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Multi-Physics Performance Assessment of Three Lab-Scale Solar-Powered Alkaline Water Electrolyzers for Green Hydrogen Production

Hossam AbdelMeguid *, Omar Alotaibi, Abdulrahman Alshaman and Abdullah Almubarak

Department of Mechanical Engineering, Faculty of Engineering, University of Tabuk, Tabuk 47913, Saudi Arabia; 431002371@stu.ut.edu.sa (O.A.); 431004604@stu.ut.edu.sa (A.A.); 431006075@stu.ut.edu.sa (A.A.)

* Corresponding author. E-mail: hssaleh@mans.edu.eg (H.A.)

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ABSTRACT: Solar-driven alkaline water electrolysis (AWE) is a promising low-cost route to green hydrogen. This study experimentally evaluates three laboratory-scale solar-powered AWE reactors with different tank materials, electrode materials, inter-electrode gaps, and electrolyte concentrations: Design 1 (acrylic, nickel foam, 30 cm, 30 wt% NaOH), Design 2 (plastic, SS316, 13 cm, 7 wt% NaOH), and Design 3 (glass, SS316, 6 cm, 5 wt% NaOH). All reactors were powered by a photovoltaic-battery system and tested under the climate of Tabuk, Saudi Arabia. A unified framework assessed electrical, electrochemical, thermal, energy, exergy, entropy, dimensionless, techno-economic, and environmental performance, and ranked the designs using TOPSIS. Reducing the electrode gap from 30 cm to 6 cm decreased the area-specific resistance from 1103 to 55 $\Omega \cdot \text{cm}^2$ and increased voltage efficiency from 11.6% to 18.6%. Design 3 achieved the highest current density (942 $\text{A} \cdot \text{m}^{-2}$), energy efficiency (18.6%), exergy efficiency (15.4%), gas-collection efficiency (57%), and the lowest specific energy consumption (212 $\text{kWh} \cdot \text{kg}^{-1}$). Its levelized cost of hydrogen decreased from 95 to 23 $\text{USD} \cdot \text{kg}^{-1}$ when projected to a commercial specific energy consumption of 50 $\text{kWh} \cdot \text{kg}^{-1}$. Wagner numbers of 0.03–0.06 indicated ohmic control. Design 3 ranked first (TOPSIS = 1.00). The analysis reproduced reported values within 0.33% while exactly satisfying first- and second-law balances.

Keywords: Green hydrogen; Alkaline water electrolysis; Solar-driven electrolysis; Overpotential; Exergy analysis; Techno-economic analysis; Multi-criteria decision analysis

1. Introduction

The transition from fossil fuels to renewable energy carriers has placed hydrogen at the centre of long-term decarbonisation strategies. Hydrogen produced by water electrolysis using renewable electricity, commonly termed green hydrogen, emits no carbon at the point of production and can store intermittent solar and wind energy in a chemical form suitable for hard-to-abate sectors. A large body of recent work has established the technical and economic feasibility of coupling photovoltaic (PV) generation to

electrolysers, sizing the electrolyser, battery, and storage subsystems, and predicting the delivered hydrogen cost for a wide range of sites and duty profiles [1–3]. These studies consistently show that the electrolyser efficiency and the renewable supply profile, rather than the financing terms, govern the levelised cost of hydrogen [4–6].

System-level research has advanced quickly. Optimal design and operation frameworks have been proposed for grid-connected and off-grid plants, for PV-wind-battery-hydrogen microgrids, and for the integration of hydrogen into wider energy systems and markets [7–9]. Techno-economic and process-design analyses have addressed capacity planning, decentralised production, power-to-methanol, and supply to industrial users, and several reviews have summarised production, transport, and storage pathways [10–12]. The recurring conclusion is that the electrolyser remains the efficiency bottleneck, and that improvements at the cell and reactor level propagate directly into lower cost and higher environmental benefit.

Among the mature electrolysis technologies, alkaline water electrolysis (AWE) is the most established and the least expensive because it avoids platinum-group catalysts and uses inexpensive nickel or stainless-steel electrodes in a potassium- or sodium-hydroxide electrolyte [13–15]. Contemporary AWE research concentrates on four themes: degradation and reverse-current phenomena under the dynamic operation imposed by renewable supply [13,14,16,17]; parametric and dynamic modelling from single cells to industrial stacks [15,18–20]; electrode and catalyst development for the hydrogen-evolution reaction [21–23]; and the techno-economic, safety and life-cycle assessment of AWE plants, including temperature effects and pilot demonstrations at the 25 kW and 250 kW scale [24–28]. This literature confirms that the cell voltage of an alkaline electrolyser is dominated by ohmic losses arising from the inter-electrode gap, the electrolyte conductivity, and the gas void fraction, and that reducing these losses is the principal route to higher efficiency [29–33].

The present study builds on a sustained research effort by the present author and co-workers on solar-driven green hydrogen for the Kingdom of Saudi Arabia. At the system level, a battery-buffered production unit was shown to decouple hydrogen generation from solar intermittency and to stabilise electrolyser operation [34]. The long-term behaviour of such systems was then studied within a degradation-aware framework: one techno-economic study identified operating strategies that preserve the lifetime value of solar-powered alkaline electrolysers [35], and a companion study quantified how electrolyser degradation propagates to the system-level solar-to-hydrogen efficiency and lifetime performance [36]. In parallel, the underlying resource and production route were characterised for the Kingdom, covering the solar-energy availability of the NEOM region [37] and green-hydrogen production from solar-driven seawater electrolysis [38]. These contributions rested on modelling and simulation; the present paper complements them with a controlled experimental comparison of three physically constructed lab-scale reactors, connecting the group's system-level studies to reactor-level measurement.

Despite this progress, most published work is either simulation-based or directed at industrial-scale hardware. Experimental studies that build several physical reactors and quantify, on a common footing, how basic construction choices—tank material, electrode material, inter-electrode gap, and electrolyte concentration—translate into electrical, electrochemical, thermal, second-law, economic, and environmental performance are scarce. In particular, laboratory prototypes are seldom analysed with a single, internally consistent framework that closes the energy and exergy balances and that ranks competing designs objectively. To the author's knowledge, no prior study reports a lab-scale, solar-powered AWE comparison in which three reactors spanning a wide range of gaps (30, 13, and 6 cm) and electrolyte concentrations (30, 7, and 5 wt% NaOH) are evaluated with a verified multi-physics pipeline and reduced to a single multi-criteria ranking.

The objective of this paper is to close that gap. Three lab-scale AWE reactors were designed, fabricated, and operated under the high-insolation climate of Tabuk, Saudi Arabia, each supplied by a PV-battery source and instrumented to measure current, voltage, power, and hydrogen volume. The measured data

were processed through a unified analysis pipeline that evaluates, for every reactor, the electrical characteristics, the Faradaic hydrogen production, the overpotential decomposition and effective resistance, the energy balance and transient thermal response, the exergy and entropy generation, a full set of transport and electrochemical dimensionless groups, the scaled techno-economics, the environmental mitigation, the solar resource and PV-coupled potential, and a data-driven model of the hydrogen production rate. The designs are compared on an equal electrochemical basis and ranked by the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS). The purpose is to identify which construction choices most strongly control performance and to provide a preliminary basis for scale-up.

The remainder of the paper is organised as follows. Section 2 describes the three reactor designs, their fabrication, and the solar-powered test rig. Section 3 presents the mathematical model underlying the analysis. Section 4 reports and discusses the results across all analysis layers, along with pipeline validation. Section 5 draws the main conclusions and states the design recommendations.

2. Materials and Methods

2.1. Reactor Designs and Fabrication

Three alkaline water electrolyser reactors were built in sequence, each intended to correct the limitations observed in its predecessor. They are identified throughout by their tank construction—Acrylic (Design 1), Plastic (Design 2), and Glass (Design 3)—because the source records use inconsistent numeric labels. The three configurations differ in tank material, electrode material, inter-electrode gap, electrolyte concentration, and gas-collection arrangement; their principal specifications are summarised in Table 1, and their computer-aided design representations are shown in Figure 1.

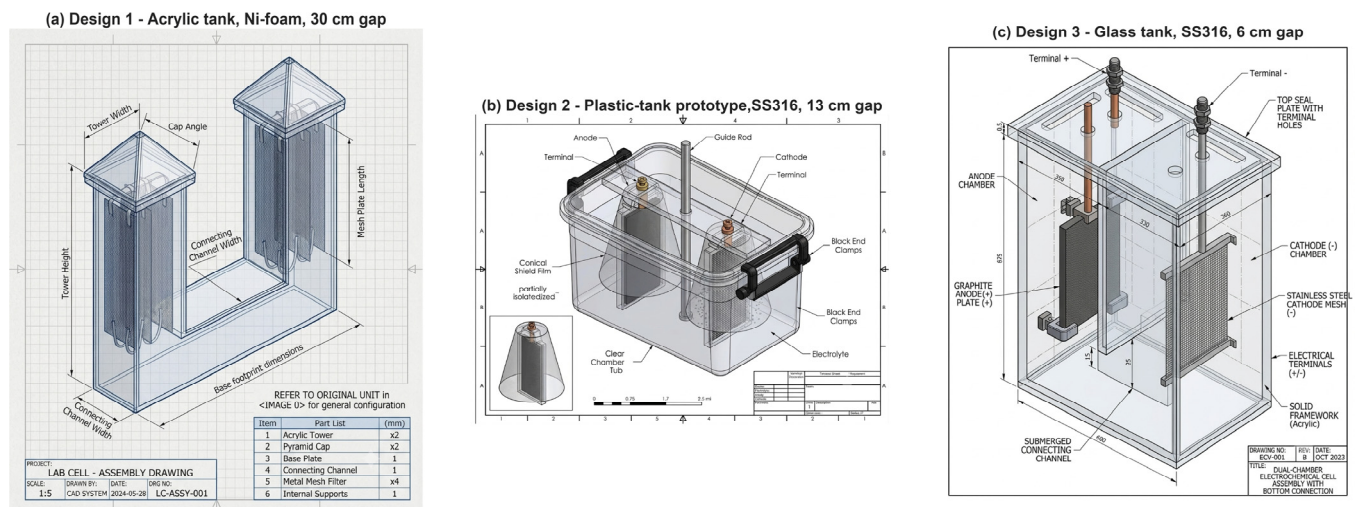


Figure 1. Computer-aided design of the three lab-scale AWE reactors: (a) Design 1, acrylic Hoffmann-type cell with nickel-foam electrodes and a 30 cm gap; (b) Design 2, plastic-tank prototype with SS316 electrodes and a 13 cm gap; (c) Design 3, sealed dual-chamber glass reactor with SS316 electrodes and a 6 cm gap.

