



PHOTOVOLTAIC-DRIVEN ALKALINE ELECTROLYSIS AS A PATHWAY TO DECENTRALISED GREEN HYDROGEN: A CRITICAL REVIEW

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Abstract

Decentralised green hydrogen generation through photovoltaic-driven alkaline water electrolysis (AEL) is attracting growing research interest as the cost of solar electricity approaches parity with grid power across much of the developing world. This paper critically examines the published evidence on three pillars of system performance: the thermodynamic and kinetic roles of the electrolyte; the catalytic and durability properties of electrode materials available at low cost; and the power-conditioning strategies required to interface a variable photovoltaic source with the largely ohmic load of an AEL stack. Four experimental papers from Andijan State Technical Institute (ASTI) [3–6] are analysed within the context of seventeen international studies to identify design principles applicable to high-irradiance, resource-limited settings. The review concludes that 30 wt% KOH, 316L stainless steel electrodes operated below 10 mA cm⁻², and MPPT-equipped power converters together constitute a technically sound and economically accessible entry configuration, capable of yielding 160–180 kg H₂ yr⁻¹ from a 5 kW solar array under Uzbekistan conditions. Pathways to reduce the levelised hydrogen cost below \$5 kg⁻¹ are discussed.

Keywords: green hydrogen, alkaline electrolyzer, photovoltaic coupling, KOH electrolyte, 316L stainless steel, MPPT, levelised cost of hydrogen, Uzbekistan.

1. Introduction

The imperative to eliminate fossil-fuel combustion from the global energy system by mid-century has stimulated a rapid reappraisal of hydrogen as an energy vector. Unlike electricity, hydrogen can be stored in bulk at ambient pressure, transported through repurposed natural-gas infrastructure, and converted back to power via fuel cells or combustion turbines at high round-trip efficiency. The Hydrogen Council estimates that clean hydrogen could abate 6 Gt CO₂ eq yr⁻¹ by 2050, roughly 20% of the decarbonisation required under a 1.5°C trajectory [1].

Water electrolysis — the electrochemical splitting of H₂O into H₂ and O₂ by an applied electric current — is the only commercially viable route to producing hydrogen whose carbon footprint can be driven to zero by using renewable electricity. Among the three mature electrolysis technologies, alkaline electrolysis stands out for its industrial pedigree: the first megawatt-scale alkaline electrolyzer entered service in 1927, and current systems routinely operate for 80,000–100,000 hours before major refurbishment [2]. The capital cost of AEL (\$400–800 kW⁻¹ at the stack level) remains roughly half that of proton-exchange-membrane electrolysis, making it the natural choice for budget-constrained projects in emerging economies [8].

The Republic of Uzbekistan is among the most solar-endowed nations in Central Asia: the Fergana Valley, home to Andijan State Technical Institute, receives more than 2,800 sunshine hours per year, and annual global horizontal irradiance exceeds $1,700 \text{ kWh m}^{-2}$. A suite of government decrees culminating in Presidential Decree PD-60 of April 2023 mandates the integration of renewable energy into industrial processes and directs universities and research institutes to build local expertise in hydrogen technologies [7]. ASTI has responded by establishing an experimental AEL research programme whose four peer-reviewed outputs [3–6] form the empirical core of the present review.

The paper is organised as follows. Section 2 describes the literature selection protocol. Sections 3–5 address, in turn, electrolyte science, electrode behaviour, and PV–AEL power coupling. Section 6 places the findings in their techno-economic context. Section 7 tabulates key study results. Section 8 identifies research gaps, and Section 9 states the conclusions.

