Original Article

Check for updates

Available online at
www.heca-analitika.com/ljes

Leuser Journal of Environmental Studies

Vol. 4, No. 2, 2026

Adaptive Solar–Electrolysis Architecture for Decentralized Energy Applications: A Preliminary Engineering Assessment

Ahmad Fachrurrozi [1], Erkata Yandri [1,2,*], Agus Rendi Wijaya [1], Marzuirman Marzuirman [1], Ramadhan Farhan Fadillah [1], Derry Pradana Nasrul [1], Ahmad Zulfikri Taning [1,2], and Aep Saepul Uyun [1,2]

[1] School of Renewable Energy - Darma Persada University. Jl. Radin Inten 2. Pondok Kelapa. East Jakarta 13450, Indonesia; rozisontoloyo@gmail.com (A.F.); erkata@gmail.com (E.Y.); agusrendiwijaya@gmail.com (A.R.W.); marzuirman@gmail.com (M.M.); ramadhann.farhannn@gmail.com (R.F.F.); derrypradhanafisika@gmail.com (D.P.N.); ahmad.z.taning@gmail.com (A.Z.T.); aepsuyun@gmail.com (A.S.U.)

[2] Center of Renewable Energy Studies, Darma Persada University, Jl. Radin Inten 2, Pondok Kelapa, East Jakarta 13450, Indonesia

* Correspondence: erkata@gmail.com

Article History

Received 9 June 2026
Revised 10 August 2026
Accepted 22 August 2026
Available Online 4 September 2026

Keywords:
Oxyhydrogen
Photovoltaic intermittency
Battery buffering
Adaptive energy management
Wet-cell electrolysis
Household energy

Abstract

The intermittency of renewable electricity presents a significant challenge for decentralized energy systems in which electrolysis is coupled to variable photovoltaic (PV) generation. This study develops a conceptual adaptive solar–electrolysis architecture for decentralized energy applications by integrating photovoltaic generation, adaptive energy management, battery buffering, wet-cell electrolysis, hydrogen-rich gas handling, safety provisions, and a potential household utilization pathway within a unified system framework. The study uses a conceptual engineering approach and does not include experimental or field measurements; it comprises functional requirement analysis, system architecture development, energy-flow formulation, adaptive operating logic, representative renewable-energy scenarios, functional comparison, and preliminary engineering assessment. Four study-specific conceptual indicators provide a structured basis for future quantitative evaluation: the Adaptive Energy Stability Index (AESI), Electrolysis Continuity Index (ECI), Renewable Adaptation Factor (RAF), and Integrated System Reliability Index (ISRI). These indicators are defined as conceptual assessment frameworks rather than established reliability standards or experimentally validated performance measures. The conceptual analysis formulates adaptive power coordination and finite battery buffering as a mechanism for managing short-term mismatches between photovoltaic generation and electrolysis demand. However, the proposed architecture cannot eliminate the effects of prolonged renewable-energy deficits because battery capacity is finite. Furthermore, when hydrogen and oxygen are not separately collected, the gas pathway considered in this study represents an H_2–O_2/HHO-type gas stream rather than experimentally verified pure hydrogen. Its actual composition, production rate, combustion behavior, and safety characteristics therefore require experimental characterization. The study establishes a preliminary system-level engineering framework for subsequent dynamic modelling, prototype development, quantitative performance assessment, safety validation, techno-economic analysis, and lifecycle environmental evaluation.

1. Introduction

The transition toward sustainable, low-carbon energy systems has increased the need for decentralized energy technologies that can use renewable resources while maintaining an appropriate degree of operational flexibility. Solar photovoltaic (PV) generation is particularly attractive for decentralized applications because electricity can be generated close to the point of consumption and integrated with energy-conversion and storage technologies. However, photovoltaic generation is inherently variable because its electrical output changes with solar irradiance, cloud conditions, temperature, time of day, and other environmental factors. When variable photovoltaic electricity is directly coupled to an electrolysis subsystem, these fluctuations can transfer to the electrolysis process and affect its electrical operating conditions and continuity. Managing renewable-energy variability is therefore an important consideration in developing renewable-powered electrolysis systems [1–3].

Water electrolysis provides an important pathway for converting renewable electricity into hydrogen-based chemical energy. The integration of electrolysis with renewable electricity has consequently received increasing attention, particularly for decentralized and hybrid energy systems in which electricity generation, energy storage, and hydrogen production must operate under variable resource conditions [3]. Recent studies have investigated integrating photovoltaic generation, battery storage, electrolysis, and energy-management strategies to improve the utilization of renewable electricity and accommodate fluctuations in energy availability. These studies demonstrate the technical relevance of combining renewable generation with storage and electrolysis. Still, they also indicate that the operating behavior of such systems depends strongly on how energy flows among the individual subsystems are coordinated. At the electrolysis level, wet-cell configurations have also been investigated for generating hydrogen-rich or HHO-type gas. Experimental studies have shown that gas-production behavior is influenced by electrical current, voltage, electrolyte characteristics, temperature, and cell configuration [4]. These findings are important when integrating wet-cell electrolysis with a variable photovoltaic source because changes in electrical input may affect the operating conditions and gas-production behavior of the electrolysis subsystem. Consequently, the electrolysis unit should not be considered independently from the renewable-energy source and energy-buffering system when the objective is to establish a stable decentralized energy pathway.

An additional technical issue arises when hydrogen and oxygen are not collected separately. Under ideal water-electrolysis conditions, hydrogen and oxygen are generated according to the theoretical reaction, $2H_2O \Rightarrow 2H_2 + O_2$, corresponding to an ideal hydrogen-to-oxygen molar ratio of approximately 2:1. However, this stoichiometric relationship does not establish the actual composition of a practical wet-cell gas stream. Gas composition, gas purity, production rate, pressure, and combustion behavior may be affected by electrode configuration, electrical operating conditions, electrolyte characteristics, temperature, gas crossover, and gas-collection conditions [4]. Accordingly, in this study, the term hydrogen-rich gas refers specifically to an H_2–O_2/HHO-type gas stream when hydrogen and oxygen are not separately collected, rather than to experimentally verified pure hydrogen. This distinction becomes particularly important when considering the gas pathway for potential household use. Hydrogen-related applications require appropriate consideration of leakage, dispersion, ignition, combustion, pressure, ventilation, and flashback hazards [5]. Hydrogen-based cooking has also been investigated as a potential pathway for low-carbon household energy utilization. Still, practical implementation depends on appliance compatibility, gas characteristics, thermal performance, safety, infrastructure, and economic conditions [6]. Therefore, successful operation of an electrolysis subsystem alone is not sufficient evidence of household cooking feasibility. The gas-generation, gas-handling, safety, and end-use stages need to be considered as interconnected elements of the overall energy system.

Previous studies provide important foundations across the relevant technology domains. Renewable-powered hydrogen research has examined the integration of photovoltaic generation, energy storage, electrolysis, and hybrid system operation [3, 7]. PV–electrolysis–battery integration has also been investigated explicitly under coupled system conditions [8], while recent energy-management studies have examined coordinated operation under variable renewable-energy conditions [9, 10]. Wet-cell and HHO investigations have examined how electrical operating conditions influence gas-production behavior [4, 11]. Hydrogen-safety studies have addressed hazards associated with leakage, dispersion, ignition, combustion, and explosion [5]. At the same time, hydrogen-for-cooking research has emphasized appliance compatibility, safety, energy performance, infrastructure, and techno-economic considerations [6].

Based on these representative studies, the research gap addressed in the present study concerns system-level operational integration rather than the absence of individual technologies. Specifically, the unresolved issue is how established renewable-energy, storage, electrolysis, gas-handling, and safety functions can be coordinated when the primary renewable-energy source is inherently variable, and the generated gas may remain an H_2–O_2/HHO-type mixture rather than purified hydrogen.

A system-level architecture is consequently required to describe how renewable-energy availability influences battery operation, how battery buffering affects electrolysis continuity, and how the characteristics of the resulting gas influence downstream handling, safety, and potential utilization.

Based on the representative literature examined in this study, the novelty of the present study is positioned at the architectural and methodological level. Rather than proposing a new photovoltaic technology, battery technology, or electrolysis technology, the study develops an adaptive operational architecture in which photovoltaic generation, adaptive energy management, finite battery buffering, wet-cell electrolysis, hydrogen-rich gas handling, safety provisions, and potential household utilization are treated as coordinated functions within a single decentralized energy framework. The adaptive strategy is intended to manage short-term differences between renewable-energy availability and electrolysis demand while explicitly recognizing the finite nature of stored energy and the unresolved characteristics of the H_2–O_2/HHO-type gas stream. The principal research question addressed by this study is: How can an adaptive photovoltaic–battery–wet-cell electrolysis architecture be conceptually structured to manage short-term renewable-energy variability while explicitly accounting for H_2–O_2/HHO gas characteristics, gas-safety requirements, and potential decentralized household utilization?

To address this question, this study aims to develop and preliminarily assess a conceptual adaptive solar–electrolysis architecture for decentralized energy applications under variable photovoltaic availability. The study focuses on establishing the functional relationships among photovoltaic generation, adaptive energy management, battery buffering, wet-cell electrolysis, gas handling, safety provisions, and potential household utilization. It further develops conceptual assessment indicators for electrical stability, electrolysis continuity, renewable-energy adaptability, and integrated system performance, while examining the expected operational response of the architecture under representative high-, moderate-, and low-renewable-energy conditions. The study is intentionally limited to conceptual system design and preliminary engineering assessment. It does not include prototype fabrication, laboratory gas-composition measurements, site-specific photovoltaic time-series validation, combustion experiments, household fuel-substitution testing, techno-economic assessment, or lifecycle environmental assessment. Consequently, the proposed architecture is not presented as an experimentally demonstrated household hydrogen system. Instead, the study establishes a preliminary engineering framework that can be subjected to dynamic modelling, prototype development, gas characterization, safety validation, household end-use assessment, techno-economic analysis, and lifecycle environmental evaluation in subsequent research.

