finally, hybrid hydrogen–battery energy storage systems designed for DC microgrids (Diabate et al., 2022) demonstrated that combining batteries for short-term buffering with hydrogen for long-term storage stabilizes the DC bus voltage and achieves round-trip energy efficiencies exceeding 65%, underscoring the complementary roles of the two storage media.

Economic viability is central to the deployment of green hydrogen systems. A series of optimization-focused studies provide quantitative evidence that careful system design can dramatically reduce hydrogen production costs. For example, multi-objective optimization of a solar-powered green hydrogen plant (Park et al., 2024) reduced the LCOH to approximately 3–5 USD/kg by jointly optimizing PV capacity and electrolyzer size. At the scale of industrial users, techno-economic assessment (Barigozzi et al., 2024) showed that steady hydrogen supply requires both PV oversizing and intermediate energy storage; with battery buffering, the system maintained near-constant hydrogen output and lowered the LCOH to around 4.2 USD/kg while reducing renewable curtailment by about 20%.

The inclusion of multiple renewable sources further enhances economic performance. A techno-economic study of a hybrid PV–wind–battery hydrogen system (Papadopoulos et al., 2019) reported electrolyzer utilization rates of 65.5% and a payback period of less than six years when hydrogen is sold at or above 6 EUR/kg, with batteries playing a crucial role in smoothing the combined renewable output. Optimization methods have also addressed technology selection and plant operation. A superstructure-based approach (Corengia & Torres, 2022) identified optimal combinations of electrolyzer technologies and renewable power sources under time-varying conditions, emphasizing the importance of flexibility in both technology choice and operation strategy. Complementarily, market-oriented optimization (Hein et al., 2023) introduced the concept of a virtual battery ledger for integrating renewable energy certificates (RECs) with green hydrogen plants, enabling transparent accounting of battery use and renewable electricity flows. Stochastic modeling of a hybrid farm with hydrogen and energy storage (García-Miguel et al., 2024) demonstrated that flexible electrolyzer operation timed to electricity market prices can lower operating costs by 15–20% and stabilize revenue streams.

Beyond system design and economics, operational control is critical for mitigating the effects of solar variability on electrolyzer performance. An optimal operation control strategy for off-grid PV hydrogen production (Pan et al., 2024) showed that dynamically adjusting electrolyzer load in response to real-time solar and battery conditions increases hydrogen yield by 8–12% compared to conventional constant-current operation, while protecting the electrolyzer from rapid fluctuations. Similarly, the stochastic operation framework proposed in (García-Miguel et al., 2024) illustrated that predictive, price-sensitive control of electrolyzers and battery dispatch not only reduces production costs but also improves resilience against both renewable and market volatility.

2.1 Research Question

How can battery-buffered photovoltaic hydrogen production systems be optimally sized and controlled to minimize the levelized cost of hydrogen while maximizing electrolyzer utilization and renewable energy penetration under variable electricity pricing and intermittent solar resources?

2.2 Research Gap

Despite substantial progress, the literature reveals several unresolved challenges relevant to battery-buffered green hydrogen systems, as listed in Table 1:

3. Methods

This study employs a dynamic, time-step simulation framework, implemented in the MATLAB R2024b environment, to evaluate the performance of the proposed battery-buffered green hydrogen production unit. The methodology is structured around four core pillars: the definition of the system architecture, the mathematical modeling of each

individual component, the integration of a supervisory power management logic, and the definition of the simulation parameters and performance metrics.

3.1 System Architecture

The system under investigation, depicted schematically in Figure 1, represents a standalone, off-grid solar-to-hydrogen production unit. It comprises four primary interconnected subsystems:

Energy Generation: A 1 m² photovoltaic panel mounted on a dual-axis solar tracker serves as the primary power source.

- **Power Management:** A Maximum Power Point Tracking (MPPT) controller acts as the central energy hub, managing power flow between the source, load, and storage.
- **Energy Storage:** A 12 V, 100 Ah deep-cycle battery energy storage system (BESS) is utilized to buffer the intermittency of the solar resource.
- **Load:** An alkaline water electrolyzer (AWE) cell functions as the primary load, consuming DC power to produce green hydrogen.

