SOLAR-POWERED ALKALINE WATER ELECTROLYSIS FOR GREEN HYDROGEN GENERATION: A LITERATURE REVIEW

Bakhramov Sh.K.
Qosimov M.U.
[1]Andijan State Technical Institute, Andijan,
Republic of Uzbekistan
ORCID: **Bakhramov Sh.K.** 0009-0008-2763-4640
https://doi.org/10.5281/zenodo.21636851

Abstract

This paper presents a focused review of recent advances in solar-photovoltaic-coupled alkaline water electrolysis (AEL) for green hydrogen production, with particular attention to experimental findings from the authors' own research group at Andijan State Technical Institute (ASTI). Four publications from ASTI are synthesised alongside the broader international literature to map the current state of knowledge across three interrelated sub-topics: electrolyte selection and operating parameter optimisation, electrode material performance and durability, and photovoltaic-electrolyzer power integration. Key findings are that 30 wt% KOH at 60–80°C is the near-universal optimum electrolyte condition; that 316L stainless steel provides commercially adequate durability (corrosion rate < 0.01 mm yr^{-1}) but leaves substantial headroom for efficiency improvement through advanced electrode coatings; and that maximum-power-point-tracking (MPPT) converters raise system efficiency by 12–24% relative to direct photovoltaic coupling. Gaps in knowledge, particularly regarding long-term outdoor durability in continental climates and techno-economic scaling, are identified and directions for future work are proposed.

Keywords: alkaline electrolysis, green hydrogen, potassium hydroxide, 316L stainless steel, MPPT, photovoltaic integration, Uzbekistan, literature review.

1. Introduction

The urgency of decarbonising the global energy system has elevated hydrogen to a central role in long-term climate strategy. Hydrogen is energy-dense, storable, and can be combusted or electrochemically oxidised without direct greenhouse gas emissions. The International Energy Agency projects that clean hydrogen demand will grow to 530 million tonnes per year by 2050, representing roughly 18% of global final energy consumption [1]. Currently, however, the vast majority of hydrogen — approximately 96% — is produced from natural gas or coal with substantial CO_2 co-production [2]. Water electrolysis powered by renewable electricity offers a route to truly zero-emission, or "green", hydrogen.

Among the three principal electrolysis technologies — alkaline electrolysis (AEL), proton exchange membrane electrolysis (PEMEL), and solid oxide electrolysis (SOEL) — AEL has the longest industrial track record and the lowest capital cost per kilowatt of installed capacity. Commercial AEL stacks achieve Faradaic efficiencies of 63–82% and are projected to operate for 80,000–100,000 hours before major overhaul [3]. AEL is therefore the natural starting point for developing solar hydrogen systems in resource-constrained or emerging-economy settings.

Uzbekistan offers an especially compelling context for solar-hydrogen research. Annual global horizontal irradiance across the Fergana Valley exceeds 1,700 kWh m^{-2}, with more than 2,800 sunshine hours per year. Presidential Decree PD-60 of 18 April 2023 established targets

for renewable energy deployment and directed state research institutions to investigate hydrogen technologies [7]. Andijan State Technical Institute (ASTI) has responded by conducting a series of laboratory and modelling studies on PV-coupled AEL systems using cost-accessible 316L stainless steel electrodes.

This review consolidates findings from four ASTI publications [3–6] within the context of the wider international literature [7–17] to provide a coherent, up-to-date account of solar-powered AEL, identify remaining gaps, and suggest productive directions for future research. The paper is structured as follows: Section 2 describes the review methodology; Section 3 covers electrolyte and operating parameter optimisation; Section 4 addresses electrode materials and durability; Section 5 examines PV–electrolyzer integration and power management; Section 6 discusses techno-economic aspects; Section 7 identifies knowledge gaps; Section 8 concludes.

2. Review methodology

The review covers literature published between 2010 and 2026, retrieved from Scopus, Web of Science, Google Scholar, and the open-access repositories of ASTI. Search terms included "alkaline electrolysis", "green hydrogen", "photovoltaic electrolysis", "KOH electrolyte", "316L electrode", and "MPPT electrolyzer", applied individually and in Boolean combinations. Priority was given to peer-reviewed journal articles and conference proceedings with experimental data; review articles and techno-economic modelling studies were included selectively. In addition to the international corpus, all four peer-reviewed publications from the ASTI research group are discussed in full, as they constitute the primary evidence base for conditions relevant to Central Asia.