Table 1. Construction, geometry and operating parameters of the three AWE reactors.

Parameter	Design 1 (Acrylic)	Design 2 (Plastic)	Design 3 (Glass)
Tank material	Acrylic (PMMA)	Plastic (PP)	Glass
Electrode material	Nickel foam	Stainless steel 316	Stainless steel 316
Inter-electrode gap	30 cm	13 cm	6 cm
NaOH concentration	30 wt%	7 wt%	5 wt%
Electrolyte volume	4.1 L	4.5 L	3.75 L
Gas collection	Transparent hoods	Inverted bottles	Sealed partitioned cover
Test duration	—	66 min	52 min

Leakage observed	No	Yes	No
Overall rating	Poor	Moderate	Excellent

Design 1 was constructed as a transparent Hoffmann-type cell from precision-cut acrylic (PMMA) sheets joined by thermal bonding and sealed with acetic silicone. Two vertical reaction chambers share a common electrolyte reservoir at the base, giving an effective volume of about 4.1 L, and transparent hoods at the top of each chamber collect the evolved gases. The electrodes were fabricated from three stacked layers of nickel foam connected by soldered nickel strips to increase the active area, and were suspended on non-conductive supports at a wide separation. The wide gap and the highly concentrated 30 wt% NaOH electrolyte were selected for chemical stability, but, as shown later, produce a large series resistance.

Design 2 was an intermediate plastic prototype built from a transparent rectangular container to evaluate the electrochemical behaviour, gas-collection mechanism, and hydraulic performance at low cost before committing to a permanent reactor. Hydrogen and oxygen were captured by inverted plastic bottles acting as buoyancy-driven collection hoods, and stainless-steel 316 plates replaced the nickel foam. The gap was reduced to 13 cm, and the electrolyte diluted to 7 wt% NaOH. The prototype confirmed the operating principle but suffered from imprecise electrode alignment and limited sealing, which increased internal resistance and led to intermittent gas collection and occasional leakage.

Design 3 was a permanent glass reactor built to improve structural rigidity, gas containment, safety, and measurement reliability. Clear glass panels were bonded into a rectangular tank of about 3.75 L and divided by an internal vertical partition into anodic and cathodic compartments that share the lower electrolyte region, minimising gas cross-over. A rigid cover sealed with silicone carries the electrode terminals, gas-extraction lines, and instrumentation ports, and a secondary cylindrical vessel serves as a bubbler and liquid-level balance. The stainless-steel 316 electrodes were fixed at a narrow 6 cm separation, and the electrolyte was further diluted to 5 wt% NaOH. This combination of a narrow gap, a compartmentalised sealed geometry, and dilute electrolyte gave the lowest series resistance and the best overall performance.

2.2. Solar-Powered Test Rig and Instrumentation

Each reactor was operated as a fully integrated renewable hydrogen platform. Electrical power was supplied by a photovoltaic array feeding a maximum-power-point-tracking (MPPT) charge controller and a rechargeable battery bank, which stabilised the DC bus against solar transients and allowed continuous electrolyser operation under variable irradiance. A microcontroller-based data-acquisition system (Arduino GIGA R1 WiFi) logged the electrical and environmental signals. Current and voltage were measured with INA226 sensors connected through external 100 A/75 mV shunts on the PV, battery, and electrolyser buses; electrolyte level was monitored with an ultrasonic sensor, and a real-time-clock module provided synchronised timestamps for local storage on a microSD card. High-current power lines were routed separately from low-voltage signal wiring to limit measurement noise. The hydrogen volume in the glass reactor was determined by water displacement.

2.3. Experimental Procedure and Comparison Basis

Experiments were conducted under the daytime climate of Tabuk (28.4° N, 36.5° E). After leak, continuity, and insulation checks, the electrolyte was introduced, and each reactor was operated for a continuous run while all channels were logged at 30 s intervals. Because the collected-gas volume was measured only for the glass reactor, all cross-design performance indicators are evaluated on the Faraday (theoretical) production basis, so that the three reactors are compared on an equal electrochemical footing. The measured collected volume of the glass reactor is retained separately to quantify its gas-collection (Faradaic) efficiency and to anchor the validation.

3. Theory and Mathematical Model

This section collects the governing relations used in the analysis. Symbols are defined at first use and are listed in the Nomenclature. The framework proceeds from the reference thermodynamics of water splitting to the electrical, electrochemical, thermal, second-law, dimensionless, economic, and environmental descriptions, and closes with the statistical model and the multi-criteria ranking.

3.1. Reference Thermodynamics

The overall electrolysis reaction and its reversible and thermoneutral voltages fix the thermodynamic limits of the process. Water is decomposed as



and the reversible cell voltage and thermoneutral voltage follow from the Gibbs energy and enthalpy of reaction,

$$E_{\text{rev}} = \frac{\Delta G}{zF} = 1.229 \text{ V}, \quad E_{\text{tn}} = \frac{\Delta H}{zF} = 1.481 \text{ V} \quad (2)$$

with $z = 2$ electrons per hydrogen molecule and F the Faraday constant; the reaction entropy is $\Delta S = \frac{\Delta H - \Delta G}{T_0} = 163.3 \text{ J mol}^{-1}\text{K}^{-1}$. The measured terminal voltages of all three reactors (about 8–13 V) greatly exceed E_{tn} , so every cell operates in the strongly irreversible, exothermic regime, which motivates the thermal, exergy, and entropy analyses below.

3.2. Electrical Characterisation and Faradaic Production

Instantaneous power, cumulative charge, and cumulative energy are obtained from the logged current and voltage,

$$P(t) = V_{\text{cell}}(t) I(t), \quad Q(t) = \int_0^t I \, dt', \quad E_{\text{el}}(t) = \int_0^t P \, dt' \quad (3)$$

evaluated by the trapezoidal rule. The current density is $j = I/A_{\text{el}}$, and a current-weighted representative voltage $V_{\text{rep}} = \frac{\sum n V_n I_n}{\sum n I_n}$ is used for efficiency accounting because it reflects the operating point at which most charge, and therefore most hydrogen, is produced. By Faraday's law the molar and volumetric hydrogen production are

$$n_{\text{H}_2}(t) = \frac{Q(t)}{zF}, \quad V_{\text{H}_2} = \frac{n_{\text{H}_2} R T_0}{p_0} \quad (4)$$

The gas-collection (Faradaic) efficiency, measured for the glass reactor from the water-displacement volume, is $\eta_F = \frac{V_{\text{H}_2}^{\text{meas}}}{V_{\text{Faraday}}}$. The specific energy consumption is $\text{SEC} = E_{\text{el}}/m_{\text{H}_2}$.

3.3. Overpotential Decomposition and Effective Resistance

The terminal voltage is resolved into its thermodynamic, activation, and ohmic contributions,

$$V_{\text{cell}} = E_{\text{rev}} + \eta_{\text{act}} + \eta_{\text{ohm}} \quad (5)$$

A small Tafel-type activation term is assumed, and the remainder is attributed to a lumped ohmic/series resistance so that the decomposition closes exactly. The area-specific resistance and the effective ionic conductivity then follow from the current-weighted means. This partition assumes the activation term rather than measuring it, so the implied ohmic dominance is an engineering estimate; independent electrochemical

measurements, for instance, impedance spectroscopy or a three-electrode polarisation, would be required to confirm it.

$$\text{ASR} = \frac{\eta_{\text{ohm}}}{j}, \quad \kappa_{\text{eff}} = \frac{d_{\text{gap}}}{\text{ASR}} \quad (6)$$

where d_{gap} is the inter-electrode gap. The gas void fraction is represented by $\varepsilon = \min(0.0119\sqrt{j}, 0.60)$, which raises the effective resistance through a Bruggeman correction. The current distribution is characterised by the Wagner number $\text{Wa} = \frac{\kappa b}{d_{\text{gap}} j}$; $\text{Wa} \ll 1$ indicates ohmically controlled, non-uniform current distribution.

3.4. Energy Balance and Transient Thermal Model

On the Faraday basis, the first-law balance closes exactly, $P_{\text{el}} = E_{\text{tn}} I + \dot{Q}_{\text{gen}}$, so the useful (higher heating value) chemical power is $E_{\text{tn}} I$ and the electrochemical heat-generation rate is $\dot{Q}_{\text{gen}} = (V_{\text{cell}} - E_{\text{tn}}) I$. A lumped-capacitance model predicts the electrolyte temperature, no temperature having been measured,

$$m c_p \frac{dT}{dt} = \dot{Q}_{\text{gen}} - U A_s (T - T_{\infty}) - \varepsilon_s \sigma A_s (T^4 - T_{\infty}^4) \quad (7)$$

with m the electrolyte mass, A_s the tank surface area, U the external convective coefficient, and ε_s the wall emissivity. Natural convection is described by the Churchill-Chu vertical-plate correlation, and the thermal time constant is $\tau = \frac{m c_p}{U A_s}$.