2. Materials and Methods

2.1. Study Design and Conceptual Engineering Approach

This study employed a conceptual engineering approach to develop and preliminarily assess an adaptive solar–electrolysis architecture for decentralized energy applications under variable photovoltaic availability. The study examined how photovoltaic generation, battery buffering, adaptive energy management, wet-cell electrolysis, hydrogen-rich gas handling, safety provisions, and potential household utilization could be coordinated within a single system-level framework. The study was intentionally conducted as a conceptual engineering assessment rather than as an experimental investigation. No physical prototype was fabricated, and no laboratory or field measurements were performed. Consequently, the present methodology does not provide experimentally measured values for gas composition, gas-production rate, electrolysis efficiency, battery performance, combustion behavior, household fuel displacement, or environmental impact. Instead, the methodology establishes the system architecture, governing relationships, adaptive operating logic, representative operating conditions, and assessment indicators required for subsequent quantitative validation.

The conceptual development followed a sequential engineering reasoning process in which the problem of renewable-energy intermittency was first translated into system-level functional requirements. These requirements were then used to define relationships among the principal subsystems and establish an adaptive energy-management strategy. The resulting architecture was subsequently examined under representative renewable-energy conditions and evaluated using conceptual indicators intended to support future simulation and experimental assessment.

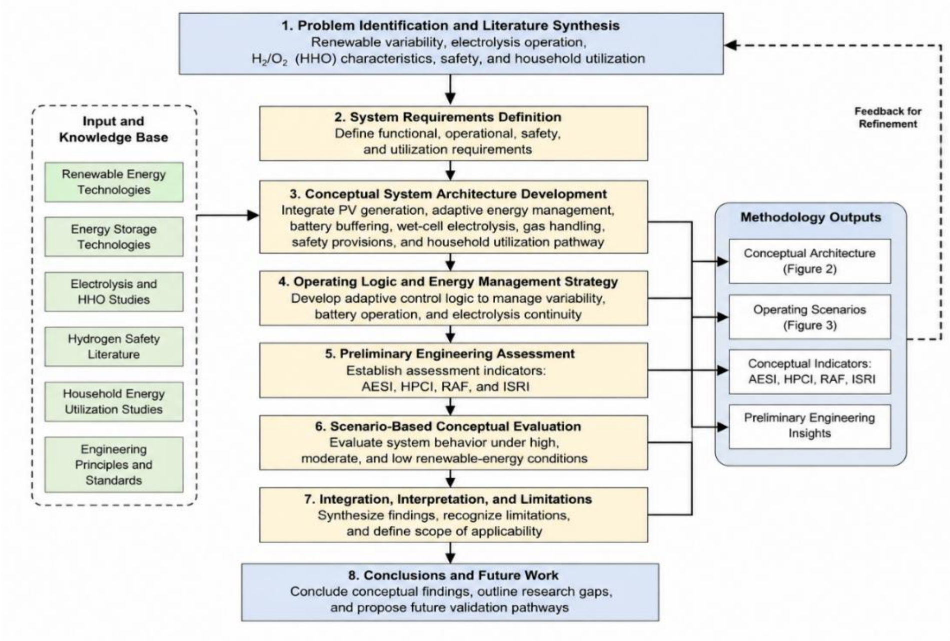

Figure 1. Conceptual engineering methodology for the development and preliminary assessment of the adaptive solar–electrolysis architecture.

An overview of this methodological sequence is presented in Figure 1.

The methodology therefore establishes a traceable relationship between the identified engineering problem, the proposed system architecture, the operating logic, and the preliminary assessment framework. This approach was selected because the study's primary contribution is developing a coordinated system architecture rather than experimentally optimizing an individual component.

2.2. Problem Definition and Functional Requirements

The central engineering problem considered in this study is the temporal mismatch between variable photovoltaic electricity generation and the electrical demand of a water-electrolysis subsystem. Photovoltaic output changes according to solar irradiance and environmental conditions, whereas electrolysis requires electrical input to sustain the water-splitting process [12, 13]. When the two systems are directly coupled, fluctuations in photovoltaic output may transfer directly to the electrolysis subsystem and affect its operating continuity. Based on this problem, the proposed architecture was designed around several interconnected functional requirements. The first requirement concerns stabilizing the electrical power supplied to the electrolysis subsystem so that short-term variations in photovoltaic generation can be accommodated without assuming the renewable source itself is constant. The second concerns electrolysis continuity, particularly during temporary reductions in photovoltaic availability. The third concerns adaptive renewable-energy utilization, whereby available photovoltaic power is dynamically allocated according to the instantaneous relationship between renewable generation, electrolysis demand, and battery state of charge.

The architecture also requires a defined pathway for hydrogen-rich gas generation and handling. In the present study, the wet-cell electrolysis subsystem is assumed to produce an H_2–O_2/HHO-type gas stream when hydrogen and oxygen are not collected separately [4]. This characteristic introduces additional requirements for controlled gas routing, water management, flow regulation, and safety provisions. The potential household application is consequently treated as a downstream utilization pathway that remains subject to experimental gas characterization and safety validation. These functional requirements were not treated as independent design targets. Instead, they were considered as mutually dependent functions within a single system. This approach allowed the study to examine how renewable-energy availability influences battery operation, how battery operation influences electrolysis continuity, and how the resulting gas pathway affects downstream handling and potential utilization.

2.3. Development of the Proposed System Architecture

The proposed architecture was developed by establishing the functional relationship among photovoltaic generation, adaptive energy management, battery buffering, wet-cell electrolysis, gas handling and safety, and potential household utilization. Photovoltaic

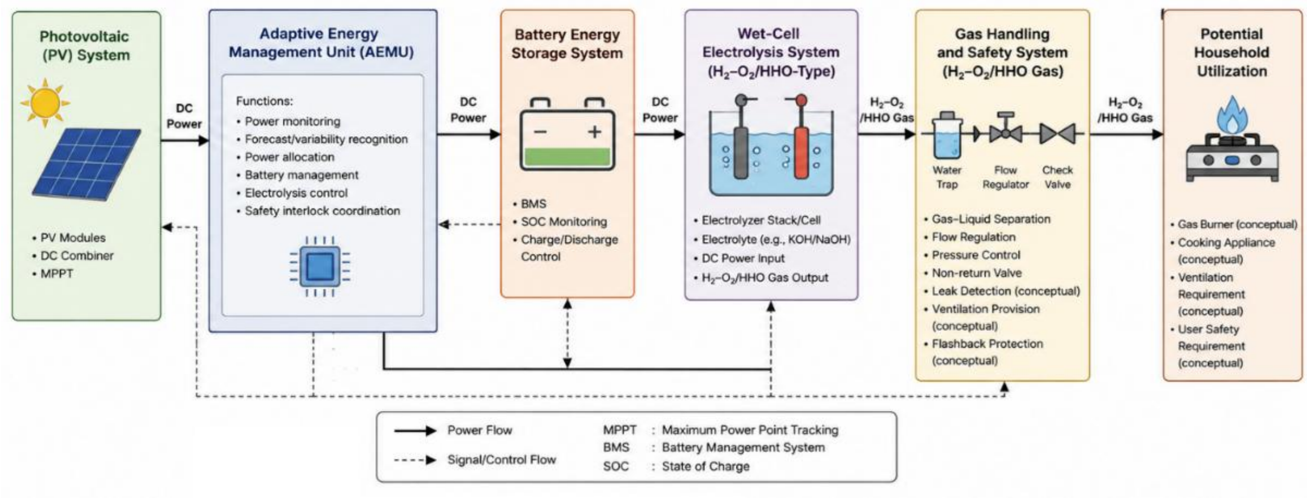

Figure 2. Conceptual architecture of the proposed adaptive solar–electrolysis system.

generation is the primary renewable electricity source, while the adaptive energy-management layer coordinates renewable generation, battery storage, and electrolysis demand. When photovoltaic generation is sufficient to meet the electrolyzer's instantaneous electrical demand, the available renewable electricity can be supplied directly to the electrolysis subsystem. When additional photovoltaic power is available beyond the instantaneous electrolysis requirement, the excess energy can be directed to battery charging within the storage system. The functional relationships among these principal subsystems are illustrated in Figure 2.

When photovoltaic generation temporarily falls below the electrolysis demand, the adaptive energy-management layer allows the battery to provide supplementary power, provided that sufficient usable stored energy is available. If the renewable-energy deficit persists and the battery reaches its minimum allowable state of charge, the architecture does not assume continued operation. Instead, electrolysis is conceptually reduced or transferred to a standby condition until adequate renewable-energy availability is restored. The electrolysis subsystem represents the energy-conversion stage in which electrical energy is converted into an H_2–O_2/HHO-type gas stream. Because hydrogen and oxygen are not assumed to be separately collected in the conceptual configuration, the downstream gas pathway is treated as a distinct engineering function requiring controlled handling and appropriate safety provisions.

The potential household utilization stage is positioned downstream of the gas-handling and safety functions. Its inclusion in the architecture does not imply that household cooking performance has been demonstrated. Rather, it represents the potential end-use pathway that would be investigated during a subsequent experimental development stage.