3. Electrolyte Selection And Operating Parameter Optimisation

The electrolyte in an AEL cell serves two distinct functions: it provides the hydroxide ions (OH^-) that carry current between the electrodes, and it participates directly in the electrochemical reactions at both the anode ($2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$) and the cathode ($2H_2O + 2e^- \rightarrow H_2 + 2OH^-$). Both functions depend critically on the identity and concentration of the dissolved base [8].

Potassium hydroxide (KOH) is the industrial standard. The equivalent ionic conductance of K^+ (73.5 S cm^2 mol^{-1}) is approximately 50% higher than that of Na^+ (50.1 S cm^2 mol^{-1}), making KOH solutions more conductive at equal molarity. Conductivity peaks between 25 and 30 wt% KOH across the typical operating temperature range of 60–80°C; at 30 wt% and 80°C, values of 0.62–0.68 S cm^{-1} are consistently reported [8, 9]. The ASTI group confirmed this behaviour experimentally, recording σ = 0.54 S cm^{-1} at 25°C and 0.68 S cm^{-1} at 80°C for 30 wt% KOH, with a temperature coefficient of 0.02 K^{-1} [4].

Sodium hydroxide (NaOH) is cheaper and more widely available, but its lower ionic conductance typically results in 5–8 percentage points lower Faradaic efficiency at equivalent concentration [8]. Carbonate solutions (K_2CO_3, Na_2CO_3) offer an interesting theoretical advantage — lower corrosiveness towards mild steel containment — but carbonate precipitation on the anode during long-term operation raises cell voltage irreversibly and disqualifies them for sustained service [9].

Operating temperature strongly modulates performance. Raising the bath from 25°C to 70°C reduces the thermodynamic cell voltage from 1.48 V to approximately 1.43 V (thermoneutral), lowers electrolyte ohmic resistance, and accelerates reaction kinetics. The

ASTI developmental study recorded a 22% reduction in cell voltage, a 28% increase in hydrogen production rate, and a 15% improvement in energy efficiency over this temperature range [4]. Optimum operating temperature for 316L stainless steel electrodes in 30 wt% KOH was identified as 60–70°C; above 80°C, corrosion rates and seal degradation become significant concerns [3, 4].

Current density selection involves a fundamental trade-off between capital cost and energy efficiency. Lower current density demands larger, more expensive electrode area for the same production rate, but reduces ohmic and activation overpotential losses. The ASTI portable electrolyzer studies deliberately operated at ultra-low j = 2.94–3 mA cm^{-2} to maximise Faradaic efficiency (96%) and electrode longevity, accepting the cost penalty of large electrode area [3, 6]. Commercial industrial AEL stacks by contrast operate at 200–400 mA cm^{-2}, accepting lower Faradaic efficiency in exchange for reduced footprint [10].

4. Electrode materials and durability

Electrode material determines the magnitude of both the hydrogen evolution reaction (HER) overpotential at the cathode and the oxygen evolution reaction (OER) overpotential at the anode. These two overpotentials together typically account for 0.4–0.8 V of the total cell voltage beyond the thermodynamic minimum of 1.23 V (or 1.48 V thermoneutral), and thus represent the primary target for efficiency improvement [9].

316L austenitic stainless steel (nominally Fe–18Cr–10Ni–2Mo) has become the workhorse electrode material in low-cost AEL research precisely because it is inexpensive, readily available in sheet form, and adequately corrosion-resistant in concentrated KOH. ASTI studies confirm corrosion rates of 0.008–0.009 mm yr^{-1} in 30 wt% KOH, consistent with literature values below 0.01 mm yr^{-1} [3, 4, 11]. However, 316L exhibits poor OER catalytic activity: the ASTI JREE study established that OER kinetics on bare SS316L account for approximately 45% of total cell voltage losses, with a Tafel slope of ~120 mV $decade^{-1}$ compared with 40–60 mV $decade^{-1}$ for advanced NiFe-based catalysts [6].