3.5. Exergy and Entropy Generation

Electrical energy is pure exergy; the useful output is the chemical exergy of the produced hydrogen ($ex_{\text{ch}} = 236.09 \text{ kJ} \cdot \text{mol}^{-1}$) and the balance is destroyed. The exergy efficiency and, by the Gouy-Stodola theorem, the entropy-generation rate are

$$\eta_{\text{ex}} = \frac{Ex_{\text{H}_2}}{Ex_{\text{in}}}, \quad \dot{S}_{\text{gen}} = \frac{Ex_{\text{dest}}}{T_0} \quad (8)$$

The entropy budget is split into ohmic and activation sources, and the Bejan ratio $\text{Be} = \frac{\dot{S}_{\text{ohm}}}{\dot{S}_{\text{ohm}} + \dot{S}_{\text{act}}}$ measures the ohmic share of the irreversibility.

3.6. Dimensionless Groups

The governing physics is compressed into scale-independent form. The transport and free-convection groups include the Prandtl, Schmidt, Rayleigh, and Nusselt numbers,

$$\text{Pr} = \frac{\nu}{\alpha}, \quad \text{Sc} = \frac{\nu}{D}, \quad \text{Ra} = \frac{g \beta \Delta T L^3}{\nu \alpha}, \quad \text{Nu} = \frac{h L_c}{k} \quad (9)$$

the bubble two-phase dynamics are described by the bubble Reynolds, Eotvos, and Sherwood numbers ($\text{Sh} = 2 + 0.6 \text{Re}_b^{1/2} \text{Sc}^{1/3}$, Ranz-Marshall), and the electrochemical/second-law behaviour by the dimensionless voltage $U^* = V_{\text{cell}}/E_{\text{rev}}$, the Wagner number and the Bejan ratio are defined above.

3.7. Efficiency Hierarchy, Techno-Economics and Environment

The voltage and energy efficiencies are $\eta_V = E_{\text{tn}}/V_{\text{rep}}$ and $\eta_{\text{en}} = \frac{m_{\text{H}_2} \text{HHV}}{E_{\text{el}}}$, while the demonstrated system efficiency of the glass reactor is $\eta_{\text{system}} = \eta_V \eta_F$. Each lab cell is scaled to a nominal 5 kW stack of N parallel cells, and the levelised cost of hydrogen is

$$\text{LCOH} = \frac{\text{CRF} \cdot \text{CAPEX} + \text{OPEX}}{\dot{m}_{\text{H}_2}^{\text{yr}}}, \quad \text{CRF} = \frac{i(1+i)^L}{(1+i)^L - 1} \quad (10)$$

with discount rate i and project life L . Net-present value, benefit-cost ratio, and payback follow from the annual cash flow, a commercial projection recomputes LCOH at a target SEC of $50 \text{ kWh} \cdot \text{kg}^{-1}$, and a Monte-Carlo study (2×10^4 samples) propagates $\pm 20\%$ CAPEX, $\pm 15\%$ production, and discount/operating spreads. The annual net CO_2 mitigation of the scaled system is

$$\dot{M}_{\text{CO}_2}^{\text{net}} = \dot{m}_{\text{H}_2}^{\text{yr}} (e_{\text{SMR}} - e_{\text{solar}}) \quad (11)$$

with $e_{\text{SMR}} = 10 \text{ kg} \cdot \text{kg}^{-1}$ (displaced grey hydrogen) and $e_{\text{solar}} = 1.5 \text{ kg} \cdot \text{kg}^{-1}$ (embodied). Finally, the three designs are ranked by TOPSIS: after vector normalisation and weighting of the benefit and cost criteria, the closeness coefficient $C_i = \frac{d_i^-}{d_i^+ + d_i^-}$ orders the reactors, $C_i = 1$ being the best.

4. Results and Discussion

The results are presented in the order of the analysis pipeline. Table 2 collects the key performance indicators of the three reactors on the Faraday basis, and the subsequent figures develop each layer of the comparison. Unless stated otherwise, quantities are current-weighted means over the logged run.

Table 2. Key performance indicators of the three AWE reactors (Faraday production basis).

KPI	Design 1 (Acrylic)	Design 2 (Plastic)	Design 3 (Glass)
Average current, I (A)	0.995	3.24	9.42
Average power, P (W)	12.7	37.7	75.0
Current density, j ($\text{A} \cdot \text{m}^{-2}$)	99.5	324	942
Representative voltage, V (V)	12.8	11.6	7.96
Voltage efficiency, η_V (%)	11.6	12.7	18.6
Energy efficiency HHV, η_{en} (%)	11.6	12.7	18.6
Exergy efficiency, η_{ex} (%)	9.56	10.5	15.4
Specific energy, SEC ($\text{kWh} \cdot \text{kg}^{-1}$)	340	309	212
Heat generation, Q_{gen} (W)	11.3	32.9	61.1
Faraday H ₂ (mL)	394	1627	3725
Predicted final temperature ($^{\circ}\text{C}$)	31.7	35.7	40.4

4.1. Electrical Characterisation

Figure 2 shows the transient electrical behaviour of the reactors. The current and power traces are strongly intermittent, the dips reflecting the solar-battery supply transients captured by the MPPT bus. The glass reactor draws by far the largest current, with an average of 9.42 A and a mean current density of $942 \text{ A} \cdot \text{m}^{-2}$, roughly an order of magnitude above the acrylic cell (0.995 A, $99.5 \text{ A} \cdot \text{m}^{-2}$); the plastic reactor is intermediate at 3.24 A. The higher current density of the glass reactor is the primary reason for its superior hydrogen output, and its cumulative energy grows almost linearly over the run. Duty cycles between 82% and 99% confirm that the reactors operate under realistic solar intermittency rather than at a fixed set point.

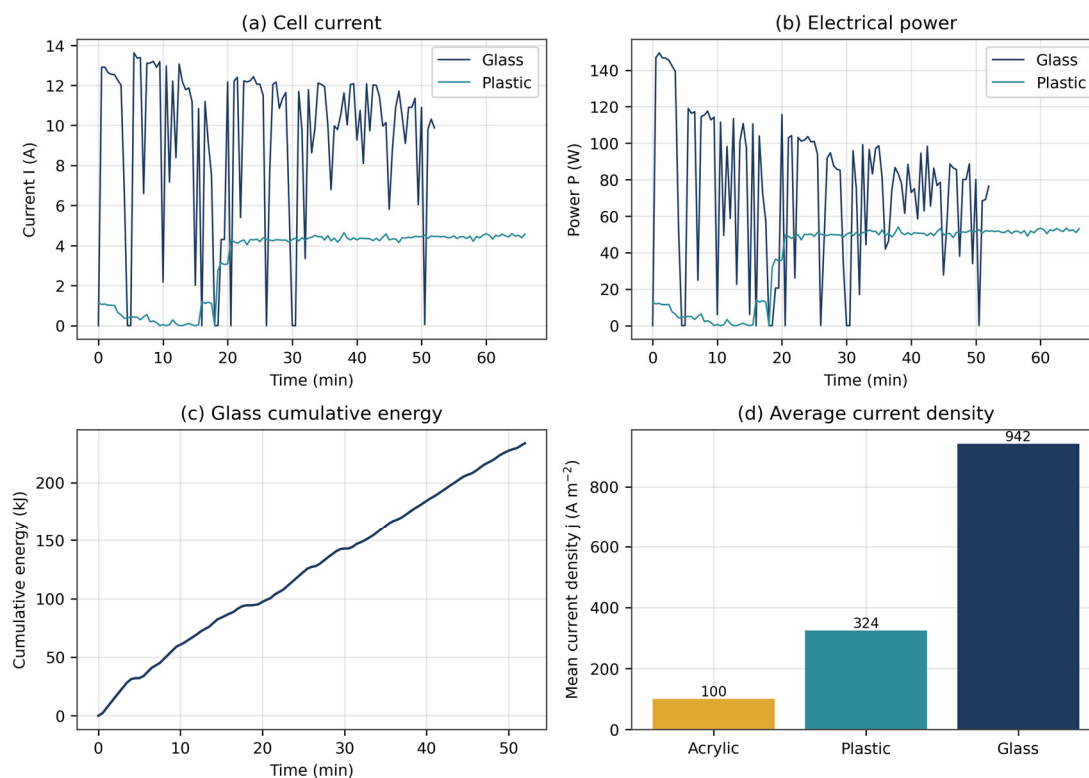


Figure 2. Electrical performance of the three reactors: (a) cell current, (b) electrical power, (c) glass cumulative energy, and (d) average current density per design.

4.2. Hydrogen Production and Faradaic Efficiency

Figure 3 presents the hydrogen production. On the Faraday basis, the glass reactor produces the most hydrogen (3725 mL, 0.31 g), followed by the plastic (1627 mL) and acrylic (394 mL) reactors, the ordering following that of the current density. For the glass reactor, the measured collected volume of 2130 mL lies about 43% below the Faraday line, giving a gas-collection (Faradaic) efficiency of 57%; the missing hydrogen is lost to cross-over, dissolution, recombination, and imperfect sealing, which is a system loss distinct from the reactor electrochemistry. The specific energy consumption falls from 340 to 212 kWh·kg⁻¹ as the design improves, driven by the higher voltage efficiency of the narrow-gap glass cell. Productivity per electrode area and per unit energy rank Glass > Plastic > Acrylic, confirming the benefit of the narrow gap and stainless-steel electrodes. These mechanisms were not experimentally separated, so the 43% shortfall is reported as a single collection loss, and its decomposition is left to future work using sealed-cell gas analysis. On a collected-hydrogen basis, the glass reactor corresponds to a higher heating value efficiency of the order of 10.6% and a specific energy consumption of the order of 371 kWh·kg⁻¹; since collection was measured only for this reactor, the cross-design comparison is necessarily made on the Faraday basis and does not establish the collected-hydrogen efficiency of the other two designs.