2.4. Hydrogen-Rich Gas Definition and Engineering Assumptions

In this study, the gas produced by the proposed wet-cell electrolysis pathway is defined as an H_2–O_2/HHO-type gas stream when hydrogen and oxygen are not separately collected. This terminology is used deliberately to distinguish the conceptual gas product from experimentally verified or commercially supplied pure hydrogen. The theoretical water-electrolysis reaction can be expressed as shown in Equation (1):

$$2H_2O \rightarrow 2H_2 + O_2 \quad (1)$$

Under ideal electrochemical conditions, this reaction corresponds to a theoretical hydrogen-to-oxygen molar ratio of approximately 2:1. However, the stoichiometric relationship does not establish the actual composition of the gas generated by a practical wet-cell system. Experimental studies have shown that HHO gas production is influenced by electrical current, voltage, electrolyte conditions, temperature, and cell configuration [4]. Accordingly, this study does not assume a specific hydrogen concentration, oxygen concentration, gas purity, gas-production rate, pressure, or combustion value for the proposed gas stream. These parameters are unknown engineering quantities that must be experimentally characterized before the gas can be considered for practical household application.

The same assumption applies to gas combustion behavior. Although hydrogen-containing gases may provide an energy-use pathway, the actual combustion characteristics depend on gas composition, flow rate, pressure, burner configuration, and operating conditions. The present study therefore does not use theoretical gas composition to infer household cooking performance. The gas-handling architecture is consequently considered an essential part of the proposed system. Controlled gas routing, water removal where necessary, flow regulation, prevention of uncontrolled accumulation, and provision for future safety devices are incorporated conceptually to reflect the characteristics of the proposed gas pathway.

2.5. Energy-Flow Formulation

The energy-flow formulation was developed to describe the interaction between photovoltaic generation, battery buffering, and electrolysis demand. The photovoltaic subsystem was treated as the primary renewable-energy input, while the battery was treated as a temporary energy buffer rather than an independent energy source. The conceptual photovoltaic output was represented using the first-order relationship, as shown in Equation (2):

$$P_{PV} = GA\eta_{PV} \tag{2}$$

Where P_{PV} represents photovoltaic output power (W), G represents solar irradiance (W/m^2), A represents the effective photovoltaic area (m^2), and η_{PV} represents photovoltaic conversion efficiency. Equation (2) provides a conceptual relationship between solar-resource availability and electrical generation. It is not intended to represent a site-specific photovoltaic model because the present study does not use measured irradiance data, detailed module characteristics, or a defined geographical installation.

To describe the interaction among renewable generation, household electricity demand, battery operation, electrolysis demand, and system losses, the system-level electrical power balance was expressed as shown in Equation (3):

$$P_{PV} + P_{bat,dis} = P_{HH} + P_{EL} + P_{bat,ch} + P_{aux} + P_{loss} + P_{curt} \tag{3}$$

Where P_{HH} represents the instantaneous household electrical demand, P_{EL} represents electrolysis power demand, $P_{bat,dis}$ and $P_{bat,ch}$ represent battery discharge and charging power, respectively, P_{aux} represents auxiliary electrical consumption, P_{loss} represents electrical conversion and distribution losses, and P_{curt} represents curtailed renewable power when available generation cannot be directly used, stored, or allocated within the defined operating limits. This formulation establishes the conceptual electrical boundary of the proposed architecture and explicitly distinguishes household electricity demand from the downstream H_2–O_2/HHO-type gas application. When photovoltaic generation is sufficient to satisfy the instantaneous household and electrolysis demands, any remaining usable energy can be allocated to battery charging subject to the battery operating constraints. When photovoltaic generation is insufficient, the battery may discharge to compensate for the instantaneous deficit provided that $SOC > SOC_{min}$ and the allowable discharge capacity is available. If the combined photovoltaic and allowable battery power remains insufficient, electrolysis demand is reduced according to the adaptive operating rules. In contrast, essential household electricity demand remains part of the system-level electrical boundary. Any residual imbalance is represented by P_{loss} and, where applicable P_{curt}.

The thermal energy potentially associated with the H_2–O_2/HHO-type gas stream was not included as a quantified term in Equation (3) because gas composition, flow rate, heating value, and burner conversion efficiency have not been experimentally characterized in the present study.

2.6. Battery Buffering and Adaptive Energy Management

Battery buffering was incorporated into the proposed architecture to address short-term differences between photovoltaic generation and electrolysis demand. The battery was not treated as a mechanism capable of eliminating renewable-energy intermittency, but rather as a finite energy reservoir that can temporarily compensate for renewable-power deficits. The conceptual state-of-charge relationship was expressed as shown in Equation (4):

$$SOC_{t+\Delta t} = SOC_t + \frac{\eta_{ch} P_{ch,t} \Delta t}{E_B} - \frac{P_{dis,t} \Delta t}{\eta_{dis} E_B} \tag{4}$$

Where SOC_t and $SOC_{t+\Delta t}$ represent the battery state of charge at consecutive time steps, $P_{ch,t}$ represents charging power, $P_{dis,t}$ represents discharge power, η_{ch} and η_{dis} represent charging and discharging efficiencies, E_B represents nominal battery energy capacity, and Δt represents the assessment time interval. Equation (4) provides a conceptual energy-balance representation and does not constitute a manufacturer-specific electrochemical battery model. Effects such as temperature dependence, degradation, aging, rate-dependent capacity, and detailed battery chemistry are outside the scope of the present conceptual assessment.

The adaptive energy-management strategy was defined using the relationship among photovoltaic power availability, electrolysis demand, and battery state of charge. The control logic was formulated as four conceptual operating rules. Rule 1—PV-sufficient operation: when $P_{PV} \geq P_{EL,req}$, photovoltaic generation directly supplies the electrolysis demand, and any available surplus is directed to battery charging subject to the defined maximum state-of-charge and charging-power limits. Rule 2—battery-assisted operation: when $P_{PV} < P_{EL,req}$ and $SOC > SOC_{min}$, the battery provides supplementary power to compensate for the instantaneous photovoltaic deficit, subject to the available discharge capacity and the defined battery operating limits. Rule 3—energy-limited operation: when photovoltaic generation and the allowable battery discharge are insufficient to satisfy the required electrolysis demand, electrolysis power is reduced to the maximum level that the available electrical input can support. Rule 4—standby operation: when the available electrical input falls below the electrolysis subsystem's minimum operating requirement or the battery reaches its minimum allowable state of charge, electrolysis is transferred to standby until sufficient renewable energy becomes available or the battery is recharged above the defined operating threshold. These rules establish the adaptive coordination mechanism of the proposed architecture while explicitly recognizing the finite nature of battery energy and the operational limits of the electrolysis subsystem. Here, SOC_{min} represents the minimum allowable battery state of charge defined for safe and controlled operation, while $P_{EL,req}$ represents the electrical power required by the electrolysis subsystem under the selected operating condition. The minimum operating requirement of the electrolyzer refers to the lowest electrical input at which stable electrolysis operation is assumed to remain feasible and is treated as a conceptual parameter requiring experimental determination.

2.7. Electrolysis Relationship

The wet-cell electrolysis subsystem was represented using the theoretical relationship between electrical charge and hydrogen generation described by Faraday's law [4, 14], as given in Equation (5):

$$n_{H2,theoretical} = \frac{It}{2F} \quad (5)$$

Where $n_{H2,theoretical}$ represents the theoretical amount of hydrogen generated in moles, I represents electrolysis current, t represents electrolysis operating time, and F represents the Faraday constant. Equation (5) describes the ideal electrochemical relationship under the assumption of complete Faradaic conversion. It is therefore used only as a theoretical engineering relationship and is not interpreted as a measured hydrogen-production rate for the proposed system. Actual gas production may differ from the theoretical value because of Faradaic losses, gas crossover, electrode characteristics, electrolyte behavior, temperature, and other practical operating effects [4]. For this reason, the present study does not assign a numerical hydrogen-production rate or electrolysis efficiency to the proposed architecture. Instead, the theoretical electrochemical relationship is used to link electrical input to potential gas generation and to provide a basis for subsequent experimental characterization.

2.8. Illustrative Engineering Parameter Set

To establish a transparent engineering basis for the proposed architecture, we defined an illustrative parameter set for a representative decentralized household-scale configuration. The parameters were selected to provide dimensional and operational reference values for the photovoltaic subsystem, battery buffer, electrolysis subsystem, and household electricity boundary rather than to represent an optimized or experimentally validated system. The parameter set is therefore used only to demonstrate how the proposed energy-flow and adaptive-management framework can be instantiated in a future simulation or prototype study. Where literature-based values are available, they are used as engineering reference points; otherwise, the values are explicitly treated as illustrative assumptions.

The illustrative parameter set should not be interpreted as a finalized household system design. The 2.0 kWp photovoltaic capacity and 5.0 kWh battery capacity establish a representative renewable-generation and finite-storage boundary. At the same time, the 12 V and 18 A electrolysis operating point is included as a literature-referenced wet-cell benchmark rather than a measured operating condition of the proposed architecture [4]. The corresponding electrical input of approximately 216 W is obtained from $P = V\,I$. The 1.16 L/min HHO value is likewise treated only as a literature benchmark and is not assigned as the expected production rate of the proposed system. Actual gas production would depend on electrode configuration, electrolyte characteristics, temperature, current density, cell connection, and other operating conditions and therefore requires experimental characterization [4, 15, 16].

The representative household electricity demand of 3.0 kWh/day is used solely as an illustrative analytical boundary for the conceptual system. It is not intended to represent an average household demand in Indonesia or another specific geographical context. A future simulation should replace this assumption with measured or statistically representative hourly household load data. Under the illustrative configuration, the 2.0 kWp PV subsystem represents the principal renewable-electricity source, while the 5.0 kWh battery provides finite short-term energy buffering. The illustrative 216 W electrolysis input is treated as a controllable electrical demand rather than a continuously guaranteed load. The household electricity boundary is represented by an illustrative daily demand of 3.0

Table 1. Illustrative engineering parameter set and literature benchmarks for the proposed decentralized solar–electrolysis architecture.

