



SOLAR-DRIVEN ALKALINE WATER SPLITTING FOR GREEN HYDROGEN GENERATION: ROLE OF ELECTROLYTE COMPOSITION, ELECTRODE SELECTION, AND PHOTOVOLTAIC POWER MANAGEMENT

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Abstract

Three student research projects conducted at Andijan State Technical Institute are unified in this paper to deliver a system-level perspective on solar-powered alkaline hydrogen generation. The first project (Ibrohimov O.B.) screened five alkaline solutions — KOH at two concentrations, NaOH at two concentrations, and K_2CO_3 — with respect to ionic conductivity and long-term electrochemical stability. The second project (Yunusov Kh.F.) characterised five electrode configurations, ranging from conventional 316L stainless steel to a bespoke Ni-Mo cathode / NiFe-oxide anode pairing. The third project (Keldiboyev I.I.) quantified how maximum-power-point-tracking (MPPT) control shapes the annual hydrogen output of a grid-independent photovoltaic (PV) electrolyzer. Taken together, the data establish that a 5 kW PV installation operating under Andijan irradiance conditions, filled with 30 wt% KOH, and fitted with Ni-Mo | NiFe composite electrodes plus MPPT control, can deliver 160–180 kg of emission-free hydrogen annually.

Keywords: green hydrogen, alkaline electrolysis, potassium hydroxide, Ni-Mo electrode, NiFe oxide, overpotential, MPPT, photovoltaic integration, Uzbekistan.

1. Introduction

Decarbonising the global energy supply ranks among the most urgent scientific and engineering challenges of this century. Molecular hydrogen has gained considerable attention as an energy carrier capable of storing and transporting renewable electricity in chemical form. The IEA projects that demand for low-emission hydrogen will grow sixfold by 2050, reaching roughly 530 million tonnes per year [1]. Yet the overwhelming majority of hydrogen produced today — approximately 96% — derives from fossil-fuel reforming and carries a substantial carbon footprint. Electrolytic splitting of water using electricity sourced from solar panels eliminates this footprint entirely, yielding only oxygen as a co-product [2].

Central Asia, and Uzbekistan in particular, holds substantial untapped solar potential. Measurements across the Fergana Valley record annual global horizontal irradiance values of 1,600–1,900 kWh m⁻² and more than 2,800 sunshine hours, favourably comparing with leading solar-energy regions worldwide. Recognising this advantage, the Government of Uzbekistan enacted Presidential Decree PD-60 on 18 April 2023, which sets binding targets for renewable capacity expansion and explicitly calls for the development of domestic hydrogen technologies [3].

Translating this resource into reliable hydrogen output requires simultaneous optimisation across three subsystems. First, the electrolyte must offer high ionic conductivity while remaining chemically stable over thousands of operating hours. Second, the electrodes must catalyse both the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER) with minimal energy loss. Third, the power-conditioning electronics must harvest the maximum available solar power even as irradiance fluctuates throughout the day. Addressing any one of these aspects in isolation tends to underestimate the coupling effects and may lead to suboptimal engineering decisions [4].

This paper synthesises findings from three parallel laboratory investigations carried out within the Renewable Energy Sources group of Andijan State Technical Institute. By reporting electrolyte screening, electrode benchmarking, and system-level modelling within a single coherent framework, it aims to provide actionable design guidance for small-scale solar hydrogen units suited to the Uzbek context.

2. Experimental

All work was carried out in the Alternative Energy Sources Laboratory at Andijan State Technical Institute. A standardised test platform was used across the three studies: borosilicate glass electrolysis cells (500 mL internal volume), a precision thermostat holding the bath at 80 ± 0.5 °C, planar electrodes with an active area of 100 cm^2 ($10 \text{ cm} \times 10 \text{ cm}$), and a bench-top power supply operating in galvanostatic mode at $j = 300 \text{ mA cm}^{-2}$.

2.1 Electrolyte screening (Ibrohimov O.B.). Aqueous solutions of KOH (25 and 30 wt%), NaOH (20 and 30 wt%), and K_2CO_3 (25 wt%) were evaluated. Identical Ni-Mo electrodes were used in every run to isolate the electrolyte variable. Ionic conductivity was determined with an LCR bridge; cell voltage was logged automatically at 10-minute intervals over 500 hours of continuous operation. Evolved hydrogen was collected by downward water displacement and its volume converted to mass at standard conditions.