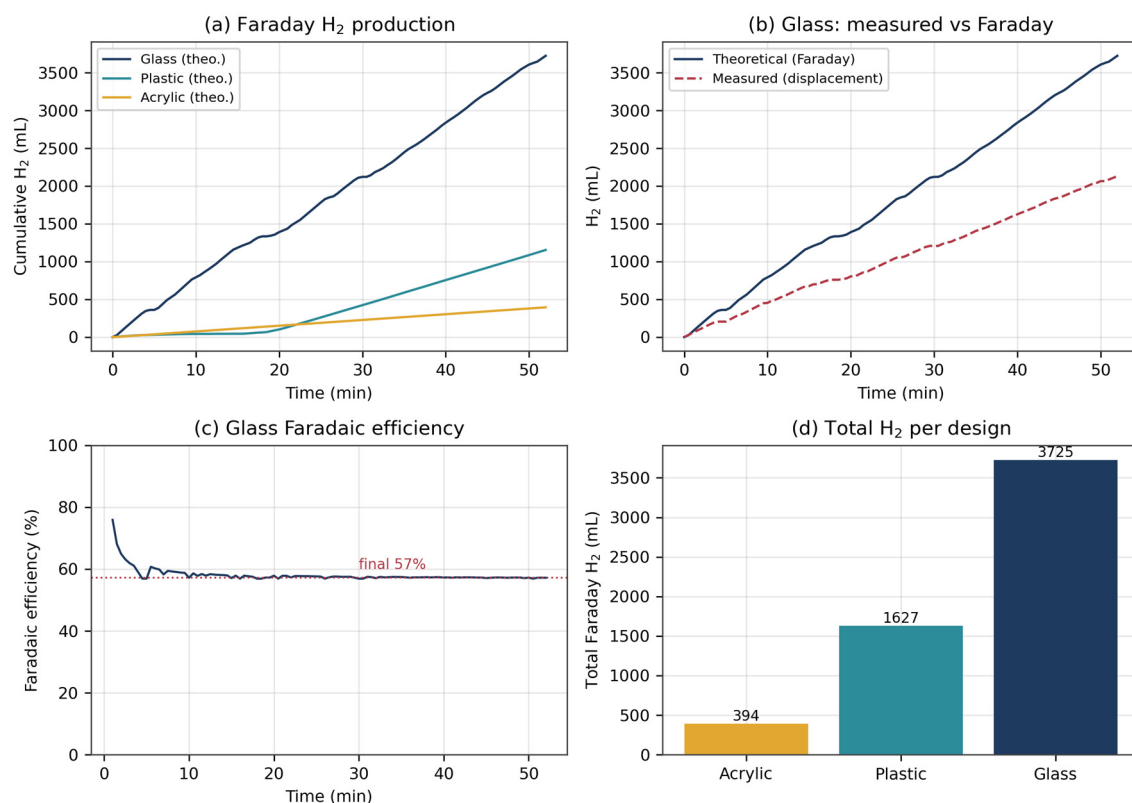


Figure 3. Hydrogen production: (a) cumulative Faraday production of the three reactors; (b) measured versus Faraday volume for the glass reactor; (c) transient Faradaic efficiency of the glass reactor; (d) total Faraday hydrogen per design.

4.3. Energy Balance and Thermal Response

Figure 4 shows the energy partitioning and the predicted thermal response. Because the terminal voltage far exceeds the thermoneutral value, most of the electrical input is dissipated as heat: the glass reactor generates about 61 W of heat against 75 W of input. The lumped-capacitance model predicts modest final electrolyte temperatures of 31.7, 35.7, and 40.4 °C for the acrylic, plastic, and glass reactors, the glass reactor being warmest because it processes the most power in the smallest volume. Thermal time constants of tens of minutes, comparable with the run duration, mean that the experiments are genuinely transient and that bulk boiling is not a concern.

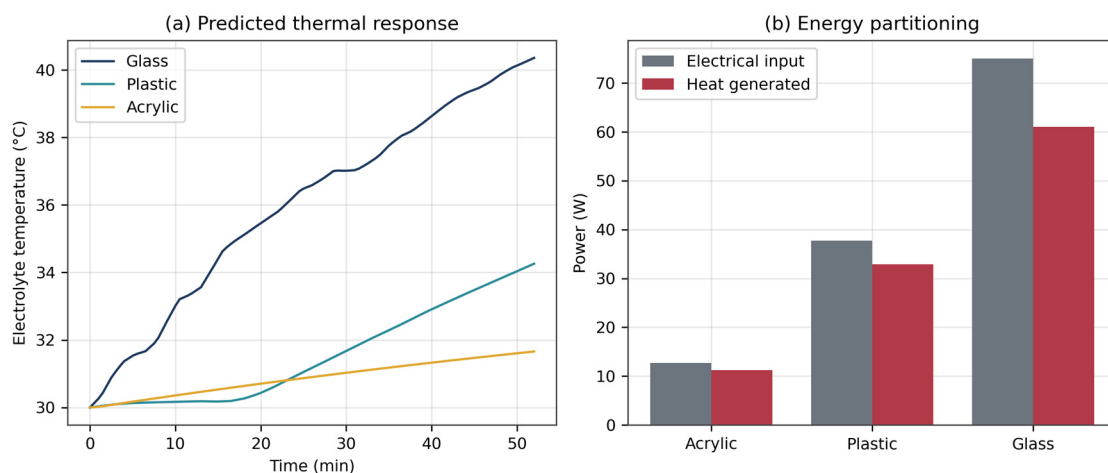


Figure 4. (a) Predicted electrolyte temperature of the three reactors from the lumped-capacitance model; (b) electrical input versus electrochemical heat generation per design.

4.4. Exergy and Entropy Generation

The second-law results are given in Figure 5. The exergy efficiency is low for every reactor and increases with design quality, from 9.6% (acrylic) through 10.5% (plastic) to 15.4% (glass). The cumulative entropy generation of the glass reactor grows steadily over the run, and the Bejan ratio of 0.90–0.95 for all designs shows that the irreversibility is overwhelmingly ohmic, that is, Joule dissipation in the electrolyte and series path rather than activation. The glass reactor destroys the most exergy in absolute terms because it processes the most power, but its relative destruction is comparable with the others, so the second-law penalty is a property of the shared electrochemistry and is reduced by the same measures that reduce the ohmic loss.

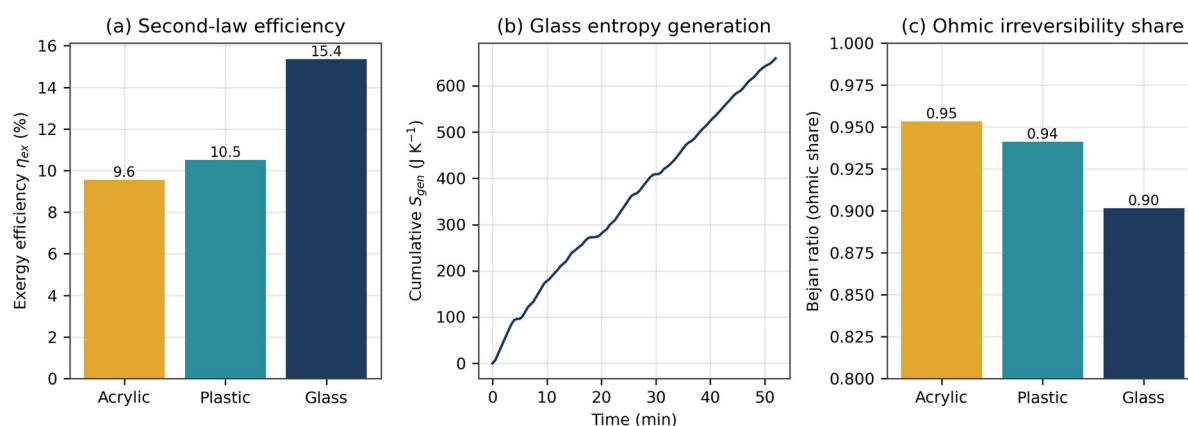


Figure 5. Second-law analysis: (a) exergy efficiency per design; (b) cumulative entropy generation of the glass reactor; (c) Bejan ratio quantifying the ohmic share of the irreversibility.

4.5. Overpotential and Electrochemistry

Figure 6 decomposes the terminal voltage and quantifies the series resistance. The measured voltage greatly exceeds the reversible value, and once the thermodynamic and assumed activation terms are removed, the remainder is a large ohmic overpotential. Narrowing the gap from 30 cm (acrylic) to 6 cm (glass) reduces the area-specific resistance from 1103 to 55 $\text{ohm}\cdot\text{cm}^2$ and raises the effective ionic conductivity from about 2.7 to 7.2 $\text{S}\cdot\text{m}^{-1}$, which is exactly why the glass reactor attains the highest voltage efficiency. The Wagner number is well below unity for every design (0.032–0.060), the compact statement that the current distribution is ohmically controlled and non-uniform. This single finding ties together the electrochemical, thermal, and second-law results: the inter-electrode gap and the electrolyte conductivity are the dominant levers on performance. This effective conductivity is a lumped quantity extracted from the series resistance and includes contact, wiring, geometric, and bubble contributions; it is not the intrinsic electrolyte conductivity, which for alkaline hydroxide solutions is of the order of tens of $\text{S}\cdot\text{m}^{-1}$ across the 5–30 wt% range at ambient temperature [39]. In fact, the extracted values lie in the order of a decade below those of the bulk electrolyte, and their ordering reflects the narrow gap of the glass cell dominating the series path rather than a higher conductivity of the more dilute 5 wt% electrolyte. Because the tank material, electrode material, gap, and electrolyte concentration change together across the three reactors, these effects cannot be separated from the present data; the comparison is between complete designs, and isolating the gap alone would require a single-variable series at fixed electrode and electrolyte, which is left to future work.