2. Review methodology

Eligible studies were identified through systematic queries of the Scopus, Web of Science, and Google Scholar databases in November–December 2025, supplemented by backward citation tracing from the most frequently cited review articles in the field. The search string comprised: (“alkaline electrolysis” OR “alkaline electrolyzer”) AND (“solar” OR “photovoltaic” OR “renewable”) AND (“KOH” OR “electrode” OR “MPPT” OR “hydrogen production”). The temporal scope was January 2008–June 2026. Inclusion criteria required: (a) peer-reviewed publication in a Scopus- or WoS-indexed venue or in a registered open-access repository; (b) reporting of at least one quantitative performance metric (efficiency, overpotential, corrosion rate, or LCOH); and (c) relevance to at least one of the three review themes. All four ASTI papers [3–6] were included by definition as primary evidence. The final corpus comprised 17 external references plus the 4 ASTI studies.

3. Electrolyte science in alkaline water electrolysis

The electrolyte in an AEL cell must simultaneously satisfy four requirements: high ionic conductivity (to minimise ohmic losses), chemical stability in oxidising and reducing environments (to avoid degradation products that foul electrodes), low vapour pressure at elevated temperature (to limit evaporative losses and corrosion of gas-handling components), and low viscosity (to facilitate bubble disengagement from electrode surfaces). No single substance satisfies all four requirements optimally, and the industrial consensus has converged on aqueous KOH as the best practical compromise [8, 9].

The conductivity of aqueous KOH reaches a maximum of $0.60\text{--}0.68 \text{ S cm}^{-1}$ at 25–30 wt% and 60–80°C, approximately 1.4 times higher than NaOH at equivalent conditions [9]. This advantage is rooted in the larger hydration enthalpy of Na^+ (-405 kJ mol^{-1}) relative to K^+ (-321 kJ mol^{-1}), which makes the sodium ion a slower-moving, more tightly hydrated species. ASTI measurements confirm this hierarchy: 30 wt% KOH at 80°C yielded $\sigma = 0.68 \text{ S cm}^{-1}$, against $\sigma = 0.49 \text{ S cm}^{-1}$ for 30 wt% NaOH under identical conditions [4]. The 39% conductivity advantage of KOH translates into a directly proportional reduction in the ohmic component of the cell voltage.

Temperature is the second major electrolyte lever. Each 10°C rise in bath temperature reduces the equilibrium water decomposition voltage by approximately 4 mV ($d\Delta G/dT$), simultaneously increasing OH^- mobility, accelerating charge-transfer kinetics at both electrodes, and reducing electrolyte viscosity. The net effect is a 15–22% improvement in

energy efficiency as temperature rises from 25°C to 70°C [4, 9]. Against this must be weighed increased evaporation from the electrolyte reservoir, accelerated degradation of rubber seals, and — for stainless-steel electrodes — a modest but measurable rise in corrosion rate above 70°C. ASTI identified 60–70°C as the optimum window for 316L electrodes in 30 wt% KOH [3, 4].

The role of current density in electrolyte-electrode interaction is often underappreciated. At low j ($< 10 \text{ mA cm}^{-2}$), the activation overpotential η_{act} dominates total losses, and KOH concentration primarily affects the ohmic term. At high j ($> 200 \text{ mA cm}^{-2}$), gas bubble coverage of the electrode surface becomes the limiting factor, and electrolyte wettability and surface-tension effects become significant. The ASTI JREE study [6] operated at $j = 3 \text{ mA cm}^{-2}$, where bubble coverage is negligible, enabling the systematic isolation of activation and ohmic overpotential contributions that would be masked at industrial current densities.

4. Electrode materials: performance and durability

The two half-reactions of water electrolysis impose different requirements on cathode and anode materials. At the cathode, the hydrogen evolution reaction ($2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$ in alkaline media) proceeds most efficiently on metals with an intermediate hydrogen-binding energy, as described by the Sabatier principle and the Volcano relationship [9]. At the anode, the oxygen evolution reaction ($2\text{OH}^- \rightarrow \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^-$) is kinetically more demanding — requiring a four-electron concerted proton-coupled electron transfer — and its overpotential is typically 2–3 times larger than the HER overpotential on the same material.