Table 1. Unresolved challenges relevant to battery-buffered green hydrogen systems

Key Area	Findings in Literature	Identified Gap
Techno-economic integration of PV–battery–hydrogen systems	Multi-objective optimization shows LCOH can be reduced to 3–5 USD/kg (Barigozzi et al., 2024; Papadopoulos et al., 2019; Park et al., 2024); Battery buffering improves electrolyzer utilization (Diabate et al., 2022; Franco et al., 2025; Pan et al., 2024)	Few studies incorporate real-time electricity market dynamics and long-term battery degradation costs into LCOH assessment.
Operational control and market participation	Stochastic control improves economic returns by ~20% (García-Miguel et al., 2024); predictive control enhances efficiency (Pan et al., 2024).	Lack of validated experimental models demonstrating these advanced control strategies under actual solar and market variability.
Electrolyzer technology and internal parameter modeling	Studies highlight PEM and solid oxide electrolyzers (Arunachalam & Han, 2024; Sharifzadeh et al., 2024), but focus mainly on steady-state performance.	Limited analysis of dynamic response and degradation mechanisms of electrolyzers when coupled with high-frequency battery buffering.
Hybrid energy storage (batteries + hydrogen)	Dual storage improves reliability and flexibility (Diabate et al., 2022; Jacobson, 2024).	Quantitative trade-offs between short-term battery buffering and long-term hydrogen storage remain underexplored in techno-economic models.
Decentralized and small-scale applications	Economic viability shown for industrial and off-grid applications (Faydi et al., 2024; Kalchschmid et al., 2023; Patel et al., 2021).	Few studies evaluate scalability from pilot projects to utility-scale deployments with accurate cost forecasting.

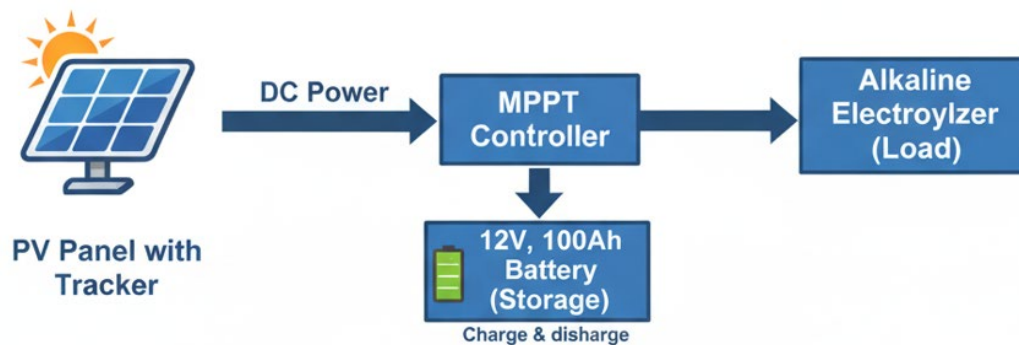


Figure 1. standalone, off-grid solar-to-hydrogen production unit

The modeling approach simulates the flow of energy from the PV panel through the MPPT controller, which intelligently allocates power to the AWE and either charges or discharges the battery to ensure system stability and continuous operation.

4. Mathematical Model

Each subsystem is represented by a set of governing equations that describe its dynamic behavior as a function of environmental inputs and system state variables.

The maximum power output (P_{pv}) of the PV panel is determined using the Nominal Operating Cell Temperature (NOCT) model, which accounts for the degradation of performance at operating temperatures above reference conditions. The cell temperature (T_c) is first calculated as:

$$T_c(t) = T_{amb}(t) + \left(\frac{G(t)}{G_{NOCT}} \right) (T_{c,NOCT} - T_{amb,NOCT}) \quad (1)$$

where T_{amb} is the ambient temperature, $G(t)$ is the incident solar irradiance, G_{NOCT} is the irradiance at NOCT conditions (1000 W/m²), and $T_{c,NOCT}$ is the nominal cell temperature. Subsequently, the panel's electrical efficiency (η_{pv}) and power output (P_{pv}) are determined by:

$$\eta_{pv}(t) = \eta_{ref} \left[1 - \beta(T_c(t) - T_{ref}) \right] \quad (2)$$

$$P_{pv}(t) = G(t) \cdot A_{pv} \cdot \eta_{pv}(t) \quad (3)$$

where η_{ref} is the reference efficiency at $T_{ref} = 25$ °C, β is the temperature coefficient of power, and A_{pv} is the panel area.