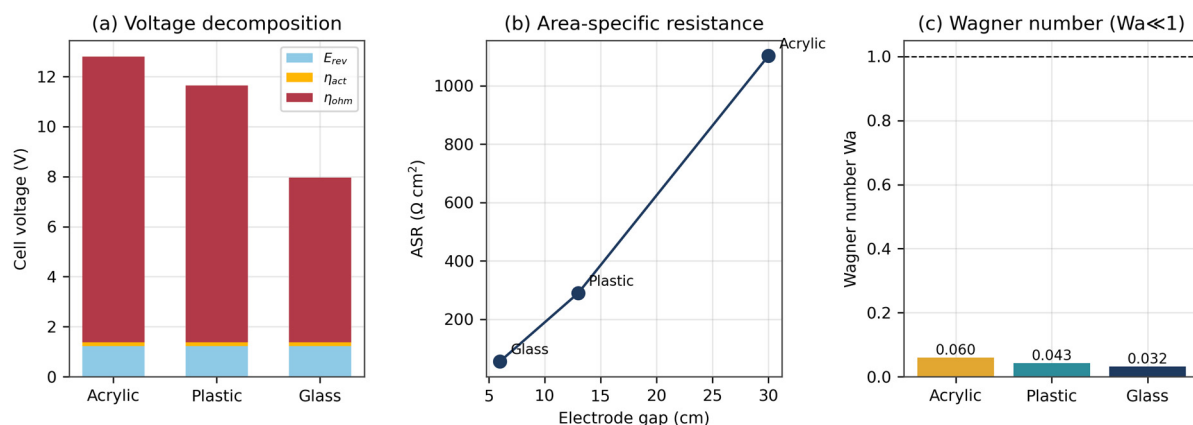


Figure 6. Electrochemistry: (a) decomposition of the cell voltage into reversible, activation and ohmic terms; (b) area-specific resistance versus electrode gap; (c) Wagner number for the three reactors.

4.6. Dimensionless Analysis

The dimensionless description is summarised in Table 3 and Figure 7. The Prandtl (about 6.8) and Schmidt (about 198) numbers are typical of an aqueous alkaline electrolyte. The Rayleigh number of order 10^8 – 10^9 places the electrolyte in the turbulent free-convection regime driven by Joule heating and bubble rise, and it grows with reactor throughput from 3.5×10^8 (acrylic) to 1.2×10^9 (glass). The bubble Reynolds number of about 111 with an Eotvos number below unity indicates small, near-spherical bubbles in the inertial-capillary regime, and the Sherwood number of about 39 reflects convection-enhanced dissolved-gas transport. The gas void fraction rises from 0.12 to 0.38 as the current density increases, and the Wagner number remains below unity throughout, reinforcing the conclusion of ohmic control.

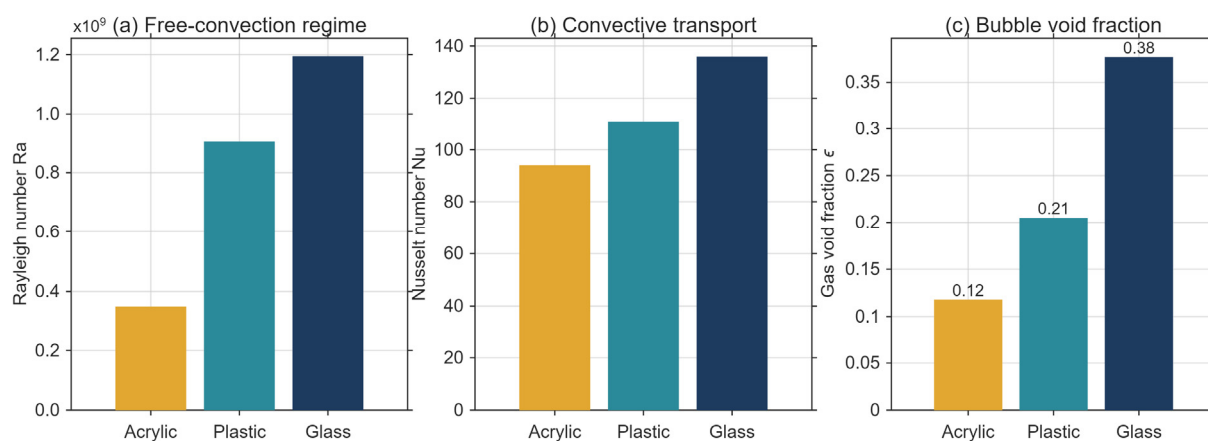


Figure 7. Dimensionless groups across the three reactors: (a) Rayleigh number; (b) Nusselt number; (c) gas void fraction.

Table 3. Representative dimensionless groups of the three reactors.

Group	Design 1 (Acrylic)	Design 2 (Plastic)	Design 3 (Glass)
Prandtl, Pr	6.80	6.80	6.80
Schmidt, Sc	198	198	198
Rayleigh, Ra	3.50×10^8	9.04×10^8	1.20×10^8
Nusselt, Nu	94.2	111	136
Bubble Reynolds, Re_b	111	111	111
Sherwood, Sh	38.9	38.9	38.9
Gas void fraction, ϵ	0.119	0.206	0.377
Wagner, Wa	0.060	0.043	0.032
Bejan ratio, Be	0.953	0.941	0.902

4.7. Techno-Economic Analysis

Figure 8 and Table 4 report the scaled techno-economics for a nominal 5 kW stack per design. At the as-measured efficiency, the levelised cost of hydrogen is high—355, 168, and 95 USD·kg^{−1} for the acrylic, plastic, and glass reactors—because the experimental specific energy consumption (about 212 kWh·kg^{−1} for the best reactor) is roughly four to eight times the commercial target. Projecting the glass reactor to a commercial SEC of 50 kWh·kg^{−1} collapses its levelised cost to about 23 USD·kg^{−1}. The Monte-Carlo distribution for the glass reactor has a 90% interval of about 38–98 USD·kg^{−1}, and the sensitivity is governed by production efficiency and CAPEX rather than by the financing terms. The engineering implication is unambiguous: cost is reduced by narrowing the gap and improving the electrodes, that is, by moving toward the glass design, not by re-financing. This 50 kWh·kg^{−1} figure is a hypothetical benchmark drawn from commercial practice, not a performance demonstrated by the present reactors.

The stack projection assumes N identical cells operating at the measured mean cell power, with the cell geometry, electrode area, and electrolyte held at their bench values; the number of parallel cells then follows from the rated power:

$$N = \frac{P_{\text{sys}}}{\bar{P}} \quad (12)$$

where $P_{\text{sys}} = 5$ kW is the rated stack power, and the mean cell power is the run average, so N is the only scale variable, and the balance-of-plant is not resolved. A rigorous scale-up would raise the total electrode area with power and add gas–liquid separators, lye circulation, a rectifier, and thermal management; commercial alkaline stacks operate at current densities of the order of 2000–6000 A·m^{−2} and cell voltages of 1.8–2.0 V [31,32], well above the present unoptimised cells. Hence, the 5 kW figures are a first-order projection and not a demonstrated stack design.

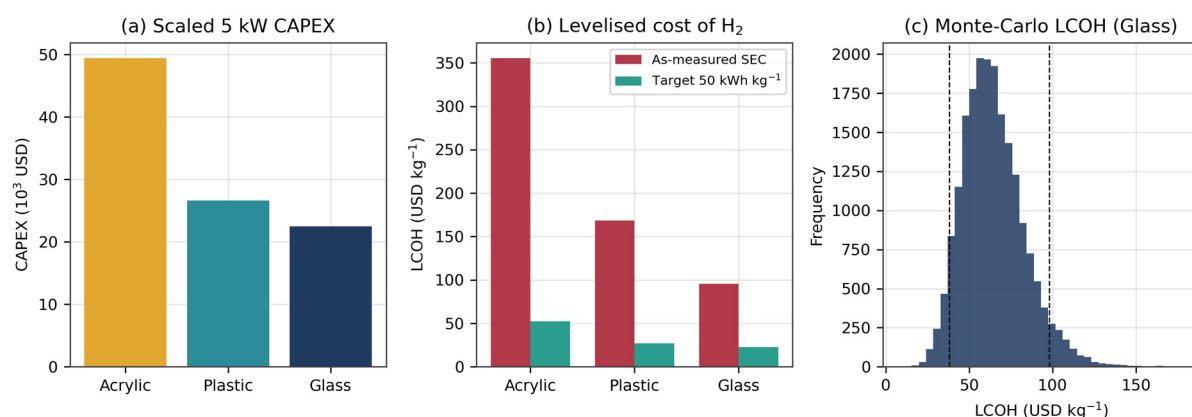


Figure 8. Techno-economics of the scaled 5 kW stacks: (a) CAPEX per design; (b) levelised cost of hydrogen as-measured and at the commercial-target SEC; (c) Monte-Carlo LCOH distribution for the glass reactor.

Table 4. Techno-economic and carbon-abatement indicators for a nominal 5 kW scaled stack.