Subsystem / Parameter	Illustrative value	Basis / interpretation
PV rated capacity	2.0 kWp	Illustrative household-scale assumption
Effective PV area	10 m^2	Derived from 2.0 kWp at approximately 20% nominal conversion efficiency
Reference PV efficiency	20%	Illustrative engineering assumption
Battery nominal capacity	5.0 kWh	Illustrative storage assumption
Usable battery energy	4.0 kWh	Illustrative value corresponding to an 80% usable-energy window
SOC_{min}	20%	Conceptual operating constraint
SOC_{max}	90%	Conceptual charging constraint
Electrolyzer operating voltage	12 V DC	Illustrative electrical assumption
Electrolyzer operating current	18 A	Literature-referenced wet-cell current level [4]
Electrolyzer electrical input	approximately 216 W	Calculated illustrative operating point from 12 V × 18 A
Literature HHO flow benchmark	1.16 L/min	Literature-reported wet-cell result under specific experimental conditions; not transferable as a performance value for the proposed system
Representative household electricity demand	3.0 kWh/day	Illustrative analytical load; not a measured household profile
Maximum illustrative electrolysis duration	4 h/day	Analytical operating assumption
Assessment horizon	24 h	Proposed basis for subsequent time-series assessment
Conceptual assessment interval	1 h	Proposed simulation time step
Gas composition	H_2–O_2/HHO-type mixture	No separation or purity is assumed
Gas-production validation	Required	Experimental measurement required before household application claims

kWh/day. Accordingly, the proposed architecture does not assume that all PV electricity is continuously allocated to electrolysis; power allocation depends on renewable availability, household demand, battery state of charge, and the electrolysis operating condition defined by the adaptive management rules.

The household boundary is therefore treated as a potential downstream application rather than a demonstrated end use. In particular, the illustrative electrolysis operating point does not establish that the generated H_2–O_2/HHO-type gas stream would provide sufficient thermal energy for household cooking. Such a determination would require experimentally measured gas composition and flow rate, burner compatibility, thermal output, combustion stability, leakage behavior, flashback resistance, and an appropriate safety assessment. The present parameter set is consequently intended to support system-level analysis rather than to establish household cooking performance. The illustrative engineering parameters in Table 1 provide the system boundary for the scenario framework, while the irradiance ranges defined below are used to examine how the adaptive operating logic responds to changes in photovoltaic availability

2.9. Representative Renewable-Energy Operating Conditions

The proposed architecture was examined under three illustrative renewable-energy operating conditions to define how the adaptive energy-management strategy responds to different levels of photovoltaic availability. Because the present study does not use site-specific irradiance measurements or a defined geographical installation, the scenarios are not intended to represent local weather classes or measured operating conditions. Instead, they provide quantitative boundary conditions for conceptual assessment using the first-order photovoltaic relationship in Equation (2). A reference irradiance of $1000\,W/m^2$ was adopted solely as an illustrative photovoltaic operating point. The selected irradiance values are not intended to represent site-specific solar-resource conditions or measured operating states. The three illustrative operating conditions are summarized in Figure 3.

High renewable-energy availability was defined as an illustrative irradiance range of $800 \le G \le 1000\,W/m^2$. WUnder this condition, photovoltaic generation is assumed to provide relatively high electrical availability and may satisfy the required electrolysis power while providing surplus energy for battery charging, depending on the selected PV capacity and system losses. The battery therefore operates primarily in charging or reserve mode when its state of charge remains below the defined upper operating limit. Moderate renewable-energy availability was defined as $400 \le G \le 800\,W/m^2$. In this range, photovoltaic generation remains available but may become insufficient to continuously satisfy the required electrolysis power. The adaptive energy-management strategy therefore permits battery-assisted operation when $SOC > SOC_{min}$ and sufficient discharge capacity is available. This condition represents the

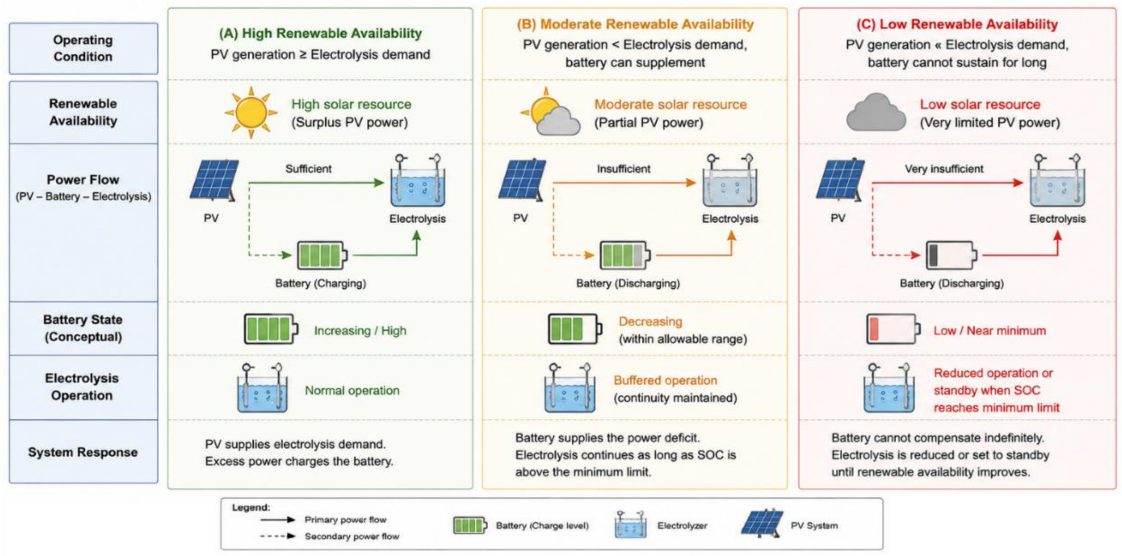

Figure 3. Illustrative renewable-energy operating conditions of the adaptive solar–electrolysis architecture under different photovoltaic irradiance ranges.

Table 2. Illustrative instantaneous power-balance conditions.

Condition	Irradiance	PV generation (kW)	Household demand (kW)	Electrolysis demand (kW)	Preliminary balance (kW)
High	1000 W/m²	2	0.125	0.216	1.659
Moderate	600 W/m²	1.2	0.125	0.216	0.859
Low	100 W/m²	0.2	0.125	0.216	−0.141

Note: Preliminary balance = $P_{PV} - P_{HH,avg} - P_{EL}$, before battery operation and system losses. Values are illustrative calculations, not experimental measurements.

operating regime in which coordination between photovoltaic generation, electrolysis demand, and finite battery storage becomes particularly relevant. Low renewable-energy availability was defined as $G < 400\ W/m^2$. Under this condition, photovoltaic generation is assumed to provide substantially reduced electrical input relative to the higher-availability scenarios. The battery may initially provide supplementary power, but its finite stored energy limits the duration of compensation. When the combined available photovoltaic power and allowable battery discharge can no longer satisfy the required electrolysis demand, electrolysis power is reduced according to the adaptive operating rules. If the available electrical input subsequently falls below the minimum operating requirement or the battery reaches SOC_{min}, electrolysis is transferred to standby until sufficient renewable energy becomes available or the battery is recharged above the defined operating threshold.

These irradiance ranges are therefore used only as illustrative scenario boundaries for evaluating the conceptual operating logic. They do not constitute experimentally measured performance conditions, site-specific solar-resource classes, or validated operating envelopes. The resulting scenarios are intended to establish a reproducible basis for subsequent simulation using measured time-series irradiance data and system-specific photovoltaic, battery, and electrolysis parameters.

2.10. Illustrative Power-Balance Example

To demonstrate the application of the proposed energy-balance formulation without implying experimental system performance, a single-time-step calculation was performed using the parameter assumptions listed in Table 1. A representative household electrical demand of 3.0 kWh/day was converted to an average equivalent power demand of 0.125 kW, while the electrolysis subsystem was represented by the literature-referenced operating point of 0.216 kW specified in Table 1. The resulting power-balance values under the three representative irradiance conditions are presented in Table 2.

Under the high-availability illustrative condition, the assumed 2.0 kWp PV subsystem provides sufficient instantaneous power to supply both the average household electrical demand and the 0.216 kW electrolysis demand, leaving a theoretical surplus of 1.659 kW before losses and other operating constraints. Under the moderate condition, the calculated surplus decreases to 0.859 kW, indicating greater dependence on coordinated energy allocation and potential battery charging constraints. Under the selected low-availability operating point of 100 W/m^2, the available PV power is insufficient to simultaneously satisfy the average household and electrolysis demands, producing an illustrative deficit of 0.141 kW before battery discharge and losses are considered. The battery can therefore provide supplementary power under this condition when its state of charge remains above SOC_{min} and sufficient discharge capacity is available. This calculation should not be interpreted as a prediction of daily household energy performance. The household demand was represented by its daily-average equivalent power rather than an hourly load profile. At the same time, the PV output was calculated from a single irradiance value using the first-order relationship in Equation (2). This illustrative example did not numerically resolve battery efficiency, auxiliary consumption, temperature effects, power-electronic losses, or detailed electrolyzer operating constraints. A subsequent time-series simulation using measured irradiance and household-load data would therefore be required to quantify system performance. The resulting 0.141 kW deficit represents the instantaneous power deficit that the battery could supply, subject to battery efficiency, discharge limits, and SOC constraints. The illustrative calculation therefore provides a direct numerical interpretation of the four adaptive operating rules. High renewable availability corresponds primarily to direct PV supply and potential battery charging; moderate availability increases the relevance of coordinated power allocation; and low availability can require battery-assisted operation, followed by electrolysis reduction or standby when available energy becomes insufficient.

