



ALKALINE WATER ELECTROLYSIS FOR HYDROGEN PRODUCTION IN HIGH-IRRADIANCE REGIONS: STATE OF THE ART, EXPERIMENTAL EVIDENCE, AND PROSPECTS FOR UZBEKISTAN

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<https://doi.org/10.5281/zenodo.21773872>

Abstract

The combination of falling photovoltaic costs and rising policy pressure on carbon-intensive hydrogen production has created a compelling economic and environmental case for solar-powered alkaline water electrolysis (AEL). This review synthesises experimental data from four peer-reviewed publications produced at Andijan State Technical Institute (ASTI) [3–6] alongside seventeen international studies to examine the state of knowledge on electrolyte chemistry, electrode materials, and photovoltaic power integration. The ASTI dataset covers a 5-order-of-magnitude range of current density (3 mA cm^{-2} to 500 mA cm^{-2}), two electrode substrates (316L stainless steel and Ni-Mo alloy), and both direct and MPPT-mediated PV coupling. Across this parameter space, three design principles emerge as robust: (i) 30 wt% KOH at 60–80°C maximises ionic conductivity and electrode durability; (ii) the anode is the primary energy bottleneck on bare 316L, contributing 45% of total voltage loss and representing the highest-return upgrade target; and (iii) MPPT control captures 12–24% additional solar energy relative to direct coupling. Applying these principles to the Andijan solar resource, a 5 kW PV system can yield 160–180 kg of emission-free hydrogen per year at a levelised cost of $\$5\text{--}8 \text{ kg}^{-1}$, with a clear technical roadmap to below $\$5 \text{ kg}^{-1}$ through electrode coating and current density scaling.

Keywords: *alkaline water electrolysis, solar hydrogen, KOH electrolyte, SS316L electrode, NiFe-LDH, MPPT control, LCOH, Central Asia.*

1. Introduction

Hydrogen is unique among energy carriers in being simultaneously a chemical feedstock, a fuel, and a medium-term energy store. Its mass-specific energy content on a lower heating value basis (120 MJ kg^{-1}) is approximately 2.8 times that of gasoline, and its electrochemical oxidation in a fuel cell produces electricity with an efficiency of 50–60%, more than double that of an internal combustion engine. These properties have made hydrogen central to decarbonisation roadmaps for hard-to-abate sectors including steelmaking, cement production, shipping, and long-haul aviation [1].

The dominant constraint on hydrogen's climate benefit is the production route. Grey hydrogen, derived from steam methane reforming, emits 9–12 kg CO_2 per kilogram of H_2 and currently accounts for the majority of the 90 million tonnes produced globally each year [2]. Electrolytic hydrogen produced from solar or wind electricity — green hydrogen — eliminates these emissions entirely. The key enabling technology is the electrolyzer, and among the available types, alkaline electrolysis offers the best-documented combination of longevity, capital cost, and tolerance of variable power input [8].

The review addresses three nested questions: What are the optimal operating conditions for AEL in the electrolyte and temperature domain? What electrode materials offer the best balance of catalytic activity, durability, and cost for resource-limited settings? How should a PV array be coupled to an AEL stack to maximise annual hydrogen yield? Answers to these questions are sought in the ASTI data and the international literature, and remaining knowledge gaps are identified to guide the next phase of research.

2. Review methodology

This review follows a structured narrative approach. The target literature was identified through three complementary means: (a) keyword searches in Scopus and Web of Science using the terms “alkaline electrolysis” AND (“solar energy” OR “photovoltaic” OR “renewable energy”) AND (“KOH” OR “electrode” OR “MPPT”), filtered to 2008–2026; (b) citation network analysis tracing references cited by three anchor reviews [8, 9, 16]; and (c) targeted retrieval of grey literature and institutional publications from ASTI. Papers were evaluated for methodological rigour (controlled experimental conditions, calibrated instrumentation, reproducibility data) and relevance to the three review themes. Seventeen external peer-reviewed sources plus the four ASTI publications were retained for detailed discussion. Where reported results conflict, the discrepancy is noted and tentatively attributed to differences in experimental protocol.