Indicator	Design 1 (Acrylic)	Design 2 (Plastic)	Design 3 (Glass)
CAPEX (10 ³ USD)	49.4	26.7	22.5
Annual H ₂ (kg·yr ^{−1})	29.4	32.3	47.2
LCOH as-measured (USD·kg ^{−1})	355	168	95.4
LCOH at 50 kWh·kg ^{−1} (USD·kg ^{−1})	52.2	27.2	22.5
Net present value (10 ³ USD)	−101	−51.5	−41.4
Benefit-cost ratio	0.017	0.036	0.063
Net CO ₂ mitigation (t·yr ^{−1})	0.250	0.275	0.401

4.8. Preliminary Carbon-Abatement Estimate

Figure 9 shows the environmental performance. Each kilogram of solar hydrogen displaces about 10 kg of CO₂ from steam-methane reforming while carrying only about 1.5 kg of embodied CO₂, so all designs are strongly net-positive with an abatement ratio of about 6.7. The scaled 5 kW systems avoid 0.25–0.40 t CO₂ per year, and over a 20-year life, the glass system mitigates about 8.0 t CO₂. The stoichiometric water demand of about 9 kg per kg of hydrogen is modest. As with every other layer, the environmental benefit tracks production and therefore favours the most efficient glass reactor. This is a first-order carbon-abatement calculation, not a life-cycle assessment: it compares a fixed steam-methane-reforming emission factor with an assumed embodied factor for solar hydrogen and omits the manufacture, replacement, and end-of-life treatment of the photovoltaic panels, batteries, and balance-of-plant. Published life-cycle assessments of alkaline electrolysis show that these stages contribute materially to the footprint and depend strongly on the electricity mix as well as the plant lifetime [40,41]. Hence, the values are indicative only and should be read as an abatement bound rather than a full environmental assessment.

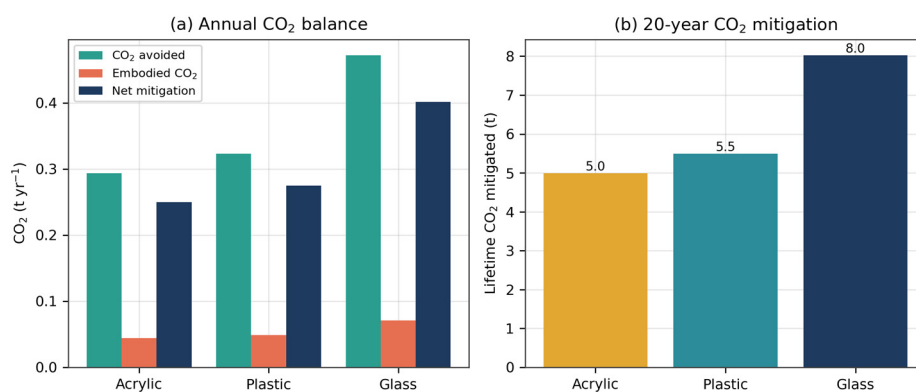


Figure 9. Environmental performance: (a) annual CO₂ avoided, embodied and net mitigation per design; (b) 20-year lifetime CO₂ mitigation.

4.9. Solar Resource and PV-Coupled Potential

Figure 10 characterises the Tabuk solar resource. The site receives high direct-beam insolation with peaks near 0.8 kW·m⁻² and daily totals above 6 kWh·m⁻²; June is slightly more energetic than May (about 10.1 versus 9.6 kWh·m⁻² per day) but hotter, which mildly derates the temperature-corrected PV output. With a diffuse fraction of about 16%, a 1.6 m² panel could produce roughly 12 g of hydrogen per day at the glass-reactor efficiency. The resource is well matched to solar electrolysis and confirms the suitability of the location for green-hydrogen production.

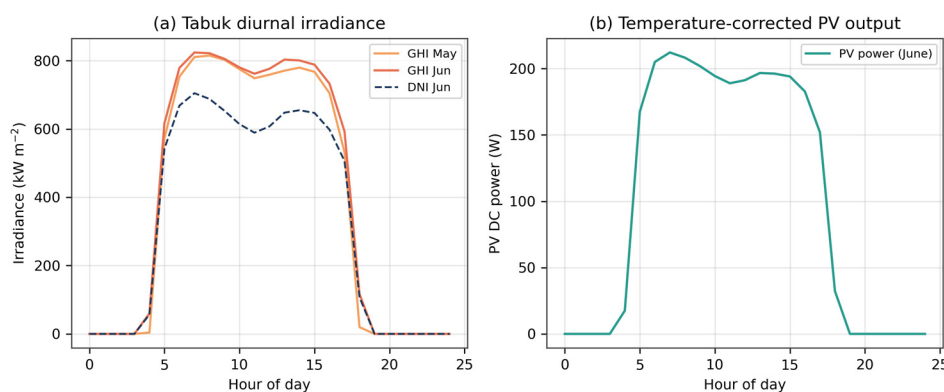


Figure 10. Tabuk solar resource: (a) diurnal global and direct-normal irradiance for May and June; (b) temperature-corrected PV DC power.

4.10. Data-Driven Modelling of the Production Rate

Figure 11 reports a data-driven model of the instantaneous hydrogen production rate of the glass reactor from the electrical features (current, charge, voltage, and time). Because the rate is governed by Faraday's law, it is dominated by the current, which is confirmed as the most important predictor. A Gaussian-process regression validated by five-fold cross-validation reaches a coefficient of determination of 0.45 with a root-mean-square error of $9.9 \text{ mL} \cdot \text{min}^{-1}$, and an ordinary least-squares model reaches 0.57; the residual scatter reflects the supply intermittency and the noise introduced by differentiating the cumulative volume rather than model bias, the bias being below $0.55 \text{ mL} \cdot \text{min}^{-1}$. The models, therefore, quantify the reproducibility of the noisy rate signal and support the Faradaic interpretation of the data.

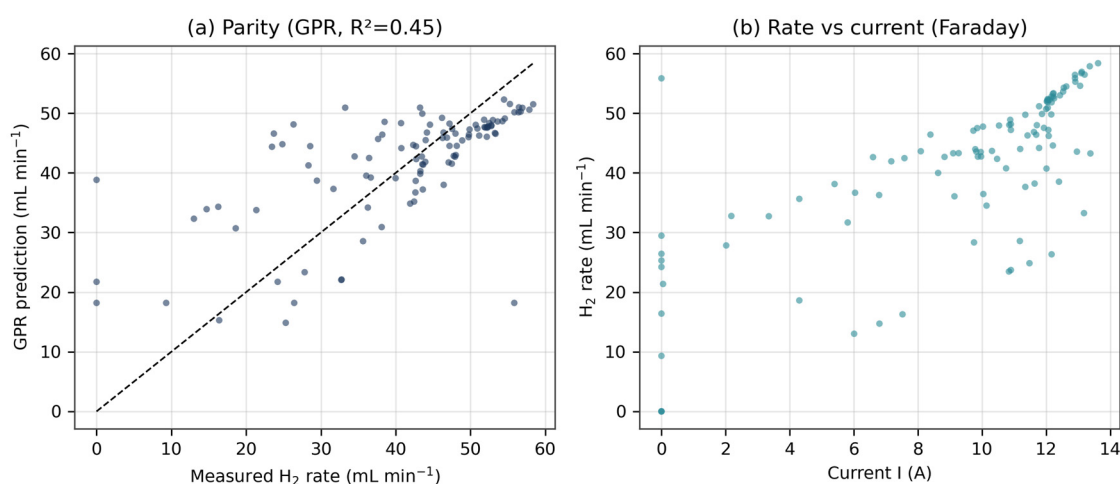


Figure 11. Data-driven modelling of the glass-reactor production rate: (a) parity of the cross-validated Gaussian-process prediction against measurement; (b) production rate versus current.

4.11. Comparative Assessment and Multi-Criteria Ranking

Figure 12 summarises the head-to-head comparison. Combining the electrochemical, energy, exergy, thermal, economic, and environmental indicators through TOPSIS, with the benefit criteria maximised and the specific energy consumption and levelised cost minimised, the glass reactor ranks first with a closeness coefficient of 1.00, followed by the plastic (0.46) and acrylic (0.00) reactors. The efficiency-SEC trade-off is anchored by the glass reactor, which simultaneously has the lowest specific energy consumption and the highest efficiency, so it lies on the favourable corner of the design space. The glass configuration is therefore the recommended design and a first-order basis for scale-up. Several of the criteria are drawn from the same current and voltage records and are therefore correlated, which can reward the same underlying feature more than once. The complete decision matrix is given in Table 5 Complete TOPSIS decision matrix (benefit criteria maximised, cost criteria minimised), and Table 6 Sensitivity of the TOPSIS closeness coefficient and rank to the weighting scheme; rank in parentheses. reports the closeness coefficient and rank under five weighting schemes, namely equal, entropy, efficiency-weighted, economic-weighted, and a de-correlated subset that retains one criterion per correlated family. The glass reactor remains first in every scheme, whereas the plastic closeness coefficient varies of the order of 0.39 to 0.63. Hence, the ranking is not an artefact of the weighting.

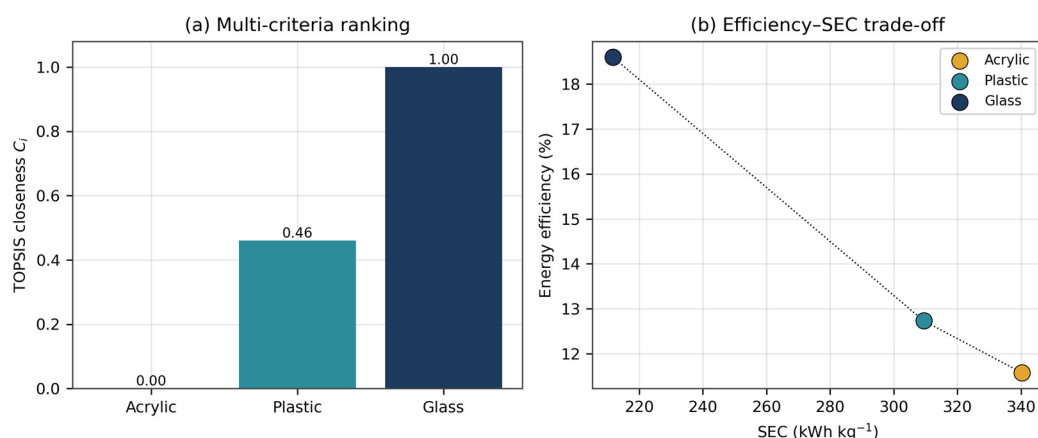


Figure 12. Comparative assessment: (a) TOPSIS closeness coefficient per design; (b) efficiency-SEC trade-off across the three reactors.