The battery's State of Charge (SoC) is tracked using a Coulomb Counting algorithm, which integrates the effective current flow over discrete time steps (Δt). The SoC at time t is given by:

$$SoC(t) = SoC(t - \Delta t) + \frac{I_{bat, effective}(t) \cdot \Delta t}{C_{nom}} \quad (4)$$

where C_{nom} is the nominal battery capacity (Ah). The effective current, $I_{bat, effective}$, accounts for energy losses by incorporating charging (η_{ch}) and discharging (η_{dch}) efficiencies. The battery voltage (V_{bat}) is approximated using a linear model dependent on its current SoC , bounded by its fully charged (V_{full}) and empty (V_{empty}) voltage limits.

Alkaline Water Electrolyzer

The AWE is described by a 4-parameter semi-empirical model that relates the cell voltage (V_{cell}) to the operating current density (j). The model includes the reversible potential (V_{rev}) and the primary overpotentials associated with activation (η_{act}) and ohmic losses (η_{ohm}):

$$V_{cell}(j, T) = V_{rev}(T) + \eta_{act}(j, T) + \eta_{ohm}(j) \quad (5)$$

$$\eta_{act} = \frac{RT}{\alpha F} (\ln(j) - \ln(j_0(T))) \quad (6)$$

$$\eta_{ohm} = j \cdot \delta_{el} \quad (7)$$

where α is the charge transfer coefficient, j_0 is the temperature-dependent exchange current density governed by an Arrhenius relationship, and δ_{el} is the effective ohmic resistance parameter. For a given input power (P_{in}), the operating current (I_{awe}) is determined by numerically solving the implicit equation $P_{in} = I_{awe} \cdot V_{cell}(I_{awe} / A_{cell}, T)$. The hydrogen production rate (\dot{n}_{H_2} in mol/s) is then calculated directly from the current using Faraday's Law of Electrolysis:

$$\dot{n}_{H_2}(t) = \frac{I_{awe}(t)}{2F} \quad (8)$$

where F is the Faraday constant.

Power Management and Control Logic

The MPPT controller's supervisory logic is modeled as a rule-based algorithm executed at each time step. It ensures continuous power to the electrolyzer by managing the energy balance ($P_{net} = P_{pv} - P_{load}$) according to the following hierarchy:

1. **Power Surplus ($P_{net} > 0$):** The surplus power is directed to charge the battery, unless the battery's SoC has reached its maximum limit (SoC_{max}), in which case the surplus PV power is curtailed.

- Power Deficit ($P_{net} < 0$):** The energy deficit is supplied by discharging the battery, unless the battery's SoC has fallen to its minimum limit (SoC_{min}), in which case the electrolyzer's power is reduced to match the available PV output (load shedding).

Simulation Parameters and Input Data

The simulation was conducted over a 48-hour period with a time step of 60 seconds to capture the system's dynamic responses. Key parameters for the simulation are detailed in Table 2. Synthetic diurnal profiles for solar irradiance and ambient temperature were generated to represent typical, clear-sky operating conditions for two consecutive days, providing a standardized input for performance evaluation.