2.11. Conceptual Performance Assessment

To provide a structured basis for evaluating the proposed architecture, four conceptual indicators were introduced: the Adaptive Energy Stability Index (AESI), Electrolysis Continuity Index (ECI), Renewable Adaptation Factor (RAF), and Integrated System Reliability Index (ISRI). These indicators were developed specifically for the present conceptual study and are not presented as established international standards, experimentally validated performance metrics, or certified reliability measures. Their purpose is to establish a consistent framework that can later be populated with experimental or simulation data. The AESI was defined as shown in Equation (6):

$$AESI = 1 - \min\left(1, \frac{\sigma(P_{EL})}{\sigma(P_{PV} + \varepsilon)}\right) \qquad (6)$$

Where $\sigma(P_{EL})$ represents the standard deviation of electrical power supplied to the electrolysis subsystem, $\sigma(P_{PV})$ represents the standard deviation of photovoltaic output power, and ε represents a small positive numerical term used to avoid division by zero. AESI provides a conceptual measure of the degree to which the adaptive architecture reduces the variability of electrical input to the electrolyzer relative to the variability of the photovoltaic source. The ECI was defined as shown in Equation (7):

$$ECI = \frac{t_{EL,operating}}{t_{EL,required}} \qquad (7)$$

Where $t_{EL,operating}$ represents the duration during which the electrolysis subsystem remains within its defined operating condition and $t_{EL,required}$ represents the total period during which electrolysis operation is required. ECI therefore provides a conceptual measure of electrolysis continuity and explicitly allows interruptions when available renewable and stored energy become insufficient. The RAF was defined as shown in Equation (8):

$$RAF = min\left(1, \frac{E_{PV} + E_{B,usable}}{E_{EL}}\right) \qquad (8)$$

Where E_{PV} represents photovoltaic energy available during the assessment period, $E_{B,usable}$ represents usable battery discharge energy, and E_{EL} represents the electrical energy required by the electrolysis subsystem. RAF provides a conceptual representation of the ability of the combined renewable-energy and usable battery resources to satisfy the electrolysis energy demand during the defined assessment period. Finally, the ISRI was expressed as shown in Equation (9):

$$ISRI = \frac{AESI + ECI + RAF}{3} \qquad (9)$$

In this study, ISRI is interpreted as a conceptual integrated-performance indicator of integrated operational behavior and should not be interpreted as a statistical probability of system reliability or a validated reliability metric. The three underlying indicators are given equal weighting because the present conceptual study does not provide sufficient experimental evidence to justify differential weighting. Safety is intentionally not incorporated as an arbitrary numerical component of ISRI. Instead, safety is evaluated separately through engineering requirements because a defensible quantitative safety score would require experimentally measured and validated safety parameters. Because the present study does not contain time-series experimental data, numerical values are not assigned to AESI, ECI, RAF, or ISRI. Their formulation is intended to establish a reproducible framework for subsequent simulation and experimental validation.

2.12. Functional Comparison and Preliminary Assessment Procedure

The proposed architecture was compared conceptually with representative renewable-hydrogen, PV–electrolysis–battery, hydrogen-based energy-management, and wet-cell HHO configurations to identify differences in system-level functionality. The comparison considered coordination between photovoltaic generation and electrolysis, the role of battery buffering, the response to renewable-energy variability, the electrolysis continuity strategy, gas handling and safety, and the potential downstream household application. The comparison was intentionally qualitative because the present study does not provide experimental data from either the proposed architecture or a direct-coupled reference system. Consequently, the comparison identifies a functional distinction rather than establishing quantitative superiority.

The assessment procedure began by identifying the engineering problem and translating it into functional requirements. These requirements were then mapped to the proposed architecture and its individual subsystems. The energy-flow relationships were subsequently formulated to describe the interaction among photovoltaic generation, battery buffering, and electrolysis demand. The adaptive operating logic was then examined under the representative renewable-energy conditions described above. The conceptual indicators were subsequently introduced to establish a structured basis for future quantitative evaluation. Finally, a qualitative functional comparison was performed against representative system configurations using predefined architectural dimensions, with the classification rules described above.

For the functional comparison, each evaluation dimension was classified as explicitly included, configuration-dependent, or not identified as a defined function within the system configuration described by the cited study. “Explicitly included” indicates that the study directly incorporates the function as a component, subsystem, control objective, or stated system requirement. “Configuration-dependent” indicates that the function depends on the specific system configuration reported and may vary by system boundary, component arrangement, or operating strategy considered in the cited study. “Not identified” indicates that the function is not reported as part of the system boundary or analysis of the cited study. The classification was based on the architecture, objectives, and system description reported in the cited literature rather than on measured performance. Where a function varied among configurations within a study, the classification was assigned according to the configuration explicitly represented by the cited evidence and was not generalized to technologies or systems beyond that evidence.

2.13 Methodological Scope and Limitations

The methodology presented in this study is deliberately limited to conceptual engineering development and preliminary system-level assessment. No physical prototype, laboratory test, or field experiment was performed. Therefore, the methodology does not provide direct evidence concerning actual gas composition, gas-production rate, electrolysis efficiency, battery performance, combustion behavior, household fuel displacement, environmental impact, or long-term system reliability. The H_2–O_2/HHO-type gas pathway is particularly subject to this limitation because its actual composition cannot be determined from the theoretical electrolysis reaction alone. Experimental characterization is required to establish hydrogen and oxygen concentrations, gas flow rate, pressure, temperature, water-vapor content, and other relevant properties. Similarly, the adaptive operating strategy has not yet been implemented in a physical control system. Its present formulation therefore represents a conceptual control architecture rather than a validated control algorithm.

The proposed AESI, ECI, RAF, and ISRI indicators also remain conceptual until experimental or simulation data are available. Their sensitivity, robustness, and usefulness for representing system behavior should therefore be evaluated in subsequent studies rather than assumed from their mathematical formulation alone. The methodology therefore serves as a preliminary engineering foundation for dynamic modelling, controlled prototype development, experimental gas characterization, safety validation, techno-economic analysis, and lifecycle environmental assessment.

3. Results and Discussion

3.1. Developed Adaptive Solar–Electrolysis Architecture

The conceptual engineering assessment resulted in an adaptive solar–electrolysis architecture that establishes a

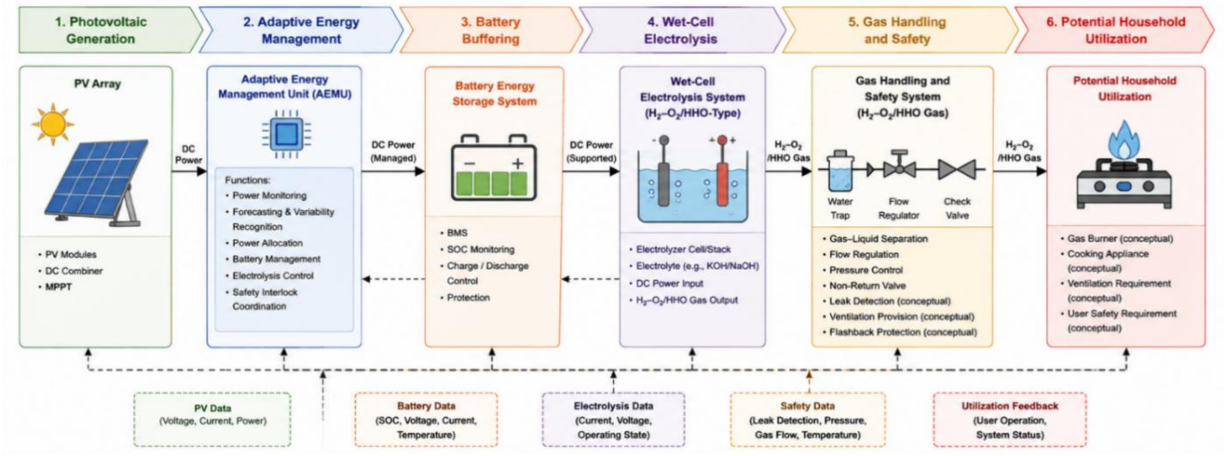

Figure 4. Integrated adaptive solar–electrolysis architecture showing photovoltaic generation, adaptive energy management, battery buffering, wet-cell electrolysis, hydrogen-rich gas handling and safety, and potential household utilization.

coordinated relationship between photovoltaic generation, adaptive energy management, battery buffering, wet-cell electrolysis, hydrogen-rich gas handling, safety provisions, and potential household utilization. The architecture was developed from the functional requirements and is intended to address the temporal mismatch between variable photovoltaic electricity generation and the electrolysis subsystem's electrical demand. The resulting architecture differs from a simple direct-coupled photovoltaic–electrolysis arrangement primarily by introducing an adaptive energy-management layer and finite battery buffering between renewable electricity generation and electrolysis operation. Instead of assuming that the electrical power available from the photovoltaic system remains sufficiently stable for continuous electrolysis, the proposed configuration recognizes that renewable generation varies over time and that this variability must be accommodated through coordinated power allocation.

When photovoltaic generation is sufficient to meet instantaneous electrolysis demand, the available renewable electricity can be directed to electrolysis, while any remaining energy may be allocated to battery charging. When photovoltaic generation temporarily falls below the electrolysis requirement, the adaptive energy-management layer allows the battery to provide supplementary power, provided that sufficient usable stored energy remains available. When the energy deficit persists and the battery reaches its defined minimum operating condition, electrolysis is reduced or transferred to standby operation. This operating relationship provides the proposed architecture's principal system-level contribution. The contribution is not the introduction of new photovoltaic, battery, or electrolysis technology, but the coordination of established functional elements through an adaptive operational framework. Previous studies have demonstrated the integration of renewable generation, electrolysis, and energy storage within coupled hydrogen systems. At the same time, energy-management research has further emphasized coordinated operation under variable renewable-energy conditions [7–10].