Table 5. Complete TOPSIS decision matrix (benefit criteria maximised, cost criteria minimised).

Criterion	Type	Acrylic	Plastic	Glass
η_{en} (%)	benefit	11.57	12.73	18.60
η_{ex} (%)	benefit	9.56	10.51	15.36
VH_2 (mL)	benefit	394	1627	3725
NPV (kUSD)	benefit	−100.8	−51.5	−41.4
CO_2 , net ($\text{t}\cdot\text{yr}^{-1}$)	benefit	0.250	0.275	0.401
SEC ($\text{kWh}\cdot\text{kg}^{-1}$)	cost	340	309	212
LCOH ($\text{USD}\cdot\text{kg}^{-1}$)	cost	355	168	95

Table 6. Sensitivity of the TOPSIS closeness coefficient and rank to the weighting scheme; rank in parentheses.

Weighting Scheme	Acrylic	Plastic	Glass
Equal	0.00 (3)	0.50 (2)	1.00 (1)
Entropy	0.00 (3)	0.52 (2)	1.00 (1)
Efficiency-weighted	0.00 (3)	0.43 (2)	1.00 (1)
Economic-weighted	0.00 (3)	0.63 (2)	1.00 (1)
De-correlated subset	0.00 (3)	0.39 (2)	1.00 (1)

4.12. Verification and Consistency Checks

The analysis was verified against the independently reported design-table values and by internal conservation checks, as summarised in Table 7. The Faraday hydrogen of the glass reactor agrees with the reported value to within 0.33%, the voltage efficiency and heat dissipation of the plastic reactor are reproduced almost exactly, and the computed Faradaic efficiency of 57.2% matches the reported 56.3%. The first-law and second-law balances close to 0.00% and −0.05%, respectively. The near-exact reproduction of four independently reported quantities and the exact energy and exergy closure confirm the physical and numerical consistency of the pipeline, so the comparative conclusions rest on a verified and internally consistent basis. These are verification and internal-consistency checks: the exact energy and exergy closure follows from the calculation definitions and is not an independent experimental validation. In fact, no electrolyte temperature was logged, the runs were not repeated, and a formal measurement-uncertainty analysis was not performed; independent validation against instrumented, replicated experiments is left to future work.

Table 7. Validation of the analysis against reported values and conservation checks.

Check	Computed	Reference	Error
Faraday H ₂ , glass (mL)	3725	3737	−0.33%
Voltage efficiency, plastic (%)	12.7	12.7	≈0
Heat dissipation, plastic (W)	32.7	32.7	≈0
Faradaic efficiency, glass (%)	57.2	56.3	+1.6%
Energy-balance closure	0.00%	0	exact
Exergy-balance closure	−0.05%	0	exact

5. Conclusions

Three lab-scale solar-powered alkaline water electrolyzers, differing in tank material, electrode material, inter-electrode gap, and electrolyte concentration, were designed, fabricated, and compared under the climate of Tabuk, Saudi Arabia. A unified, verified multi-physics pipeline evaluated every reactor on a common Faraday basis across the electrical, electrochemical, energy, thermal, exergy, entropy, dimensionless, techno-economic, and environmental layers, and ranked the designs by TOPSIS. It was found that:

- Reducing the inter-electrode gap from 30 cm to 6 cm reduced the area-specific resistance from 1103 to 55 ohm·cm² and raised the voltage efficiency from 11.6% to 18.6%; the gap and the electrolyte conductivity are the dominant design levers within this multi-variable comparison.
- The glass reactor (Design 3) was best on every benefit criterion, with the highest current density (942 A·m^{−2}), energy efficiency (18.6%) and exergy efficiency (15.4%), the lowest specific energy consumption (212 kWh·kg^{−1}), and a measured gas-collection efficiency of 57%.
- All three reactors are ohmically controlled, with a Wagner number well below unity (0.032–0.060) and a Bejan ratio of 0.90–0.95, so the dominant irreversibility is Joule dissipation in the electrolyte and series path.
- At the as-measured efficiency, the levelised cost of hydrogen is high (95 USD·kg^{−1} for the glass reactor) and is dominated by the experimental specific energy consumption; projecting to a commercial 50 kWh·kg^{−1} lowers it to about 23 USD·kg^{−1}, and the cost is governed by efficiency and CAPEX rather than financing.
- On a preliminary carbon-abatement basis (not a full life-cycle assessment), all designs are net-positive, with a CO₂ abatement ratio of about 6.7 and a lifetime mitigation of about 8.0 t CO₂ for the scaled glass system, and the high-insolation Tabuk site is well matched to solar electrolysis.
- The glass reactor ranked first by TOPSIS (closeness coefficient 1.00) and is recommended as a first-order basis for scale-up; the analysis reproduced the reported values to within 0.33% and closed the energy and exergy balances exactly.

Future work will extend the comparison to longer, temperature-instrumented runs, will measure the gas-collection efficiency of every reactor, and will apply the verified pipeline to an optimised narrow-gap stack in order to approach the commercial efficiency target.

Nomenclature

A_{el} electrode area (m²); ASR area-specific resistance (ohm·cm²); Be Bejan ratio; c_p specific heat (J·kg^{−1}·K^{−1}); E_{el} electrical energy (J); E_{rev} , E_m reversible and thermoneutral voltage (V); ex_{ch} chemical exergy of H₂ (kJ·mol^{−1}); F Faraday constant (96,485 C·mol^{−1}); HHV higher heating value; I current (A); j current density (A·m^{−2}); $LCOH$ levelised cost of hydrogen (USD·kg^{−1}); m_{H_2} hydrogen mass (kg); Q_{gen} heat generation (W); SEC specific energy consumption (kWh·kg^{−1}); S_{gen} entropy generation (W·K^{−1}); V_{cell} , V_{rep} terminal and representative voltage (V); Wa Wagner number; z electrons per H₂.

Greek: ε void fraction; η efficiency; η_{act} , η_{ohm} activation and ohmic overpotential (V); κ ionic conductivity ($S \cdot m^{-1}$); τ thermal time constant (s).

Subscripts: *en* energy; *ex* exergy; *F* Faradaic; *V* voltage.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

Generative artificial intelligence (Claude Sonnet 5.0) was used solely for language editing and proofreading. The author reviewed and verified all scientific content and assumes full responsibility for the content and integrity of the work.

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Author Contributions

H.A. conceived the study, developed the methodology, supervised the research, validated the results, interpreted the findings, and reviewed and edited the manuscript. O.A. contributed to the investigation, software, formal analysis, data curation, visualization, and writing of the original draft. A.A. (Abdulrahman Alshaman) contributed to the investigation, experiments, software, and data collection. A.A. (Abdullah Almubarak) contributed to the investigation, validation, visualization, and data collection. All authors reviewed and approved the final manuscript.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The experimental data and analysis code that support the findings of this study are available from the corresponding author on reasonable request.

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The author declares no competing interests.

References

1. Dudkina E, Villar J, Bessa RJ, Crisostomi E. The Role of Batteries in Maximizing Green Hydrogen Production with Power Flow Tracing. In Proceedings of the 2024 4th International Conference on Smart Grid and Renewable Energy (SGRE), Doha, Qatar, 8–10 January 2024; pp. 1–6. DOI:10.1109/SGRE59715.2024.10428749
2. Hein K, Bertin D, Yuan J, Zhang H, Maquart V, Lavillonniere E. Optimal Operation of Green Hydrogen Generation Plant with Solar PV, Renewable Energy Certificates and Virtual Battery Ledger. In Proceedings of the IECON 2023—49th Annual Conference of the IEEE Industrial Electronics Society, Singapore, 16–19 October 2023; pp. 1–7. DOI:10.1109/IECON51785.2023.10312380