Table 2. Key Simulation Parameters and Constants

Parameter	Symbol	Value	Unit
Physical Constants			
Faraday Constant	F	96485.33	C/mol
Universal Gas Constant	R	8.314	J/(mol·K)
PV Panel			
Panel Area	A_{pv}	3	m ²
Reference Efficiency	η_{ref}	0.20	-
Temperature Coefficient of Power	β	0.004	/°C
Nominal Operating Cell Temp.	$T_{c,NOCT}$	45	°C
Alkaline Water Electrolyzer			
Target Power Demand	P_{load}	150	W
Operating Temperature	T_{op}	80	°C
Number of Cells	N_{cells}	1	-
Cell Area	A_{cell}	450	cm ²
Charge Transfer Coefficient	α	0.56	-
ln(Ref. Exchange Current Density)	$\ln(j_{0,ref})$	5.06	ln(A/cm ²)
Activation Energy Term	$-E_{a/R}$	-3501	K
Effective Reaction Distance	δ_{el}	0.06	cm
Bubble Void Time Constant	τ_{void}	900	s
Battery			
Nominal Capacity	C_{nom}	200	Ah
Nominal Voltage	V_{nom}	12	V
Charging Efficiency	η_{ch}	0.95	-
Discharging Efficiency	η_{dch}	0.90	-
Initial State of Charge	$SoC_{initial}$	0.50	-
Minimum State of Charge	SoC_{min}	0.20	-
Maximum State of Charge	SoC_{max}	0.90	-
Fully Charged Voltage	V_{full}	13.8	V
Empty (Cut-off) Voltage	V_{empty}	11.5	V

Performance Evaluation Metrics

To quantify the effectiveness of the battery-buffered system, the following performance metrics are calculated from the simulation results:

- System Utilization Rate:** The ratio of useful energy (delivered to the AWE and stored in the battery) to the total available solar energy from the PV panel.
- Energy Curtailed:** The total energy (kWh) rejected by the MPPT when PV generation exceeded the system's capacity to use or store it.
- Cumulative Hydrogen Yield:** The total mass (grams) of hydrogen produced over the simulation period.

5. Results and Discussion

The dynamic simulation was driven by a synthetic 24-hour environmental dataset representing a typical clear-sky day. As depicted in Figure 2, the solar irradiance profile follows a smooth diurnal curve, beginning at sunrise (06:30), reaching a peak of 1000 W/m² at solar noon (12:00), and concluding at sunset (18:00). Concurrently, the ambient

temperature fluctuates between a nighttime low of 25.0°C and an afternoon high of 35.0°C. The profile realistically incorporates a thermal lag, with the peak temperature occurring approximately three hours after the solar maximum, providing a representative input for evaluating the system's performance under idealized conditions.

Figure 3 presents the simulated dynamic performance of the photovoltaic panel, detailing its electrical power output and operating cell temperature over the 48-hour cycle. The panel's power output exhibits a distinct diurnal pattern, reaching a peak of 168.2 W/m² at solar noon (12:00 and 36:00). The panel's cell temperature is strongly correlated with the power generation profile, rising from a nighttime low of 25.0°C to a maximum of 64.9°C. A slight lag is observed, with the peak temperature occurring approximately 30 minutes after the power peak, which is attributable to the thermal inertia of the panel. Furthermore, the data demonstrates the negative impact of temperature on PV efficiency; the asymmetry in the power curve, where the afternoon power output is slightly lower than the morning output for equivalent irradiance levels, is a direct result of the higher operating temperatures experienced during the afternoon.