3. Thermodynamics and kinetics of ael: role of the electrolyte

The electrochemical splitting of water is characterised by a standard Gibbs free energy of $\Delta G^\circ = +237.1 \text{ kJ mol}^{-1}$ at 25°C, corresponding to a minimum decomposition voltage of $E^\circ = 1.23 \text{ V}$. The thermoneutral voltage, which also accounts for the entropy term, is $E\theta = 1.48 \text{ V}$; operating below this value requires external heat input, while operating above it generates waste heat. In practice, AEL cells run at 1.7–2.1 V due to ohmic and kinetic losses, meaning the excess power ($0.22\text{--}0.62 \text{ V} \times j \text{ A cm}^{-2}$) is entirely dissipated as heat in the electrolyte and electrodes [9].

The choice between KOH and NaOH hinges almost entirely on ionic mobility. The molar conductivity of K^+ in dilute aqueous solution ($73.5 \text{ S cm}^2 \text{ mol}^{-1}$) exceeds that of Na^+ ($50.1 \text{ S cm}^2 \text{ mol}^{-1}$) by 47% — a difference that persists at the high concentrations used in AEL and translates directly into lower ohmic losses. ASTI experiments [4] confirm a 39% conductivity advantage for 30 wt% KOH over 30 wt% NaOH. Despite KOH's higher cost ($\$0.8\text{--}1.2 \text{ kg}^{-1}$ vs. $\$0.4\text{--}0.6 \text{ kg}^{-1}$ for NaOH in Uzbekistan), the lifetime of an AEL electrolyte charge is measured in years, meaning the absolute cost difference is negligible relative to the efficiency gain.

Operating temperature modulates all three components of the cell voltage: thermodynamic ($-4 \text{ mV } ^\circ\text{C}^{-1}$ reduction in E°), ohmic (conductivity increases $\sim 2\% \text{ } ^\circ\text{C}^{-1}$ over the range 25–80°C), and activation (HER and OER exchange current densities rise exponentially with temperature, reducing overpotentials). The compounded effect is a 15–22% improvement in energy efficiency from 25°C to 70°C reported consistently across the ASTI studies [3, 4] and the international literature [9, 11]. The upper useful temperature for 316L electrodes is approximately 70°C; above this threshold, ASTI observed a transition in the electrode corrosion mechanism from passive film dissolution to localised pitting.

4. Electrode materials: catalysis, durability, and upgrade pathways

Electrode selection in AEL is governed by four criteria that interact in non-trivial ways: catalytic activity (low overpotential at the operating current density), long-term stability (resistance to dissolution, delamination, and passivation in concentrated alkali), electronic conductivity (low ohmic contribution from the electrode body), and cost (acquisition price and

fabrication complexity). No single material satisfies all four criteria equally well, and practical system design involves navigating trade-offs among them.

The ASTI research programme has focused on 316L stainless steel as the primary electrode material, a choice driven by local availability and cost (sheet 316L costs approximately \$3–5 m⁻² in Uzbekistan). Across 1,000-hour accelerated corrosion tests in 30 wt% KOH at 60–70°C, the ASTI group measured mass-loss rates of 0.008–0.009 mm yr⁻¹ [3, 4], consistent with the Cr₂O₃ passive film maintaining protective integrity in alkaline media below 80°C. At the ultra-low operating current density of $j = 3 \text{ mA cm}^{-2}$ employed in the portable electrolyzer studies, Faradaic efficiencies of 96% were measured by gas displacement and confirmed by gas chromatography (H₂ purity > 99.5%) [3, 6].

The quantitative decomposition of cell voltage losses reported in the JREE study [6] provides an unusually clear picture of where improvement effort should be directed. Using EIS and Tafel analysis, the authors attribute 450 mV (45% of excess voltage) to OER kinetics on the bare SS316L anode, 280 mV (28%) to HER kinetics on the SS316L cathode, 170 mV (17%) to electrolyte ohmic resistance, and ~100 mV (10%) to bubble-induced mass-transport resistance. This loss budget identifies the anode as the overwhelmingly dominant performance bottleneck. NiFe-LDH catalysts, which achieve OER overpotentials of 270–310 mV (Tafel slope ~40 mV dec⁻¹) in 1 M KOH [13], would reduce the anode contribution from 450 mV to below 300 mV — a potential 15-percentage-point gain in cell energy efficiency without changing any other system component.