Nickel and nickel-based alloys represent the next tier of electrode materials. Pure Ni (99.9%) reduces the cathode HER overpotential from ~400 mV (316L) to ~280 mV at 300 mA cm^{-2}, 80°C. Ni-Mo alloys, where molybdenum shifts the H-binding energy toward the thermoneutral optimum on the volcano plot, further reduce the cathode overpotential to 110–150 mV — a 2.5-fold improvement over 316L [9, 12]. On the anode side, NiFe layered double hydroxide (NiFe-LDH) coatings have emerged as the leading OER catalyst in alkaline media, with Tafel slopes of 40–60 mV $decade^{-1}$ and overpotentials of 270–320 mV at 300 mA cm^{-2} [13].

The practical case for 316L nonetheless remains strong for off-grid and distributed applications. ASTI's life-cycle projection, based on 1,000-hour accelerated corrosion testing, estimates electrode replacement intervals exceeding 20 years at j = 3 mA cm^{-2} [3, 4]. The projected hydrogen production cost of \$28 kg^{-1} at 2,000 operating hours per year is high in absolute terms but may be acceptable for isolated communities with no grid access [3]. A realistic pathway to improved economics without the capital cost of noble-metal catalysts is to apply electrodeposited Ni-Mo or NiFe-LDH coatings to a 316L substrate, exploiting the structural advantage of the latter while gaining catalytic activity from the former.

5. Photovoltaic–electrolyzer integration and power management

Coupling an AEL cell to a photovoltaic array introduces a fundamental power quality challenge: the I–V characteristic of the PV array shifts continuously with irradiance and cell temperature, while the AEL cell presents a nearly flat current-voltage curve above its activation voltage. In direct coupling, the operating point moves along the AEL polarisation curve as irradiance varies, producing large excursions in current density and Faradaic efficiency throughout the day [10, 14].

Maximum-power-point-tracking (MPPT) converters address this mismatch by continuously adjusting the duty cycle of a DC–DC converter to hold the PV array at its maximum power point while delivering a regulated current to the electrolyzer. The energy gain from MPPT depends on the variability of the solar resource: under the highly variable irradiance typical of partly-cloudy continental climates, gains of 12–15% (ASTI devos.uz study [4]) and 19–24% (ASTI student research [5]) have been measured relative to direct coupling. The P&O (perturb-and-observe) algorithm employed in the ASTI studies converges within 2–5 seconds, which is short relative to typical cloud transient durations of tens of seconds, meaning the controller tracks real solar conditions effectively [4, 5].

System-level efficiency is often quoted differently depending on the efficiency boundary selected. The ASTI devos.uz paper [4] reports ηsystem = 13.2%, calculated as ηPV (20%) × ηconverter (97%) × ηelectrolyzer (70% Faradaic × 95% gas utilisation). The JREE paper [6] reports a lower ηLHV = 9.6% because it uses the lower heating value (LHV) of hydrogen rather than Faradaic equivalence as the output metric, and operates at ultra-low j where electrode losses are smaller but the PV array is substantially underloaded. Readers comparing efficiency claims across publications should therefore take care to identify which boundaries and conventions are applied.

Annual hydrogen yield projections from the IJCTCM optimisation study [5] indicate that a 5 kW PV array with Ni-Mo/NiFe electrodes and MPPT control can produce 160–180 kg H_2 yr^{-1} under Andijan irradiance conditions (1,750 kWh m^{-2} yr^{-1}). Scaling to 10 kW raises this to 330–360 kg yr^{-1}. For comparison, a single heavy-duty fuel-cell truck consumes approximately 30–40 kg H_2 per 100 km, meaning a 10 kW solar-hydrogen unit could fuel a small local transport fleet for several thousand kilometres per year [1].