The architecture also explicitly incorporates the gas-handling pathway into the system-level design. Because the proposed wet-cell configuration does not assume separation of hydrogen and oxygen, the generated product is treated as an H_2–O_2/HHO-type gas stream rather than experimentally verified pure hydrogen. This distinction influences the subsequent gas-handling and safety requirements and prevents the household application from being interpreted as a conventional pure-hydrogen utilization pathway.

As illustrated in Figure 4, the proposed architecture forms a continuous functional chain from renewable electricity generation to potential end-use utilization. However, the conceptual connection between these subsystems should not be interpreted as evidence of experimentally demonstrated system performance. Each subsystem and its interaction require subsequent engineering validation before practical implementation can be established.

3.2. Functional Assessment of the Proposed Architecture

The functional assessment compared the proposed architecture with the functional requirements established during the conceptual design stage. The assessment focused on whether the architecture defines a mechanism for addressing renewable-energy variability, provides conditional battery-assisted electrolysis operation during temporary energy deficits, defines the generated-gas handling pathway, incorporates proposed safety provisions, and establishes

Table 3. Functional requirement mapping of the proposed adaptive solar–electrolysis architecture.

Functional Requirement	Proposed Functional Response	Assessment
Energy stabilization	Adaptive allocation of photovoltaic power and temporary battery support	Addressed conceptually
Electrolysis continuity	Battery support during temporary photovoltaic deficits	Addressed with finite-duration limitation
Renewable-energy adaptation	Adaptive coordination according to available photovoltaic power	Addressed conceptually
Hydrogen-rich gas generation	Wet-cell electrolysis supplied by coordinated electrical input	Addressed conceptually
Gas handling and safety	Dedicated gas-routing and safety provision layer	Addressed as an engineering requirement
Potential household utilization	Defined downstream utilization pathway	Addressed as a future application

Table 4. Expected functional response under representative renewable-energy conditions.

Renewable-Energy Condition	Primary Energy Pathway	Battery Function	Expected Electrolysis Response	Engineering Interpretation
High availability	PV → Electrolysis	Charging / reserve	Normal conceptual operation	Renewable surplus may be stored
Moderate availability	PV + Battery → Electrolysis	Temporary supplementary supply	Buffered operation	Adaptive coordination becomes important
Low availability	PV + Battery → Electrolysis, subject to SOC	Discharging	Reduced or standby operation when SOC limit is reached	Prolonged deficit cannot be compensated indefinitely

a potential pathway toward decentralized utilization. The resulting functional requirement mapping is presented in Table 3.

The assessment indicates that the principal functional requirements identified during the design stage are represented within the proposed architecture. In particular, the combination of adaptive energy management and battery buffering provides a conceptual mechanism to accommodate short-term differences between photovoltaic generation and electrolysis demand. The significance of this result lies in the explicit relationship established between renewable-energy availability and electrolysis operation. In a direct-coupled configuration, a reduction in photovoltaic output is directly reflected in the electrical power available to the electrolyzer. In the proposed architecture, the same reduction can initially be accommodated through battery discharge when sufficient stored energy is available. This creates a temporary energy-buffering mechanism that may reduce the immediate influence of renewable-energy fluctuations on electrolysis operation.

However, the assessment also identifies a fundamental boundary of the architecture. Battery buffering cannot compensate indefinitely for a sustained renewable-energy deficit because the available stored energy is finite. Therefore, the proposed architecture should be interpreted as a mechanism for managing short-term intermittency rather than eliminating renewable-energy intermittency. This distinction matters because an adaptive control architecture should not be evaluated solely on whether it can maintain operation under favorable conditions. Its engineering value also depends on how explicitly it defines the conditions under which operation must be reduced or suspended. By incorporating a minimum battery operating condition into the adaptive logic, the proposed architecture avoids assuming unlimited energy availability during prolonged low-resource conditions. The functional assessment therefore indicates that the proposed architecture is internally coherent at the conceptual level, while its actual operational feasibility remains subject to future dynamic modelling and experimental testing.

3.3. Adaptive Operating Response under Variable Renewable-Energy Conditions

The conceptual operating response was examined under high-, moderate-, and low-renewable-energy conditions. Because the study does not employ site-specific photovoltaic measurements, these conditions represent illustrative engineering scenarios rather than experimentally measured environmental conditions. The expected functional response of the architecture under these conditions is summarized in Table 4.

The three conceptual operating conditions were interpreted using the illustrative irradiance boundaries: 800–1000 W/m² for high availability, 400–<800 W/m² for moderate availability, and below 400 W/m² for low availability. Under high renewable-energy availability, photovoltaic generation is assumed to provide sufficient

Table 5. Conceptual engineering assessment framework for the proposed adaptive solar–electrolysis architecture.

Indicator	Assessment Dimension	Required Future Data	Intended Interpretation
AESI	Electrical power stability	PV and electrolyzer power time series	Degree of stabilization of electrolysis input
ECI	Electrolysis continuity	Electrolysis operating-state time series	Fraction of required period with acceptable operation
RAF	Renewable-energy adaptability	PV energy, usable battery energy, electrolysis demand	Ability of renewable and stored energy to satisfy demand
ISRI	Integrated operational performance	AESI, ECI, RAF	Combined normalized assessment of energy and operational dimensions

electrical power for the electrolysis subsystem, while excess renewable electricity is directed toward battery charging. In this condition, the battery acts primarily as a reserve that can subsequently support operation when photovoltaic availability decreases.

The moderate-availability condition provides a more informative scenario for examining the proposed adaptive concept because photovoltaic generation is assumed to fluctuate around the electrolysis demand. During temporary reductions in renewable generation, the operating logic permits battery discharge to compensate for the resulting power deficit, provided that the battery remains above the defined minimum SOC and sufficient discharge capacity is available. The adaptive energy-management layer therefore coordinates available photovoltaic power, battery discharge, and electrolysis demand. This condition illustrates the intended operational role of the proposed architecture. Rather than treating the battery simply as an independent storage component, the architecture uses it as a temporary balancing mechanism between renewable generation and electrolysis demand. This coordination aligns with the broader direction of renewable-hydrogen research, where energy storage and energy-management strategies are increasingly considered important for managing variable renewable resources [10].

Under low renewable-energy availability, photovoltaic generation is insufficient to sustain the electrolysis requirement for an extended period. The battery may initially compensate for the deficit, but the available stored energy progressively decreases. Once the minimum allowable state of charge is reached, the proposed operating logic requires reducing electrolysis or transferring it to standby operation. The low-resource scenario therefore illustrates an important boundary condition of the conceptual assessment. The adaptive architecture does not remove electrolysis's fundamental dependence on available energy. Instead, it introduces a mechanism for delaying the effect of short-term renewable-energy deficits while preserving an explicit operating boundary for prolonged deficits. This distinction makes the operating boundary of the proposed concept more explicit because continuous operation is not assumed when the combined renewable and stored energy resources are insufficient.

3.4. Preliminary Engineering Assessment

The preliminary engineering assessment was conducted to evaluate whether the proposed architecture provides a coherent basis for assessing electrical stability, electrolysis continuity, renewable-energy adaptability, and integrated system behavior. The assessment uses four conceptual indicators introduced earlier: the AESI, ECI, RAF, and ISRI. The conceptual assessment framework and the corresponding indicators are summarized in Table 5.

The AESI provides a conceptual means of evaluating whether adaptive energy management and battery buffering reduce the variability of electrical power supplied to the electrolysis subsystem. Its relevance arises from the central problem addressed by the study, namely the variability of photovoltaic electricity. A future experimental or simulation-based assessment could calculate AESI from simultaneous photovoltaic and electrolyzer power measurements and thereby determine the extent to which the adaptive layer stabilizes the electrical input. The ECI addresses a different dimension of system behavior by considering the proportion of the required operating period during which electrolysis remains within its defined operating condition. This indicator is particularly relevant to the proposed architecture because the system is designed to accommodate temporary renewable-energy deficits without assuming that electrolysis can remain operational indefinitely.

The RAF conceptually represents the relationship between available photovoltaic energy, usable battery energy, and electrolysis demand. It therefore connects the energy resources available to the system with the energy required to sustain electrolysis. The ISRI integrates AESI, ECI, and RAF into a single conceptual indicator. However, ISRI is not interpreted as a statistical reliability probability or a certified reliability metric. It represents only the integrated behavior of the three normalized dimensions defined in this study. Safety is intentionally treated separately because assigning a numerical safety score without experimentally validated safety data would introduce an unsupported assumption. No numerical values are assigned to these indicators in the present study because the required time-series electrical and electrolysis measurements are not available. This limitation is important because assigning numerical values to conceptual indicators without supporting data would incorrectly convert a methodological framework into an apparent experimental result. The contribution of these indicators therefore lies in establishing a future assessment structure, rather than claiming measured performance.

3.5. Hydrogen-Rich Gas Characteristics and Safety Implications

The proposed wet-cell electrolysis configuration produces an H_2–O_2/HHO-type gas stream when hydrogen and oxygen are not separately collected. These characteristic matters because the gas cannot be interpreted as experimentally verified pure hydrogen based solely on the theoretical electrolysis reaction. Under ideal water electrolysis, hydrogen and oxygen are produced in a theoretical 2:1 molar ratio. However, this relationship does not establish the actual composition of a practical gas stream. Experimental investigations of HHO systems have shown that gas-production behavior can vary with electrical current, voltage, electrolyte characteristics, and cell configuration [4].