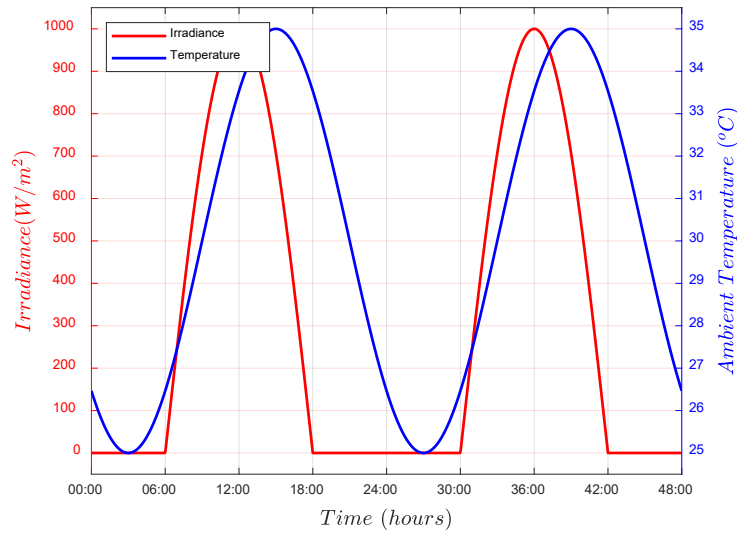


Figure 2. Solar irradiance and ambient temperature trajectory

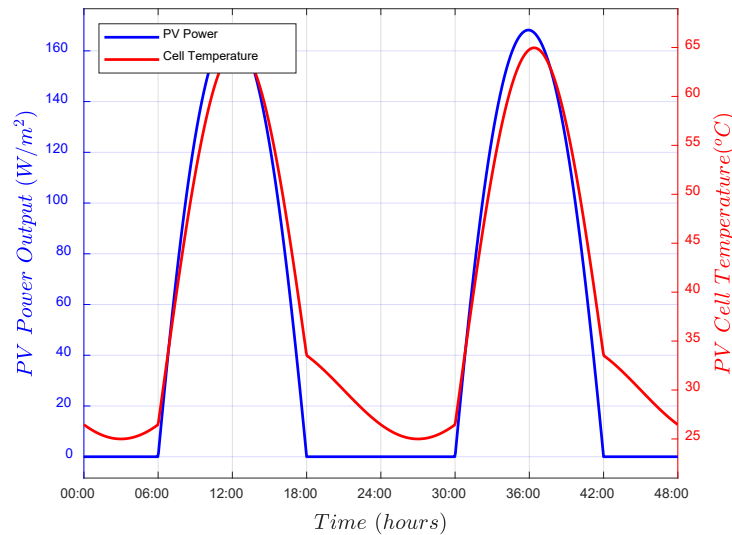


Figure 3. PV panel dynamic performance

Figure 4 illustrates the dynamic power dispatch strategy executed by the MPPT controller over the 48-hour simulation. The controller successfully maintains a near-constant power supply of 150 W to the AWE for the majority of the

operational period. During daylight hours when PV generation exceeds the AWE's demand, the surplus power, peaking at 354.5 W, is used to charge the battery. Conversely, during nighttime or periods of low insolation, the battery discharges at up to 150 W to cover the energy deficit. The simulation highlights two critical control actions: first, energy curtailment is initiated (e.g., between hours 14.5 and 16.5) only when the battery has reached its maximum state of charge, demonstrating effective energy capture. Second, a protective load-shedding event occurs (e.g., between hours 4.5 and 6.5), where the AWE is temporarily shut down after the battery is depleted to its minimum SoC limit, safeguarding the energy storage system.