6. Techno-economic context

The levelised cost of hydrogen (LCOH) from renewable electrolysis has fallen sharply: from approximately \$16 kg^{-1} in 2010 to \$2–8 kg^{-1} in 2025 for utility-scale installations, driven by declining PV module costs and improved electrolyzer efficiency [2, 10]. The lower end of this range is competitive with grey hydrogen in regions with carbon pricing above \$80 tCO_2^{-1}. Small-scale distributed systems, such as those studied at ASTI, currently sit near the upper end of the range: the ASTI devos.uz analysis finds LCOH of \$5.2–7.8 kg^{-1} for < 10 kW systems and \$3.5–5.0 kg^{-1} for 10–100 kW systems at a 20–25% solar capacity factor [4]. The IJCT portable system estimate of \$28 kg^{-1} at 2,000 operating hours per year illustrates that ultra-small systems are not yet cost-competitive but may serve niche off-grid applications where the alternative is diesel generation [3].

Capital cost breakdown for the ASTI reference system is approximately: electrolyzer \$800 kW^{-1}, PV system \$400 kW^{-1}, balance of plant \$300 kW^{-1}, totalling \$1,500 kW^{-1} [4]. This is broadly consistent with IRENA's 2023 estimate of \$500–1,500 kW^{-1} for small alkaline electrolyzers [15]. The dominant lever for cost reduction at small scale is electrode area

utilisation: increasing current density from 3 mA cm^{-2} to 200 mA cm^{-2} reduces the required electrode area by nearly two orders of magnitude for the same production rate, dramatically lowering the electrolyzer capital cost, even if it modestly reduces Faradaic efficiency [10, 14].

7. Summary of key studies

Table 1 compiles the principal experimental studies reviewed in this paper alongside their key performance metrics.

Table 1. Summary of selected studies on solar-powered alkaline water electrolysis

Study	Configuration	Key finding	Efficiency	Ref.
Portable six-cell AEL (IJCT, 2026)	6 × 316L SS, 30% KOH, 70°C, 7.75 A	H_2 purity >99.5%, corrosion <0.008 mm/yr	ηFaradaic = 96%	[3]
Solar-driven AEL – techno-economic (Dev. Sci., 2025)	150 Wp PV + MPPT, 316L SS, 30% KOH	MPPT adds 12–15%; LCOH $2–8/kg	ηsystem = 13.2%	[4]
AEL system optimisation for Central Asia (IJCTCM, 2026)	PV 5–100 kW, 316L SS, 25–30% KOH, 25–80°C	Solar-to-H_2 = 13–15%; projected lifetime >20 yr	η = 13–15%	[5]
Performance evaluation – portable AEL (JREE, in press)	SS316L, ultra-low j = 3 mA/cm^2, PV coupled	OER on SS316L = 45% of total losses; 9.6% LHV eff.	ηLHV = 9.6%	[6]
Brauns & Turek (Processes, 2020)	Industrial AEL, variable RE input	Dynamic RE coupling strategies benchmarked	63–82%	[8]
Zeng & Zhang (PECS, 2010)	Review of AEL electrolytes & electrodes	KOH optimal; Ni-based cathodes superior	Up to 82%	[9]

8. Knowledge gaps and future directions

The reviewed body of work, including the ASTI publications, reveals several important gaps that future research should address:

- Long-term outdoor durability data are lacking. The longest stability tests reported by ASTI cover 1,000 hours under controlled laboratory conditions [3, 4]. Real outdoor operation with diurnal and seasonal thermal cycling, humidity variation, and dust deposition on PV modules may accelerate electrode and membrane degradation differently from laboratory predictions. Field trials of at least 5,000 hours are needed to validate lifetime projections.
- Advanced electrode coatings on 316L substrates have not yet been evaluated at ASTI. Electrodeposited Ni-Mo cathodes and NiFe-LDH anodes can reduce combined overpotential by 30–50% compared with bare 316L [12, 13], which would raise system efficiency and reduce LCOH substantially without the mechanical complexity of switching electrode substrates.

- Membrane and diaphragm characterisation is absent from the ASTI publications. The Zirfon® membrane widely used in industrial AEL cells adds ohmic resistance but prevents gas cross-contamination. Understanding how membrane resistance evolves in 30 wt% KOH at elevated temperature over thousands of hours is critical for system design.
- Electrolyzer operation at elevated pressure (10–30 bar) increases hydrogen partial pressure and can reduce downstream compression costs. Pressurised AEL has been demonstrated at laboratory scale but has not been explored at ASTI. The interaction between elevated pressure and 316L corrosion behaviour in KOH warrants investigation.
- Socio-economic feasibility for Uzbek end-users has not been quantified. A bottom-up analysis incorporating local labour costs, electricity tariff structures, potential hydrogen end-use markets (transport, fertiliser production, industrial heat), and the forthcoming national carbon market would sharpen investment cases for pilot projects.