For this reason, the present study does not assign a specific hydrogen concentration, oxygen concentration, gas purity, production rate, pressure, or combustion value to the proposed gas. These parameters remain experimentally undetermined and represent essential subjects for subsequent prototype development. The uncertainty in gas composition also affects the interpretation of the potential household application. A gas stream containing hydrogen and oxygen cannot automatically be treated as equivalent to purified hydrogen supplied through a conventional hydrogen-fuel infrastructure. Its combustion characteristics, flame stability, leakage behavior, and flashback tendency depend on the actual gas composition and operating conditions. Hydrogen-safety studies identify leakage, dispersion, ignition, combustion, and explosion as important engineering considerations [5]. Accordingly, the proposed architecture incorporates gas handling and safety as system-level functions rather than optional downstream components. The conceptual gas-handling pathway is intended to provide controlled routing of the generated gas, water management, flow regulation, and prevention of uncontrolled gas accumulation. Future prototype development would additionally require experimentally validated leak detection, ventilation, ignition-source control, pressure regulation, and flashback protection.

These provisions should not be interpreted as evidence that the proposed architecture has already demonstrated household safety. They instead represent the engineering requirements that must be satisfied before the proposed gas pathway could reasonably progress toward household application. The result of this assessment is therefore primarily a definition of the safety boundary surrounding the proposed concept. The study identifies the relevant hazards and the measurements required to address them, while avoiding unsupported claims of safe household combustion.

3.6. Potential Household Energy Application

The proposed architecture establishes a conceptual pathway linking renewable electricity generation with potential decentralized household energy utilization. The electrolysis subsystem converts photovoltaic electricity into an H_2–O_2/HHO-type gas stream, which is then directed through the gas-handling and safety stage before reaching the potential end-use application. The potential significance of this pathway lies in its ability to connect decentralized renewable electricity with chemical-energy conversion at the point of use. Nevertheless, the present study does not demonstrate household cooking performance and therefore does not claim that the proposed gas can replace conventional household fuels.

Previous studies examining hydrogen for cooking have identified potential benefits associated with low-carbon energy use while also emphasizing the importance of appliance compatibility, safety, energy performance, infrastructure, and techno-economic considerations [6]. These considerations are particularly important for the present concept because the gas generated by the proposed wet-cell system is not assumed to be purified hydrogen. Before household utilization could be considered, the actual gas composition and flow characteristics would need to be established experimentally. These measurements would provide the basis for evaluating burner compatibility, flame stability, thermal performance, leakage behavior, and flashback resistance. The household application would also require appropriate ventilation and operational control because hydrogen-containing gas mixtures can behave differently from conventional gaseous fuels. The gas-generation and utilization pathway would therefore need to incorporate appropriate isolation, emergency shutdown, flow control, and ventilation provisions.

Consequently, the household component of the proposed architecture should be understood as a future application pathway rather than a demonstrated technical result. Accordingly, the household utilization stage is treated as a defined downstream system boundary whose practical implementation depends on experimental gas characterization and safety validation. This distinction prevents the conceptual architecture from being interpreted as evidence that a household cooking system has already been developed or validated.

3.7. Functional Comparison with Existing Approaches

The proposed architecture was further examined against representative renewable-powered electrolysis configurations reported in the recent literature to clarify the functional position of the present concept. The comparison was not intended to establish quantitative superiority in hydrogen production, energy efficiency, reliability, safety, or economic performance because the present study does not provide experimental measurements or a controlled benchmark system. Instead, the comparison focuses on how the principal functional elements are coordinated within the overall system architecture.

Previous studies have demonstrated that renewable-powered hydrogen systems can combine photovoltaic or other renewable-energy sources with electrolysis, energy storage, and downstream energy-conversion components. Abdin et al. emphasized that renewable hydrogen systems require coordinated integration of generation, electrolyzers, storage, and conversion components because their interaction strongly influences system design and operation [7, 9]. Similarly, Alobaid and Adomaitis developed a computational framework for a coupled photovoltaic–electrolysis–battery system. They demonstrated the importance of considering renewable generation, electrolysis demand, battery storage, and system-level operating conditions together [8]. These studies establish an important foundation for integrated renewable-hydrogen system design, but their primary focus differs from the conceptual architecture developed in the present study.

Energy-management research has also addressed coordinating renewable generation, storage, hydrogen technologies, and electrical loads. Van et al. reviewed energy-management strategies for hydrogen-based microgrids. They showed that energy-management systems play an important role in balancing renewable generation, storage, and system demand under variable operating conditions [10]. The present study adopts the same general system-level principle. However, it applies this principle to a more narrowly defined decentralized architecture in which photovoltaic generation, finite battery buffering, wet-cell electrolysis, H_2–O_2/HHO-type gas handling, and a potential household utilization pathway are considered as interconnected functions.

At the electrolysis level, previous studies have shown that wet- and dry-cell HHO production is influenced by electrical current, voltage, electrolyte concentration, temperature, operating time, and cell configuration [4]. These findings support treating the wet-cell subsystem as an experimentally characterized operating component rather than assuming its gas-production performance from theoretical electrolysis alone. Accordingly, the proposed architecture does not claim a specific gas-production rate or efficiency, but instead identifies gas characterization as a necessary future validation stage.

As summarized in Table 6, previous studies provide established foundations for renewable-powered electrolysis, battery-supported hydrogen systems, energy-management strategies, and wet-cell HHO generation [4, 7, 8, 10]. The proposed concept integrates these functions within a single adaptive system boundary that considers variable photovoltaic availability, finite battery buffering, adaptive electrolysis operation, H_2–O_2/HHO-type gas handling, safety requirements, and potential decentralized household utilization. The comparison is qualitative and architectural: “explicitly included” denotes a directly represented component, subsystem, control objective, or requirement; “configuration-dependent” denotes functions that vary with system configuration; and “not identified” denotes functions not reported within the cited system boundary.

This comparison is intended to clarify the architectural scope rather than demonstrate quantitative superiority, since no common experimental benchmark or validated time-series dataset is currently available. It also complements the conceptual assessment framework in Table 5, which defines future quantitative evaluation through AESI, ECI, RAF, and ISRI. Thus, the functional comparison establishes architectural differentiation, whereas the proposed indicators provide a basis for evaluating electrical stability, electrolysis continuity, renewable-energy adaptability, and integrated operational behavior once suitable experimental and time-series data become available.

3.8. Environmental Implications

The proposed architecture may be relevant to decentralized low-carbon energy systems because photovoltaic generation provides the primary electrical input for electrolysis. In principle, renewable electricity can be converted into a hydrogen-containing energy carrier without directly relying on fossil-fuel-derived

Table 6. Functional comparison of representative literature approaches and the proposed adaptive solar–electrolysis architecture.

Evaluation dimension	Renewable-hydrogen hybrid systems [7]	PV–electrolysis–battery systems [8]	Hydrogen-based EMS [10]	Wet-cell HHO studies [4]	Proposed adaptive architecture
Renewable-energy integration	Included	PV–electrolysis coupling	EMS-based integration	Not central	Coordinated PV–battery–electrolysis
Battery buffering	Configuration-dependent	Included	EMS-coordinated	Not primary	Finite short-term buffer
Adaptive energy management	Configuration-dependent	Model/control dependent	Central function	Not identified	Central function
Renewable variability response	Configuration-dependent	Evaluated in modelling	EMS-managed	Operating-condition dependent	PV–battery–electrolysis coordination
Electrolysis continuity	Configuration-dependent	Renewable/battery dependent	EMS-managed	Operating-condition dependent	Managed using battery SOC limits
Wet-cell electrolysis	Configuration-dependent	Electrolyzer dependent	Broad hydrogen technologies	Directly investigated	Wet-cell H_2–O_2/HHO pathway
H_2–O_2/HHO pathway	Configuration-dependent	Hydrogen pathway	Hydrogen-system pathway	Directly investigated	Explicit H_2–O_2/HHO-type pathway
Gas characterization	Configuration-dependent	Model dependent	Not primary	Investigated	Required future validation
Gas safety integration	Application-dependent	Configuration-dependent	Operational consideration	Safety-related conditions considered	System-level requirement
Household utilization	Application-dependent	Not primary	Broader applications	Gas-use applications	Future utilization pathway
System-level coordination	Broad integration	PV–electrolysis–battery integration	Energy-flow coordination	Electrolysis focused	Integrated PV–battery–electrolysis–gas–safety architecture

Note: "Configuration-dependent" indicates that the function depends on the specific system design reported in the cited study. The comparison is qualitative and architectural and does not represent a quantitative performance comparison.

electricity at the point of generation. However, the environmental implications of the proposed architecture cannot be quantified from the present conceptual assessment. No lifecycle assessment, greenhouse-gas inventory, fossil-fuel displacement analysis, battery lifecycle assessment, or water-use assessment was performed. Accordingly, the present study does not claim a specific reduction in greenhouse-gas emissions or a quantified environmental advantage over conventional household energy systems.

The environmental significance of the architecture should instead be regarded as a prospective implication that requires future quantitative investigation. A lifecycle assessment would need to account for the environmental burdens associated with photovoltaic manufacturing, battery production and replacement, electrolyzer materials, water consumption, component lifetime, maintenance, and end-of-life management. The same consideration applies to the household energy pathway. Any environmental benefit from replacing conventional household fuels depends on the amount of conventional energy displaced, the electricity source used to manufacture and operate the system, system lifetime, and the performance of the household end-use device. Therefore, the present study establishes a potential pathway toward renewable-based decentralized energy utilization but does not quantify the environmental benefit.

3.9. Engineering Limitations and Validation Requirements

The conceptual results identify several areas that require further engineering validation before the proposed architecture can progress toward practical implementation. The first limitation concerns the absence of experimental measurements. Without measured photovoltaic, battery, electrolysis, and gas-production data, the proposed indicators cannot yet be assigned numerical performance values. The second limitation concerns the gas stream itself. Because hydrogen and oxygen are not assumed to be separately collected, the actual composition of the H_2–O_2/HHO-type gas remains unknown. Direct measurement of hydrogen concentration, oxygen concentration, total gas flow rate, pressure, temperature, and water-vapor content is therefore required. The third limitation concerns the adaptive control strategy. Although the conceptual operating logic establishes how photovoltaic generation, battery buffering, and electrolysis should interact, the control strategy has not yet been implemented in a physical controller or evaluated against real-time renewable-energy data. The fourth limitation concerns household utilization. The present results do not establish burner performance, flame stability, thermal efficiency, leakage resistance, flashback protection, ventilation requirements, or user safety. The fifth limitation concerns economic and environmental performance. Neither techno-economic analysis nor lifecycle environmental assessment has been performed.