3. Muthia R, Pramudya ASP, Maulana MR, Purwanto WW. Techno-economic analysis of green hydrogen production by a floating solar photovoltaic system for industrial decarbonization. *Clean Energy* **2024**, *8*, 1–14. DOI:10.1093/ce/zkae032
4. Alturki A. Advancing the Economic Frontier of Green Hydrogen: A Systematic Modeling and Optimization Approach. In Proceedings of the 2024 IEEE Conference on Technologies for Sustainability (SusTech), Portland, OR, USA, 14–17 April 2024; pp. 324–331. DOI:10.1109/SusTech60925.2024.10553437
5. El-Hamalawy AF, Farag HEZ, Asif A. Optimal design of grid-connected green hydrogen plants considering electrolysis internal parameters and battery energy storage systems. *Energy Convers. Manag.* **2024**, *302*, 118127. DOI:10.1016/j.enconman.2024.118127
6. Superchi F, Mati A, Pasqui M, Carcasci C, Bianchini A. Techno-economic study on green hydrogen production and use in hard-to-abate industrial sectors. *J. Phys. Conf. Ser.* **2022**, *2385*, 12054. DOI:10.1088/1742-6596/2385/1/012054
7. Gao B, He Y, Zhao Y, Liu W, Liu J, Peng X. Development and Application of Green Hydrogen Energy Production Technology. *Lect. Notes Electr. Eng.* **2023**, *1017*, 607–620. DOI:10.1007/978-981-99-0553-9_63
8. Marouani I, Guesmi T, Alshammari BM, Alqunun K, Alzamil A, Alturki M, et al. Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future. *Processes* **2023**, *11*, 2685. DOI:10.3390/pr11092685
9. Criollo A, Minchala-Avila LI, Benavides D, Ochoa-Correa D, Tostado-Véliz M, Meteab WK, et al. Green Hydrogen Production—Fidelity in Simulation Models for Technical–Economic Analysis. *Appl. Sci.* **2024**, *14*, 10720. DOI:10.3390/app142210720
10. Pan L, Chen L, Pang Y, Chen J, Shi F, Li R, et al. Optimal operation control strategy for off-grid photovoltaic hydrogen production system considering hydrogen production efficiency. *J. Renew. Sustain. Energy* **2024**, *16*, 065502. DOI:10.1063/5.0218151
11. Mucci S, Mitsos A, Bongartz D. Cost-optimal Power-to-Methanol: Flexible operation or intermediate storage? *J. Energy Storage* **2023**, *72*, 108614. DOI:10.1016/j.est.2023.108614
12. Barigozzi G, Brumana G, Franchini G, Ghirardi E, Ravelli S. Techno-economic assessment of green hydrogen production for steady supply to industrial users. *Int. J. Hydrogen Energy* **2024**, *59*, 125–135. DOI:10.1016/j.ijhydene.2024.02.033
13. Wang G, Mukundan R, Peng X. Investigation of Degradation Mechanism of Liquid Alkaline Water Electrolyzer Under Dynamic Operation Condition. *Meet. Abstr.* **2024**, *MA2024-02*, 3178–3178. DOI:10.1149/MA2024-02453178mtgabs
14. Im S, Kim WS, Tamboli AM, Sim J, Jung Y, OH J, et al. Preventing Electrode Degradation Against Reverse Current By Interrupting Ion Transfer during Shut-Down in Alkaline Water Electrolysis. *Meet. Abstr.* **2024**, *MA2024-02*, 3228–3228. DOI:10.1149/MA2024-02463228mtgabs
15. Niroula S, Chaudhary C, Subedi A, Thapa BS. Parametric Modelling and Optimization of Alkaline Electrolyzer for the Production of Green Hydrogen. *IOP Conf. Ser. Mater. Sci. Eng.* **2023**, *1279*, 012005. DOI:10.1088/1757-899X/1279/1/012005
16. Bora DK. Green Hydrogen Production with 25 kW Alkaline Electrolyzer Pilot Plant Shows Hydrogen Flow Rate Exponential Asymptotic Behavior with the Stack Current. *Hydrogen* **2025**, *6*, 75. DOI:10.3390/hydrogen6040075
17. Maurya S, Leonard DP, Kang SY. Investigating Reverse Current Phenomena Induced by Start/Stop Cycling in Lab-Scale Single-Cell Liquid Alkaline Water Electrolyzers. *Meet. Abstr.* **2024**, *MA2024-02*, 3177–3177. DOI:10.1149/MA2024-02453177mtgabs
18. d’Amore-Domenech R, Navarro E, Mora E, Leo TJ. Alkaline Electrolysis at Sea for Green Hydrogen Production: A Solution to Electrolyte Deterioration. Volume 10: Ocean Renewable Energy. American Society of Mechanical Engineers. In Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering, Madrid, Spain, 17–22 June 2018. DOI:10.1115/OMAE2018-77209
19. Wang R, Xu Z, Dai Z, Yang L, Shen X. Consumption Modeling and Influencing Factors Analysis of Alkaline Water Electrolyzer. *Lect. Notes Electr. Eng.* **2024**, *1169*, 287–299. DOI:10.1007/978-981-97-1072-0_30
20. Zemmit A, Benchenina Y, Bouzaki MM, Loukrizi A. Advanced Electrolyzer Modeling and Simulation for Optimized Green Hydrogen Production. *Alger. J. Signals Syst.* **2024**, *9*, 255–260. DOI:10.51485/ajss.v9i4.248
21. Łosiewicz B. Technology for Green Hydrogen Production: Desk Analysis. *Energies* **2024**, *17*, 4514. DOI:10.3390/en17174514
22. Cai Q, Hong W, Jian C, He X, Liu W. Recent Development of Self-Supported Alkaline Hydrogen Evolution Reaction Electrocatalysts for Industrial Electrolyzer. *Adv. Energy Sustain. Res.* **2023**, *4*, 2200178. DOI:10.1002/aesr.202200178
23. Esfandiari N, Aliofkhaezai M, Colli AN, Walsh FC, Cherevko S, Kibler LA, et al. Metal-based cathodes for hydrogen production by alkaline water electrolysis: Review of materials, degradation mechanism, and durability tests. *Prog. Mater. Sci.* **2024**, *144*, 101254. DOI:10.1016/j.pmatsci.2024.101254
24. Jin L, Nogueira Nakashima R, Lund Frandsen H, Comodi G. Alkaline Electrolysis for Green Hydrogen Production: Techno-Economic Analysis of Temperature Influence and Control. In Proceedings of the 36th International Conference on

- Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2023), Las Palmas de Gran Canaria, Spain, 25–30 June 2023; pp. 908–919. DOI:10.52202/069564-0082
25. El-Hamrawy AF, Farag HE, Asif A. Optimal Design of Alkaline Based Electrolysis Hydrogen Production Plants. In Proceedings of the 2024 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), Kingston, ON, Canada, 6–9 August 2024; pp. 915–919. DOI:10.1109/CCECE59415.2024.10667329
26. Lindquist G. Research and Development Needs to Enable Renewable-Powered Liquid Alkaline Electrolyzers. *Meet. Abstr.* **2024**, *MA2024-01*, 1840–1840. DOI:10.1149/MA2024-01341840mtgabs
27. Ehlers JC, Feidenhans'l AA, Therkildsen KT, Larrazábal GO. Affordable Green Hydrogen from Alkaline Water Electrolysis: Key Research Needs from an Industrial Perspective. *ACS Energy Lett.* **2023**, *8*, 1502–1509. DOI:10.1021/acsenerylett.2c02897
28. Haoran C, Xia Y, Wei W, Yongzhi Z, Bo Z, Leiqi Z. Safety and efficiency problems of hydrogen production from alkaline water electrolyzers driven by renewable energy sources. *Int. J. Hydrogen Energy* **2024**, *54*, 700–712. DOI:10.1016/j.ijhydene.2023.08.324
29. Dubouis N, Aymé-Perrot D, Degoulange D, Grimaud A, Girault H. Alkaline electrolyzers: Powering industries and overcoming fundamental challenges. *Joule* **2024**, *8*, 883–898. DOI:10.1016/j.joule.2024.02.012
30. de Groot TT. (Invited) Challenges and Opportunities of Alkaline Water Electrolysis. *Meet. Abstr.* **2023**, *MA2023-01*, 1972–1972. DOI:10.1149/MA2023-01361972mtgabs
31. Huang D, Wen Q, Xiong B, Lu A, Ai X, Zhong Z, et al. Iron Electrodeposition-Induced Degradation on Industrial Alkaline Water Electrolyzer: Multiphysics Model and Economic Analysis. **2024**, *under review*. DOI:10.2139/ssrn.4720710
32. Kwon J, Choi S, Park C, Han H, Song T. Critical challenges and opportunities for the commercialization of alkaline electrolysis: High current density, stability, and safety. *Mater. Chem. Front.* **2024**, *8*, 41–81. DOI:10.1039/D3QM00730H
33. Karl A, Jodat E, Kungl H, Eichel RA. De-Risking PEM-Electrolysis: Advanced Characterization for the Pathway Towards the GW-Scale. *Meet. Abstr.* **2024**, *MA2024-02*, 3198–3198. DOI:10.1149/MA2024-02453198mtgabs
34. AbdelMeguid H, Alotaibi O, Alshaman A, Almubarak A, Alrehaili H. Decoupling Solar Intermittency: A Performance Evaluation of a Battery-Buffered Green Hydrogen Production Unit for Sustainable Energy Systems. In Proceedings of the International Conference on Industrial Engineering and Operations Management 2026, Tabuk, Saudi Arabia, 2–4 February 2026. DOI:10.46254/GC03.20250211
35. AbdelMeguid H, Alshaman A, Almubarak A, Alotaibi O, Alrehaili H. Maximizing Lifetime Value: A Techno-Economic Analysis of Degradation-Aware Operating Strategies for Solar-Powered Alkaline Electrolyzers. In Proceedings of the International Conference on Industrial Engineering and Operations Management 2026, Tabuk, Saudi Arabia, 2–4 February 2026. DOI:10.46254/GC03.20250224
36. AbdelMeguid H, Almubarak A, Alotaibi O, Alshaman A, Alrehaili H. Quantifying the System-Level Impact of Alkaline Electrolyzer Degradation on Solar-to-Hydrogen Efficiency and Lifetime Performance. In Proceedings of the International Conference on Industrial Engineering and Operations Management 2026, Tabuk, Saudi Arabia, 2–4 February 2026. DOI:10.46254/GC03.20250223
37. Aljohani Z, Asiri A, Al-awlaqi S, Aljohani T, Abdelmeguid H. Assessment of Solar Energy Availability and Its Potential Applications in NEOM Region. *Renew. Energy Res. Appl.* **2023**, *5*, 11–19. DOI:10.22044/rera.2023.12674.1201.
38. AbdelMeguid HS, Al-johani HF, Saleh ZF, Almalki AA, Almalki AM. Advancing Green Hydrogen Production in Saudi Arabia: Harnessing Solar Energy and Seawater Electrolysis. *Clean Energy Sustain.* **2023**, *1*, 10006. DOI:10.35534/ces.2023.10006
39. Le Bideau D, Mandin P, Benbouzid M, Kim M, Sellier M. Review of necessary thermophysical properties and their sensitivities with temperature and electrolyte mass fractions for alkaline water electrolysis multiphysics modelling. *Int. J. Hydrogen Energy* **2019**, *44*, 4553–4569. DOI:10.1016/j.ijhydene.2018.12.222
40. Koj J, Wulf C, Schreiber A, Zapp P. Site-Dependent Environmental Impacts of Industrial Hydrogen Production by Alkaline Water Electrolysis. *Energies* **2017**, *10*, 860. DOI:10.3390/en10070860
41. Gerloff N. Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production. *J. Energy Storage* **2021**, *43*, 102759. DOI:10.1016/j.est.2021.102759