316L austenitic stainless steel (Fe–18Cr–10Ni–2Mo, wt%) is the most widely used electrode substrate in small-scale AEL research for practical rather than catalytic reasons: it is inexpensive ($\$1\text{--}3 \text{ kg}^{-1}$ in sheet form), widely available in Uzbekistan, machinable with standard tools, and passivated by a chromium oxide film that resists concentrated alkali at moderate temperatures. ASTI measured a corrosion rate of $0.008\text{--}0.009 \text{ mm yr}^{-1}$ in 30 wt% KOH at 60–70°C over 1,000-hour tests, implying an electrode lifetime in excess of 20 years before the 1 mm plate would be consumed [3]. The Faradaic efficiency of 316L cells at $j = 3 \text{ mA cm}^{-2}$ reached 96%, confirming that gas crossover and parasitic side reactions are negligible at ultra-low current density [3, 6].

The principal weakness of 316L is catalytic inactivity toward OER. The JREE study [6] used electrochemical impedance spectroscopy and Tafel analysis to establish that OER kinetics on bare SS316L consume approximately 450 mV of overpotential (Tafel slope $\sim 120 \text{ mV decade}^{-1}$), accounting for 45% of the total voltage losses above the thermoneutral value of 1.48 V. By contrast, NiFe layered double hydroxide catalysts achieve OER overpotentials of 270–300 mV (Tafel slope $40\text{--}60 \text{ mV decade}^{-1}$) in the same KOH medium [12]. This 150 mV gap, if closed by depositing a NiFe-LDH coating on the 316L anode substrate, would raise the overall cell energy efficiency from $\sim 72\%$ to approximately 80–82% — a gain that justifies the additional processing step.

For the cathode, Ni-Mo electrodeposited alloys represent the most cost-effective upgrade path from bare steel. Mo incorporates into a Ni matrix and shifts the apparent equilibrium adsorption energy of H toward the optimal position on the Volcano plot, reducing the HER Tafel slope from $\sim 120 \text{ mV decade}^{-1}$ (Ni) to $\sim 40 \text{ mV decade}^{-1}$ (Ni-Mo) and cutting the cathode overpotential to 110–150 mV at 300 mA cm^{-2} [11, 12]. Both NiFe-LDH anodes and Ni-Mo cathodes can be electrodeposited from aqueous plating baths at room temperature onto 316L

substrates at minimal capital cost, making them the logical near-term upgrade for the ASTI experimental platform.

5. Photovoltaic–ael coupling and power management

The output of a photovoltaic array is determined by the intersection of its current-voltage (I–V) characteristic with the load line of the connected circuit. A bare AEL stack presents an approximately constant-voltage load above its activation threshold, meaning that as irradiance rises and falls, the operating current changes proportionally — the array is rarely at its maximum-power point. The energy left unharvested in this mismatch is the primary motivation for interposing a power converter with MPPT logic [10, 14].

MPPT converters employ iterative algorithms to perturb the converter duty cycle and observe the resulting change in output power, converging to the maximum-power operating point within a few converter cycles. The perturb-and-observe (P&O) variant used in ASTI studies [4, 5] achieves steady-state tracking accuracy within 1–2% of the true maximum power point and responds to irradiance steps in under five seconds — well within the temporal resolution of typical cloud-shadow transients (tens to hundreds of seconds). The measured energy harvesting gain over direct coupling ranged from 12–15% in the devos.uz study [4] to 19–24% in the IJCTCM optimisation paper [5], reflecting differences in the variability of the simulated irradiance profile.

A subtlety that the ASTI body of work implicitly illustrates is the distinction between Faradaic efficiency and energy efficiency. The portable electrolyzer studies [3, 6] report Faradaic efficiencies of 96% at $j = 3 \text{ mA cm}^{-2}$, meaning that 96% of the charge delivered to the cell produces hydrogen. The energy efficiency (hydrogen LHV divided by electrical energy input), however, is only 9.6–13.2% [4, 6] because the cell voltage at that operating point (1.69 V) remains 38% above the thermoneutral voltage (1.48 V). This distinction is important: a system can be near-perfect in terms of current utilisation while remaining poor in energy terms if the electrode overpotentials are large.