For the cathode, the Volcano principle provides the theoretical framework for materials selection: the optimal HER catalyst binds atomic hydrogen with a free energy close to zero (thermoneutral adsorption), placing it near the apex of the Volcano curve. Platinum group metals occupy this optimal position but are prohibitively expensive. Among earth-abundant alternatives, Ni-Mo alloys — with Mo's d-band modifying the H-binding energy of Ni — achieve HER overpotentials of 100–150 mV at 300 mA cm⁻², compared with 280–380 mV for pure Ni and 380–420 mV for SS316L [12, 13]. Both NiFe-LDH anodes and Ni-Mo cathodes can be electrodeposited from inexpensive aqueous baths at room temperature, requiring only a regulated DC power supply and the appropriate plating chemistry — both already available in the ASTI laboratory.

5. Photovoltaic-ael integration and power electronics

Photovoltaic arrays generate direct current whose magnitude and voltage are determined by the incident irradiance, the cell temperature, and the connected load. The power-irradiance relationship is approximately linear up to the short-circuit current, but the voltage drops sharply as current approaches the short-circuit value. The maximum-power point (MPP) — the operating point that maximises the product $V \times I$ — shifts with irradiance and temperature, tracing a locus in V – I space that the AEL cell load line generally does not follow.

Under direct coupling, the intersection of the PV I – V curve with the AEL polarisation curve defines the instantaneous operating point. When irradiance drops below a threshold (typically 200–300 W m⁻² for the ASTI system), the intersection falls below the AEL activation voltage and hydrogen production ceases entirely, even though the array is still generating power that is wasted as heat in the cell [10]. An MPPT converter separates the PV array operating point from the AEL load, holding the former at the MPP while regulating the current delivered to the latter.

The net effect is both a higher average production rate and a lower irradiance threshold below which the system shuts off.

Scaling from the 150 Wp prototype studied in [4] to a 5 kW system studied in [5] requires attention to the converter topology. At 150 Wp, a single-phase synchronous buck-boost converter suffices. At 5 kW, interleaved multi-phase topologies are preferred to reduce input and output current ripple, which can otherwise cause current density oscillations in the AEL cell and accelerate membrane fatigue. The ASTI programme has not yet addressed multi-kW power electronics design, representing a gap to be filled as the research scales up.

6. Techno-economic dimensions

The levelised cost of hydrogen (LCOH), defined as the net present value of all system costs over the operating lifetime divided by the cumulative hydrogen production, is the primary metric for comparing green hydrogen with fossil-derived alternatives. For solar AEL systems, LCOH is sensitive to three variables above all others: the capital cost of the electrolyzer (primarily a function of electrode area, which in turn depends on current density), the capital cost and performance of the PV array (primarily a function of module efficiency and local irradiance), and the system capacity factor (the fraction of the year during which conditions permit hydrogen production).

ASTI techno-economic data [4] report a total installed cost of $\$1,500 \text{ kW}^{-1}$ for a 150 Wp system ($\$800 \text{ kW}^{-1}$ electrolyzer, $\$400 \text{ kW}^{-1}$ PV, $\$300 \text{ kW}^{-1}$ balance of plant). Operating at $j = 3 \text{ mA cm}^{-2}$, the large electrode area required (221 cm^2 for a 125 W system) and the resulting 2,000 operating hours per year yield $\text{LCOH} = \$28 \text{ kg}^{-1}$ [3]. At 10–100 kW scale, ASTI estimates LCOH at $\$3.5\text{--}5.0 \text{ kg}^{-1}$ [4], consistent with IRENA's projection of $\$4\text{--}6 \text{ kg}^{-1}$ for small-scale electrolysis in high-irradiance developing nations [15].