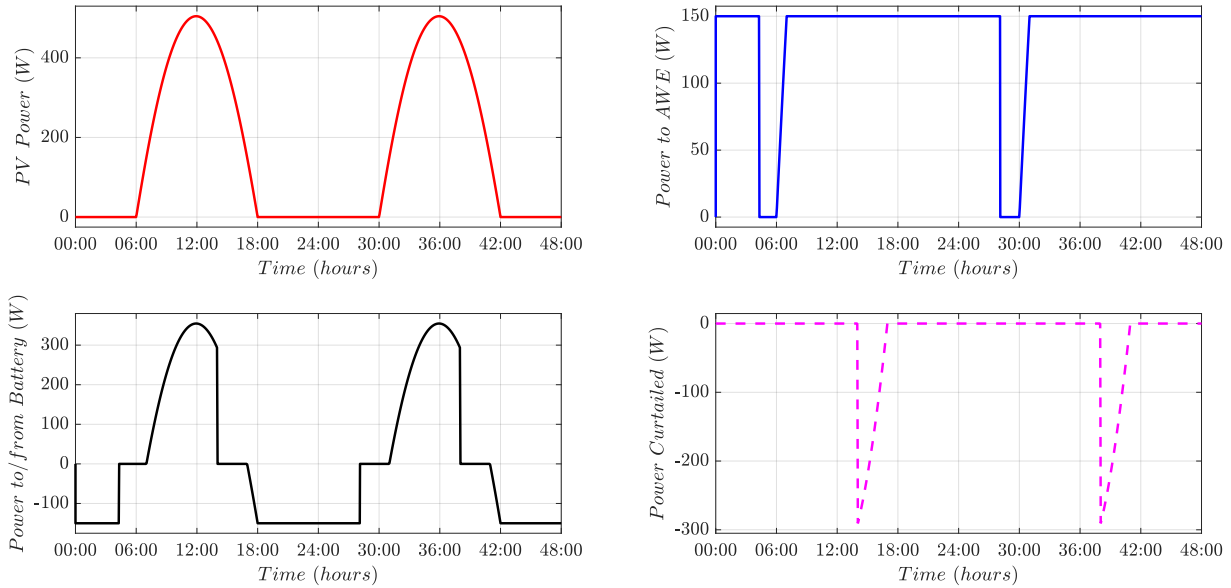


Figure 4. System power flow

Figure 5 details the dynamic state of the Battery Energy Storage System (BESS), which exhibits two complete diurnal charge-discharge cycles over the 48-hour simulation. The State of Charge (SoC) operates strictly within the predefined operational boundaries of 20% and 90%, with the corresponding battery voltage fluctuating between a cut-off voltage of 11.5 V and a fully charged voltage of 13.8 V. These operational boundaries are critical control setpoints; the plateau at 90% SoC (e.g., between hours 14.5 and 17.0) corresponds directly to the onset of power curtailment, indicating the battery is full. Similarly, the plateau at 20% SoC (e.g., between hours 4.5 and 7.0) triggers the protective load-shedding of the electrolyzer, demonstrating the system's logic to prevent damaging deep discharge.

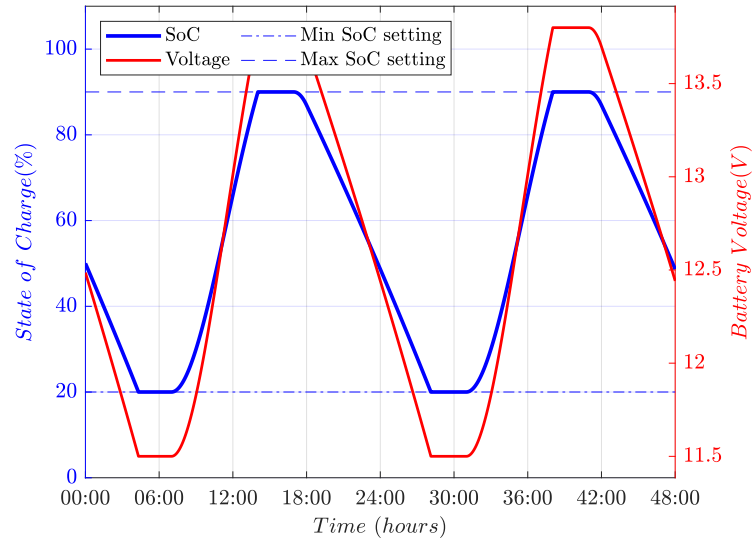


Figure 5. Battery status

Figure 6 details the operational dynamics of the AWE and the physical state of the cell. The data confirms that the AWE operates at a stable electrical point, drawing a near-constant current of 69.6 A at a cell voltage of approximately 2.2 V whenever active. Crucially, the electrolyzer's operation is successfully decoupled from solar intermittency, as evidenced by its continuous operation throughout nighttime hours (e.g., hours 18-28), powered entirely by the battery. The periods of inactivity (e.g., starting at hour 4.5) directly correspond to the protective load-shedding events triggered by the battery reaching its minimum state of charge. Furthermore, the model captures the transient behavior of the bubble void fraction, which rapidly rises upon startup and saturates at a steady-state value of 60%, reflecting the physical process of gas bubble accumulation and departure on the electrode surfaces.