Annual hydrogen yield estimates from the IJCTCM study [5] project 160–180 kg $\text{H}_2 \text{ yr}^{-1}$ for a 5 kW PV system with MPPT and Ni–Mo/NiFe electrodes at Andijan irradiance. This corresponds to a specific yield of 32–36 kg H_2 per installed kW of solar capacity per year, comparable to figures reported for similar systems in Southern Europe and the Gulf region [14, 15].

6. Techno-economic analysis

The economics of solar hydrogen production are determined primarily by the capital cost of the electrolyzer and PV array, the capacity factor of the solar resource, and the Faradaic and energy efficiency of the electrolysis stack. For small distributed systems, the specific capital cost (\$ per kg $\text{H}_2 \text{ yr}^{-1}$ of nameplate capacity) is higher than for utility-scale plants because fixed costs — power electronics, gas handling, safety enclosures — do not scale linearly with rated power.

The ASTI techno-economic analysis [4] places capital costs at \$800 kW^{-1} for the electrolyzer, \$400 kW^{-1} for the PV array, and \$300 kW^{-1} for balance of plant, totalling \$1,500 kW^{-1} . At a 25% solar capacity factor and a 20-year system life, the resulting LCOH is \$5.2–7.8 kg^{-1} for systems below 10 kW, falling to \$3.5–5.0 kg^{-1} for 10–100 kW installations. The stand-alone portable system characterised in the IJCT paper [3] yields \$28 kg^{-1} at 2,000 operating

hours per year — a figure that reflects the very low current density (3 mA cm^{-2}) and correspondingly large electrode area relative to hydrogen output.

IRENA projects that the LCOH from electrolysis could fall below $\$2 \text{ kg}^{-1}$ by 2030 for utility-scale systems in high-irradiance locations, driven by PV module cost reductions (projected $<\$0.10 \text{ W}^{-1}$ by 2030) and electrolyzer learning rates of 18% per doubling of cumulative capacity [15]. For Uzbekistan, which lacks the scale advantages of multi-GW projects, a realistic near-term target is $\$4\text{--}6 \text{ kg}^{-1}$ for systems in the 100 kW–1 MW range. Achieving this requires increasing current density to $150\text{--}300 \text{ mA cm}^{-2}$ (reducing electrode area by two orders of magnitude relative to the current ASTI prototype) and adopting catalytic electrode coatings to maintain energy efficiency above 75% at those higher current densities.

7. Summary of key studies reviewed

Table 1 collates the principal performance metrics from the ASTI publications and selected international benchmarks discussed in this review.

Table 1. Performance metrics of selected solar-powered AEL studies

Publication	System configuration	Principal result	η metric	Source
IJCT 2026 — six-cell portable AEL	316L SS, 30% KOH, 70°C , $j = 7.75 \text{ A}$	H_2 purity 99.5%; corrosion 0.008 mm yr^{-1}	$\eta_F = 96\%$	[3]
Dev. Sci. 2025 — techno-economic AEL	150 Wp PV + MPPT, 316L, 30% KOH	LCOH $\$2\text{--}8 \text{ kg}^{-1}$; MPPT gain +12–15%	$\eta_{\text{sys}} = 13.2\%$	[4]
IJCTCM 2026 — Central-Asia AEL optimisation	5–100 kW PV, 316L, $25\text{--}80^\circ\text{C}$	Solar-to- H_2 13–15%; degradation $<2\%$ per 1000 h	$\eta = 13\text{--}15\%$	[5]
JREE 2026 (in press) — portable AEL performance	SS316L, $j = 3 \text{ mA cm}^{-2}$, PV-coupled	OER = 45% of voltage losses; H_2 rate 0.29 g h^{-1}	$\eta_{\text{LHV}} = 9.6\%$	[6]
Carmo et al. (IJHE, 2013) — PEM vs AEL review	Comparative analysis of water-splitting technologies	AEL lowest CAPEX; PEM highest dynamic flexibility	63–82%	[8]
Ursúa et al. (IEEE, 2012) — AEL with renewables	Commercial AEL integrated with wind/solar	Direct coupling lowers efficiency by up to 30%	$\leq 75\%$	[10]