The primary lever for reducing LCOH at fixed system scale is increasing current density from 3 mA cm^{-2} to $150\text{--}300 \text{ mA cm}^{-2}$ — a 50–100-fold increase. This shrinks the required electrode area by the same factor, dramatically reducing electrolyzer capital cost. However, higher current density increases overpotentials, which must be compensated by switching from bare 316L to catalytic electrode coatings (NiFe-LDH anode, Ni-Mo cathode) to avoid a proportional rise in energy consumption. The techno-economic optimum lies at the current density where the capital cost saving from the smaller electrode area exactly balances the energy cost of the higher overpotential; this is typically in the range $100\text{--}300 \text{ mA cm}^{-2}$ for KOH AEL with state-of-the-art electrode materials [17].

7. Summary table of key studies

Table 1 presents a structured comparison of the four ASTI publications and two benchmark international studies, showing electrode/electrolyte configuration, headline result, and efficiency metric.

Table 1. Comparison of key studies on solar-powered alkaline water electrolysis

Reference	Electrode / electrolyte	Key outcome	Efficiency	Cite
Bakhramov & Ismailov, IJCT 2026	316L SS 30% KOH 70°C	Portable 6-cell AEL; H_2 3.8 L h^{-1} ; lifetime >20 yr	$\eta_F = 96\%$	[3]

Bakhramov & Ismailov, Dev. Sci. 2025	316L SS 30% KOH MPPT 150 Wp PV	Solar-to-H ₂ = 13.2%; LCOH \$5–8 kg ⁻¹ (<10 kW)	$\eta_{\text{sys}} = 13.2\%$	[4]
Bakhramov, IJCTCM 2026	316L SS 25–30% KOH 25–80°C 5–100 kW PV	Optimal: 30% KOH, 60–80°C, 200–400 mA cm ⁻²	$\eta = 13\text{--}15\%$	[5]
Bakhramov & Ismailov, JREE 2026 (in press)	316L SS $j = 3 \text{ mA cm}^{-2}$ PV emulator	OER = 45% of losses; Tafel 120 mV dec ⁻¹ on SS316L	$\eta_{\text{LHV}} = 9.6\%$	[6]
Brauns & Turek, Processes 2020	Industrial AEL KOH dynamic RE	Identified optimal dynamic operating windows	63–82%	[8]
Gong et al., Nat. Commun. 2014	NiO/Ni heterostructure cathode KOH	HER overpotential 100 mV; TOF 10× vs. Ni	n/a	[13]

8. KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS

The body of work surveyed here, including the ASTI publications, is characterised by laboratory-scale experiments of limited duration. Bridging to deployment-relevant scales and timescales reveals the following unresolved questions:

- Electrode coating development and validation. The cell voltage loss budget established in [6] identifies OER on bare SS316L as the largest single efficiency gap. Electrodeposition of NiFe-LDH on existing 316L anodes is the most impactful near-term intervention, but the stability of NiFe-LDH under variable current conditions (as occur in solar operation) over timescales exceeding 1,000 hours has not been demonstrated at ASTI. This is the most urgently needed experimental step.

- Scaling from prototype to pilot. The largest system studied at ASTI is 150 Wp. Moving to 5–10 kW introduces design challenges — bipolar cell stacking, forced electrolyte circulation, thermal management, gas-liquid separation — that do not arise in single-cell laboratory experiments. A 1 kW intermediate-scale prototype would allow these issues to be addressed before committing to a larger investment.

- Variable irradiance stress testing. All ASTI stability tests used constant current from a bench-top power supply. In real solar operation, the electrolyzer experiences diurnal ramp-up and ramp-down cycles, cloud-shadow transients (step changes of 50–90% in irradiance on timescales of seconds), and seasonal shutdowns. The effect of this variable loading on 316L electrode surface chemistry, membrane integrity, and gas purity over 12-month outdoor cycles is unknown.

9. Conclusions

The present review has drawn on four ASTI publications [3–6] and seventeen international studies to construct a comprehensive picture of solar-powered alkaline water electrolysis, with emphasis on conditions and resources relevant to Uzbekistan. Five principal conclusions are stated:

1. Thermodynamic and kinetic analysis consistently points to 30 wt% KOH at 60–70°C as the optimal electrolyte condition. At 80°C, ionic conductivity reaches 0.68 S cm^{-1} — 39% higher than NaOH at equal concentration — and electrode kinetics are sufficiently fast to enable Faradaic efficiencies above 94% even on bare 316L steel.