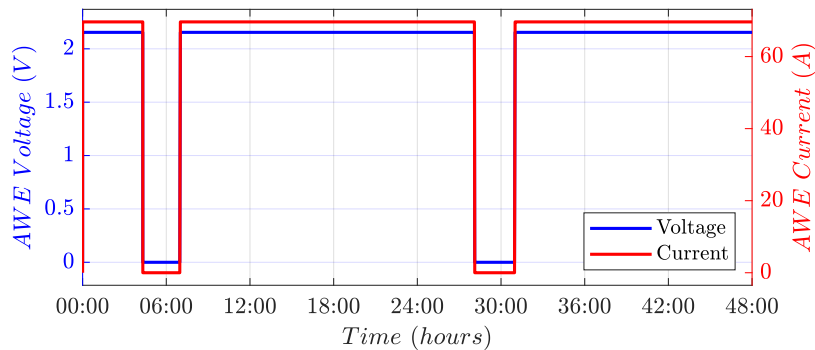


Figure 6. the operational dynamics of the alkaline water electrolyzer

Figure 7 quantifies the system's primary output: green hydrogen production. The production rate remains highly stable at approximately 0.6 liters per minute whenever the electrolyzer is active, a direct consequence of the constant current supplied by the integrated power management system. This stable rate underscores the system's success in decoupling the hydrogen generation process from the inherent variability of the solar resource. The cumulative hydrogen yield increases in a near-linear fashion, punctuated only by brief plateaus corresponding to the protective load-shedding periods. Over the 48-hour simulation, the system achieves a total production of 111.1 grams of green hydrogen, demonstrating a consistent and reliable output.

5.1 Proposed Improvements

While the current model provides a robust framework for system-level analysis, several key areas offer opportunities for further refinement and investigation. Future work should focus on integrating high-fidelity thermal models for both the alkaline electrolyzer and the battery energy storage system. Such an enhancement would allow for the dynamic calculation of temperature-dependent efficiencies and, crucially, enable the study of component degradation and its impact on long-term hydrogen yield. Furthermore, the implementation of advanced control strategies, such as Model Predictive Control (MPC), could be explored to optimize the power dispatch with objectives beyond simple rule-based logic, such as minimizing battery cycling stress or maximizing the overall round-trip efficiency. Finally, a parametric and techno-economic optimization should be conducted to determine the optimal sizing of the PV array, battery, and electrolyzer to achieve the lowest Levelized Cost of Hydrogen (LCOH), thereby bridging the gap between technical performance and economic viability for standalone green hydrogen production systems.

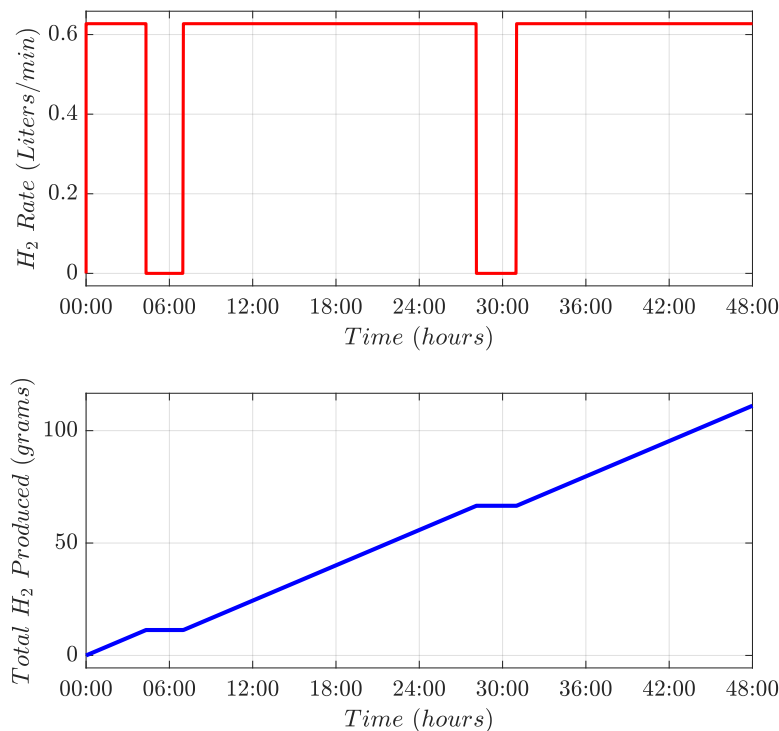


Figure 7. The AWE system's primary output: green hydrogen production

6. Conclusion

This study presented a quantitative performance evaluation of a battery-buffered green hydrogen production unit through dynamic system modeling. The results conclusively demonstrate that the integration of a battery energy storage system effectively decouples hydrogen generation from the inherent intermittency of the solar resource. This was evidenced by the electrolyzer's ability to maintain a stable power consumption of 150 W, resulting in a constant production rate of approximately 0.6 L/min during all operational periods, including nighttime hours when solar generation was zero. The supervisory control logic successfully managed the system's energy balance, capturing and