9. Conclusions

This review has synthesised findings from four ASTI experimental publications alongside 14 international studies to provide a structured account of solar-powered alkaline water electrolysis. The principal conclusions are as follows:

1. 30 wt% KOH at 60–80°C is firmly established as the optimal electrolyte condition for AEL, delivering the highest ionic conductivity and the best balance between Faradaic efficiency and electrode durability. This finding is consistent across all ASTI studies and the broader literature.

2. 316L stainless steel provides commercially adequate corrosion resistance (< 0.01 mm yr^{-1}) and Faradaic efficiency near 96% at ultra-low current density, making it a viable entry-level electrode material for off-grid solar hydrogen systems. However, OER kinetics on bare SS316L account for 45% of total cell voltage losses, and electrode coatings capable of matching NiFe-LDH activity represent the highest-impact near-term upgrade.

3. MPPT power conditioning is a high-impact, low-complexity intervention that raises daily hydrogen yield by 12–24% relative to direct PV coupling and should be considered standard practice in any solar-hydrogen installation.

4. Under Andijan irradiance conditions (1,750 kWh m^{-2} yr^{-1}), a 5 kW PV array with MPPT control can produce 160–180 kg H_2 yr^{-1}, representing a technically viable baseline for decentralised green hydrogen in Uzbekistan. Scaling to 10 kW doubles output to 330–360 kg yr^{-1}.

5. LCOH for small-scale AEL systems in Uzbekistan currently ranges from \$5–28 kg^{-1}, depending on scale and operating hours. Improving current density, adopting advanced electrode coatings, and increasing capacity factor are the three levers most likely to bring costs below \$5 kg^{-1} by 2030.

References:

[1] IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency, Paris, 2021. 224 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 (IJCT). 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 (IJCTCM). 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 (JREE). 2026; 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 of the Republic of Uzbekistan. Official Gazette, 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] Schmidt O., Gambhir A., Staffell I., Hawkes A., Nelson J., Few S. Future cost and performance of water electrolysis: an expert elicitation study. International Journal of Hydrogen Energy. 2017; 42(52): 30470–30492. DOI: 10.1016/j.ijhydene.2017.10.045.
[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.
[12] Schalenbach M., Tjarks G., Carmo M., Lueke W., Mueller M., Stolten D. Acidic or alkaline? Towards a new perspective on the efficiency of water electrolysis. Journal of The Electrochemical Society. 2016; 163(11): F3197–F3208. DOI: 10.1149/2.0271611jes.
[13] Song F., Bai L., Moysiadou A., Lee S., Hu C., Liardet L., Hu X. Transition metal oxides as electrocatalysts for the oxygen evolution reaction in alkaline solutions. Journal of the American Chemical Society. 2018; 140(25): 7748–7759. DOI: 10.1021/jacs.8b04546.
[14] Terlouw T., Bauer C., McKenna R., Mazzotti M. Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. Energy & Environmental Science. 2022; 15(9): 3583–3602. DOI: 10.1039/D2EE00023G.
[15] IRENA. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal. International Renewable Energy Agency, Abu Dhabi, 2023. 106 p.
[16] Buttler A., Spliethoff H. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: a review. Renewable and Sustainable Energy Reviews. 2018; 82(3): 2440–2454. DOI: 10.1016/j.rser.2017.09.003.
[17] Shiva Kumar S., Himabindu V. Hydrogen production by PEM water electrolysis — a review. Materials Science for Energy Technologies. 2019; 2(3): 442–454. DOI: 10.1016/j.mset.2019.03.002.
[18] Shokhrukhbek Bakhramov, Daşdemirli, Y. & Yaşar, M. Electrochemical Characterization of 316L Stainless Steel Electrodes for Alkaline Water Electrolysis in Renewable Energy Applications. Russ J Electrochem 62, 131–141 (2026). https://doi.org/10.1134/S1023193525601366