2. 316L stainless steel is an adequate entry-level electrode material, with corrosion rates of $0.008\text{--}0.009 \text{ mm yr}^{-1}$ and projected lifetimes exceeding 20 years under ASTI operating conditions. Its primary weakness is OER catalytic inactivity: OER kinetics account for 45% of the total superthreshold cell voltage loss, a deficit that can in principle be eliminated by electrodepositing a NiFe-LDH anode coating.

3. MPPT power conditioning is the single most impactful low-cost system upgrade available to existing PV-AEL installations, increasing annual hydrogen yield by 12–24% without any modification to the electrolyzer itself.

4. A 5 kW PV array with MPPT control, 30 wt% KOH electrolyte, and Ni-Mo/NiFe electrodes can produce $160\text{--}180 \text{ kg H}_2 \text{ yr}^{-1}$ at Andijan irradiance conditions, corresponding to a specific yield of $32\text{--}36 \text{ kg H}_2 \text{ kW}^{-1} \text{ yr}^{-1}$ of installed PV capacity.

5. The roadmap to LCOH below $\$5 \text{ kg}^{-1}$ at 100 kW scale in Uzbekistan requires: (a) increasing operating current density to $150\text{--}300 \text{ mA cm}^{-2}$ through catalytic electrode coatings; (b) adopting zero-gap or near-zero-gap cell architecture; and (c) achieving a solar capacity factor above 28% through storage buffering or hybrid renewable integration.

References:

- [1] Hydrogen Council. Hydrogen Decarbonization Pathways: A Life-Cycle Assessment. Hydrogen Council, Brussels, 2021. 112 p.
- [2] IEA. Global Hydrogen Review 2023. International Energy Agency, Paris, 2023. 156 p.
- [3] Bakhramov Sh.K., Ismailov A.I. Development and experimental characterization of a portable six-cell alkaline electrolyzer using 316L stainless steel electrodes. *Indian Journal of Chemical Technology*. 2026; 33(2): 170–181. DOI: 10.56042/ijct.v33i2.23605.
- [4] Bakhramov Sh.K., Ismailov A.I. Solar-driven alkaline electrolysis: technical and economic assessment for green hydrogen production. *Development of Science*. 2025; 5(9): 187–191. ISSN 3030-3907.
- [5] Bakhramov Sh.K. Optimization of renewable energy-based alkaline electrolysis systems for sustainable hydrogen production. *Chemical Technology, Control and Management*. 2026; 2026(2): 28–37. DOI: 10.59048/2181-1105.1752.
- [6] Bakhramov Sh.K., Ismailov A.I. Performance evaluation of a solar-powered portable alkaline electrolyzer for hydrogen production. *Journal of Renewable Energy and Environment*. 2026; in press. DOI: <https://doi.org/10.30501/JREE.2026.238542>.
- [7] Republic of Uzbekistan. Presidential Decree No. PD-60 on the Concept for Development of the Energy Sector. Tashkent, 18 April 2023.
- [8] Brauns J., Turek T. Alkaline water electrolysis powered by renewable energy: a review. *Processes*. 2020; 8(2): 248. DOI: 10.3390/pr8020248.



- [9] Zeng K., Zhang D. Recent progress in alkaline water electrolysis for hydrogen production and applications. *Progress in Energy and Combustion Science*. 2010; 36(3): 307–326. DOI: 10.1016/j.pecs.2009.11.002.
- [10] Ursúa A., Sanchis P. Static-dynamic modelling of the electrical behaviour of a commercial advanced alkaline water electrolyser. *International Journal of Hydrogen Energy*. 2012; 37(24): 18598–18614. DOI: 10.1016/j.ijhydene.2012.09.125.
- [11] Brauns J., Turek T. Experimental evaluation of dynamic operating concepts for alkaline water electrolyzers powered by renewable energy. *Electrochimica Acta*. 2022; 404: 139715. DOI: 10.1016/j.electacta.2021.139715.