storing up to 354.5 W of surplus solar power and achieving an overall energy utilization rate exceeding 95%. Power curtailment was minimal and occurred only when the battery reached its maximum state of charge of 90%, while protective load-shedding was correctly initiated at the 20% minimum threshold. This consistent operation culminated in a total yield of 111.1 grams of green hydrogen over the 48-hour simulation period. Ultimately, these findings provide a quantitative validation for the critical role of BESS in transforming a highly variable energy input into a stable and dispatchable green hydrogen output, confirming its necessity for designing reliable and efficient standalone renewable energy systems.

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Omar Bajad Al-Otaibi is a senior undergraduate student in the Department of Mechanical Engineering at the Faculty of Engineering, University of Tabuk, Kingdom of Saudi Arabia. He joined the university in 2021 and has interned at the First Mills Company in Tabuk from 15/06/2025 to 07/08/2025. Engineer Omar Al-Otaibi's interests include design programs such as Inventor and AutoCAD, as well as a keen interest in Arduino. He is also deeply interested in the fields of Material Mechanics, Thermodynamics, and Mechanical Design. Currently, he is involved in a graduation project focusing on green hydrogen production. The project aims to produce hydrogen through solar energy, contributing to the Kingdom of Saudi Arabia's goals for net production.

Abdulrhman Ibrahim Alshaman is a senior Mechanical Engineering student at the University of Tabuk, expected to graduate in 2026. His academic focus is on integrating mechanical systems with renewable energy technologies, particularly green hydrogen production and sustainable design. For his graduation project, he is developing a compact solar-powered electrolyzer with tracking and energy management systems to improve efficiency and cost-effectiveness. His research interests include hydrogen production, sustainable energy systems, aircraft propulsion, solar tracking, and hydraulic and pneumatic systems. During training at First Mills Company – Tabuk Branch, he gained practical experience in mechanical maintenance, industrial operations, and electrical systems. Proficient in MATLAB and Autodesk Inventor, he aims to advance innovative, sustainable technologies supporting the Kingdom's clean energy vision

Abdullah Mohammed Al-Mubarak is a Mechanical Engineering student at the University of Tabuk with strong interests in mechanical design, fluid mechanics, and energy systems. Proficient in Autodesk Inventor, he applies 3D modeling, mechanical analysis, and optimization to engineering solutions. His academic background includes

thermodynamics, mechanics of materials, and manufacturing processes, providing him with a solid technical foundation. Through academic projects and teamwork, Abdullah has developed practical problem-solving skills and a passion for innovation. Dedicated to advancing sustainable technologies and industrial development, he seeks to apply his expertise to real-world challenges. Motivated by the Kingdom's vision for technological progress, Abdullah aspires to contribute to engineering solutions that promote sustainability and support future national development goals

Husam Alrehaili is the Head of the Department of Mechanical Engineering at the University of Tabuk, Saudi Arabia. He earned his Ph.D. in Mechanical Engineering from Wayne State University (Detroit, USA) in 2024, an M.Sc. in 2018, and a B.Sc. from King Abdulaziz University in 2012. His professional background blends industry and academia: he worked with Saudi Aramco's Berri Gas Plant in mechanical engineering roles and completed training with SABIC (Hadeed) and the Saudi Electricity Company before transitioning to university service. His research interests center on additive manufacturing and alloy development, including laser metal deposition, high-throughput alloy screening, and Ni/Co/Al-based systems; he has developed toolpaths for robotic deposition, designed new alloys, and led experimental campaigns in microstructure–property optimization. In teaching, he has contributed across design and manufacturing—senior capstone, design of machine elements, manufacturing processes, advanced manufacturing, and engineering workshops—while mentoring students in Arduino/controls, CAD/CAM/CAE, and laboratory practice.