8. Knowledge gaps and future research directions

Cross-referencing the ASTI results with the international literature reveals five categories of open questions that represent productive targets for future investigation:

- Outdoor long-term trials. All ASTI experiments used a controlled laboratory environment. Real outdoor operation in Andijan introduces diurnal and seasonal temperature swings of up to 50°C, dust loading on PV modules that may reduce irradiance by 5–15% in summer, and relative humidity variations that affect membrane water uptake and electrolyte concentration. A 12-month outdoor pilot would reveal whether laboratory efficiency projections hold under field conditions.

- Catalytic electrode coatings. The OER deficit of bare 316L (450 mV overpotential) identified in [6] is the single largest efficiency loss in the ASTI system. Electrodeposition of NiFe-LDH on the existing 316L anode substrate is a low-capital intervention that modelling suggests could raise cell energy efficiency from 72% to 80–82%. Experimental validation of this upgrade on the ASTI platform is a high-priority near-term step.

- Diaphragm characterisation. The ASTI publications do not report on separator or diaphragm properties. In industrial AEL cells, Zirfon® PERL membranes add 20–40 mΩ cm² of ohmic resistance but reduce gas crossover to < 1% v/v. Understanding the trade-off between separator resistance and hydrogen purity under variable current conditions is essential for designing safe off-grid systems.

- Pressurised operation. Delivering hydrogen at 10–30 bar from a pressurised AEL cell eliminates the need for a separate mechanical compressor, reducing system cost and complexity. At elevated pressure, gas bubble size decreases and void fraction on the electrode surface falls, partially offsetting the increased thermodynamic voltage. The interaction of elevated pressure with 316L corrosion behaviour in 30 wt% KOH has not been reported in the ASTI literature.

- End-use scenario analysis. The ASTI publications report hydrogen production volumes but do not specify the intended end-use. A comparative analysis of hydrogen value across candidate applications in Uzbekistan — back-up power for telecommunications, fertiliser feedstock replacement, or fuel for agricultural machinery — would sharpen the economic case and guide the choice of system scale and storage mode.

9. Conclusions

This critical review has examined the published evidence on photovoltaic-driven alkaline water electrolysis with a dual focus on four ASTI experimental publications and the broader international literature. The following conclusions are drawn:

1. 30 wt% KOH at 60–70°C is the empirically validated optimum electrolyte condition for AEL on 316L electrodes, offering the highest achievable ionic conductivity ($\sigma = 0.68 \text{ S cm}^{-1}$ at 80°C) and the best balance of efficiency and electrode longevity.

2. 316L stainless steel delivers Faradaic efficiency of 96% and corrosion rates below 0.009 mm yr⁻¹ at ultra-low current density, validating projected electrode lifetimes exceeding 20 years. The primary deficiency is OER catalytic activity, where SS316L contributes 45% of total cell voltage losses — a gap addressable by NiFe-LDH anode coatings.

3. MPPT power conditioning raises the daily hydrogen yield by 12–24% relative to direct PV coupling and should be regarded as a standard rather than optional component in any solar-hydrogen installation.

4. Under Andijan irradiance of $1,750 \text{ kWh m}^{-2} \text{ yr}^{-1}$, a 5 kW PV system with MPPT and Ni-Mo/NiFe electrodes can produce $160\text{--}180 \text{ kg H}_2 \text{ yr}^{-1}$, a level sufficient to meet the energy needs of roughly 10 households or to fuel a small transport fleet.

5. Current LCOH for small ASTI-type systems ranges from \$5 to \$28 kg^{-1} depending on scale. Raising current density to $150\text{--}300 \text{ mA cm}^{-2}$ and adopting catalytic coatings represent the most impactful levers for driving costs toward the \$4–6 kg^{-1} range achievable for 100 kW–1 MW systems in Uzbekistan by 2030.

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