These limitations define a clear pathway for subsequent research. Dynamic modelling should first be conducted using measured or representative photovoltaic time-series data to determine the temporal interaction between PV generation, battery buffering, and electrolysis demand. The resulting model can then be used to calculate AESI, ECI, RAF, and ISRI under different renewable-energy conditions. The next stage should involve controlled prototype development in which electrical performance and gas-production characteristics can be measured directly. Experimental gas characterization should then establish whether the conceptual assumptions concerning the H_2–O_2/HHO-type gas stream are valid under the selected operating conditions. Only after these measurements have been obtained should combustion and household utilization testing be undertaken. This staged approach would allow the conceptual architecture to progress systematically from system-level design toward experimentally validated engineering performance.

3.10. Overall Discussion of the Conceptual Findings

Taken together, the conceptual assessment indicates that the principal engineering issue is not the availability of individual renewable-energy, storage, electrolysis, or gas-handling technologies, but coordinating their operating boundaries under variable renewable input. The energy-balance formulation and illustrative operating scenarios show how PV availability, household electrical demand, battery state of charge, and electrolysis demand can be treated within a common decision framework. The four adaptive operating rules provide a conceptual mechanism for prioritizing direct PV supply, permitting battery-assisted operation within defined SOC limits, reducing electrolysis power when available energy becomes insufficient, and transferring the electrolysis subsystem to standby when minimum operating conditions are no longer satisfied.

The conceptual indicators AESI, ECI, RAF, and ISRI further translate these system objectives into dimensions that can be evaluated quantitatively once time-series electrical and electrolysis data become available. Their current value is therefore methodological rather than evidentiary. Similarly, the H_2–O_2/HHO-type gas pathway establishes an explicit boundary between electrical-to-gas conversion and potential household utilization, but its actual composition, production rate, combustion behavior, and safety performance remain unresolved. The overall assessment therefore supports the internal consistency of the proposed conceptual framework while identifying the specific measurements and modelling activities required to determine whether the architecture provides measurable operational advantages.

4. Conclusions

This study developed a conceptual adaptive solar–electrolysis architecture for decentralized energy applications that integrates photovoltaic generation, battery buffering, wet-cell electrolysis, hydrogen-rich gas handling, safety provisions, and a potential household utilization pathway. The proposed four-rule adaptive strategy coordinates PV supply, battery-assisted operation, electrolysis power reduction, and standby operation according to renewable-energy availability and battery state of charge, providing a conceptual mechanism for managing short-term energy deficits while recognizing the finite capacity of energy storage. The study also introduced four conceptual indicators—AESI, ECI, RAF, and ISRI—for future quantitative evaluation. Since the present study does not include time-series or experimental data, these indicators are not presented as validated performance measures. In addition, the wet-cell configuration produces an H_2–O_2/HHO-type gas stream rather than verified pure hydrogen, making gas composition, production characteristics, and household-use safety unresolved engineering parameters. Therefore, the proposed architecture should be regarded as a preliminary system-level framework; further validation requires time-series modelling, electrical and gas-production characterization, controlled prototype testing, and comprehensive safety assessment.

Author Contributions: Conceptualization, E.Y.; methodology, E.Y. and A.F.; investigation, A.F., A.R.W., M.M, R.F.F., and D.P.N.; resources, E.Y. and A.Z.T.; formal analysis, A.F., A.R.W., and A.S.U.; writing—original draft preparation, A.F.; writing—review and editing, E.Y., A.Z.T., and A.S.U.; visualization, A.F. and D.P.N.; supervision, E.Y.; project administration, E.Y.; All authors have read and agreed to the published version of the manuscript.

Funding: This study does not receive external funding.

Ethical Clearance: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No experimental dataset was generated in this conceptual study. All conceptual assumptions, governing relationships, and assessment formulations are provided within the article.

Conflicts of Interest: All the authors declare no conflicts of interest.

References

1. Al-Ghussain, L., Lu, Z., Alrbai, M., Al-Dahidi, S., He, X., Elgowainy, A., and Wang, M. (2025). Global Techno-Economic and Life Cycle Greenhouse Gas Emissions Assessment of Solar and Wind Based Renewable Hydrogen Production, *Applied Energy*, Vol. 401, 126595. doi:10.1016/j.apenergy.2025.126595.

2. Razi, F., and Dincer, I. (2020). A Critical Evaluation of Potential Routes of Solar Hydrogen Production for Sustainable Development, *Journal of Cleaner Production*, Vol. 264, 121582. doi:10.1016/j.jclepro.2020.121582.

3. Nasser, M., Megahed, T. F., Ookawara, S., and Hassan, H. (2022). A Review of Water Electrolysis–Based Systems for Hydrogen Production Using Hybrid/Solar/Wind Energy Systems, *Environmental Science and Pollution Research*, Vol. 29, No. 58, 86994–87018. doi:10.1007/s11356-022-23323-y.

4. El Soly, A. K., El Kady, M. A., Farrag, A. E. F., and Gad, M. S. (2021). Comparative Experimental Investigation of Oxyhydrogen (HHO) Production Rate Using Dry and Wet Cells, *International Journal of Hydrogen Energy*, Vol. 46, No. 24, 12639–12653. doi:10.1016/j.ijhydene.2021.01.110.

5. Guo, L., Su, J., Wang, Z., Shi, J., Guan, X., Cao, W., and Ou, Z. (2024). Hydrogen Safety: An Obstacle That Must Be Overcome on the Road towards Future Hydrogen Economy, *International Journal of Hydrogen Energy*, Vol. 51, 1055–1078. doi:10.1016/j.ijhydene.2023.08.248.

6. Mukelabai, M. D., Wijayantha, K. G. U., and Blanchard, R. E. (2022). Hydrogen for Cooking: A Review of Cooking Technologies, Renewable Hydrogen Systems and Techno-Economics, *Sustainability*, Vol. 14, No. 24, 16964. doi:10.3390/su142416964.

7. Abdin, Z., Al Khafaf, N., McGrath, B., Catchpole, K., and Gray, E. (2023). A Review of Renewable Hydrogen Hybrid Energy Systems towards a Sustainable Energy Value Chain, *Sustainable Energy & Fuels*, Vol. 7, No. 9, 2042–2062. doi:10.1039/D3SE00099K.

8. Alobaid, A., and Adomaitis, R. A. (2023). Optimal Design of a Coupled Photovoltaic–Electrolysis-Battery System for Hydrogen Generation, *Sustainable Energy & Fuels*, Vol. 7, No. 6, 1395–1414. doi:10.1039/D2SE01555B.

9. Ye, W., Huang, S., Herdem, M. S., Sun, W., Nathwani, J., and Wen, J. Z. (2025). Transformer-Based Predictive Energy Management in Hydrogen-Integrated Renewable Systems, *Energy*, Vol. 341, 139474. doi:10.1016/j.energy.2025.139474.

10. Van, L. P., Chi, K. Do, and Duc, T. N. (2023). Review of Hydrogen Technologies Based Microgrid: Energy Management Systems, Challenges and Future Recommendations, *International Journal of Hydrogen Energy*, Vol. 48, No. 38, 14127–14148. doi:10.1016/j.ijhydene.2022.12.345.

11. El Soly, A. K., Gad, M. S., and El Kady, M. A. (2023). Experimental Comparison of Oxyhydrogen Production Rate Using Different Designs of Electrolyzers, *International Journal of Hydrogen Energy*, Vol. 48, No. 93, 36254–36270. doi:10.1016/j.ijhydene.2023.06.022.

12. Ouabi, H., Lajouad, R., Kissaoui, M., and El Magri, A. (2024). Hydrogen Production by Water Electrolysis Driven by a Photovoltaic Source: A Review, *E-Prime - Advances in Electrical Engineering, Electronics and Energy*, Vol. 8, 100608. doi:10.1016/j.prime.2024.100608.

13. Yandri, E. (2019). Methods for the Development and Testing of Polymeric Hybrid Photovoltaic Thermal (PVT) Collector for Indoor Experiments, *MethodsX*, Vol. 6, 2620–2635. doi:10.1016/j.mex.2019.10.021.

14. Chatenet, M., Pollet, B. G., Dekel, D. R., Dionigi, F., Deseure, J., Millet, P., Braatz, R. D., Bazant, M. Z., Eikerling, M., Staffell, I., Balcombe, P., Shao-Horn, Y., and Schäfer, H. (2022). Water Electrolysis: From Textbook Knowledge to the Latest Scientific Strategies and Industrial Developments, *Chemical Society Reviews*, Vol. 51, No. 11, 4583–4762. doi:10.1039/D0CS01079K.

15. Vethamani, A. B., and Thangavel, V. (2025). Climatic Effects on Solar-Driven HHO Production: An Experimental Insight, *International Journal of Hydrogen Energy*, Vol. 119, 283–293. doi:10.1016/j.ijhydene.2025.03.196.

16. Fadillah, M., Yandri, E., Manihuruk, R., Simanjuntak, R. H., Sumardi, and Ariati, R. (2026). Measurement-Based Energy Modeling and Reliability Assessment of a Hybrid PV–Battery–Diesel Pumping System under Probabilistic Rainfall Extremes, *Measurement: Energy*, Vol. 10, 100105. doi:10.1016/j.meaene.2026.100105.