2.2 Electrode characterisation (Yunusov Kh.F.). Five electrode configurations were tested in 30 wt% KOH at 80 °C: (i) 316L austenitic stainless steel (nominally Fe-18Cr-10Ni-2Mo), (ii) commercially pure nickel (99.9 wt%), (iii) electrodeposited Ni-Mo alloy (Ni:Mo = 80:20 by mass), (iv) hydrothermally synthesised NiFe layered-double-hydroxide (NiFe-LDH) coating on a Ni substrate, and (v) a paired composite cell combining the Ni-Mo cathode with the NiFe-LDH anode. Electrochemical characterisation comprised cathodic and anodic linear sweep voltammetry (scan rate 1 mV s^{-1}), electrochemical impedance spectroscopy (EIS; frequency range 0.1 Hz to 100 kHz; amplitude 10 mV rms), and a 100-hour galvanostatic endurance test at 300 mA cm^{-2} .

2.3 PV-electrolyzer system modelling (Keldiboyev I.I.). A programmable DC source emulating the PV I-V characteristic was used to replay a recorded irradiance time-series for Andijan city (latitude 40.8° N ; data year 2022). Experiments were run in two modes: direct coupling of the PV emulator to the electrolyzer, and coupling through a digitally controlled MPPT converter implementing the perturb-and-observe (P&O) algorithm. Annual hydrogen production was extrapolated from daily measurements and cross-checked with Faradaic calculations. Both 5 kW and 10 kW nominal PV capacities were modelled.

3. Results and discussion

3.1 Electrolyte selection (Ibrohimov O.B.)

Measured conductivities, steady-state operating voltages, and Faradaic efficiencies at $j = 300 \text{ mA cm}^{-2}$ are compiled in Table 1.

Table 1. Electrochemical characteristics of candidate electrolyte solutions (80 °C, $j = 300 \text{ mA cm}^{-2}$)

Solution	Conc. (wt%)	σ (mS/cm)	Operating voltage (V)	Faradaic eff. (%)
KOH	25	580	1.85	76–80
KOH	30	620	1.80	78–82
NaOH	20	420	1.96	71–74
NaOH	30	490	1.90	73–76
K ₂ CO ₃	25	310	2.10	65–68

30 wt% KOH stood out on every metric: conductivity reached 620 mS cm^{-1} , the cell ran at 1.80 V, and Faradaic efficiency settled in the 78–82% band. Reducing KOH concentration to 25% lowered conductivity by approximately 7% and raised the cell voltage by 50 mV. NaOH solutions were consistently inferior to their KOH counterparts of equal concentration, a result attributable to the lower equivalent ionic conductance of Na^+ relative to K^+ . K₂CO₃ showed the weakest performance: within 500 hours a whitish deposit formed on the anode surface, identified by energy-dispersive X-ray spectroscopy as potassium carbonate crystals, which progressively blocked active sites and raised the cell voltage by more than 150 mV. On the basis of these findings, 30 wt% KOH was selected as the standard electrolyte for all subsequent experiments [5].

3.2 Electrode performance (Yunusov Kh.F.)

HER and OER overpotentials measured at 300 mA cm^{-2} alongside overall efficiencies and durability ratings are listed in Table 2.

Table 2. Electrochemical benchmarking of electrode materials (30 wt% KOH, 80 °C)

Electrode	HER η (mV)	OER η (mV)	Overall eff. (%)	Durability
316L SS	380–420	420–460	62–65	Poor
Ni (99.9%)	260–300	380–430	67–70	Moderate
Ni-Mo alloy	110–150	350–390	74–78	Good
NiFe oxide	230–270	270–320	72–76	Good
Ni-Mo NiFe	100–140	260–300	78–82	Excellent

The Ni-Mo | NiFe composite cell recorded the lowest HER overpotential (100–140 mV) and the lowest OER overpotential (260–300 mV) simultaneously, translating into an overall Faradaic efficiency of 78–82%. The mechanistic basis for Ni-Mo's exceptional HER activity is well established: molybdenum shifts the free energy of hydrogen adsorption on nickel towards the thermoneutral Sabatier optimum, placing Ni-Mo near the apex of the HER volcano plot. For the NiFe-LDH anode, iron substitution into the nickel hydroxide lattice raises the average oxidation state of nickel during OER, generating highly active $\text{Ni}^{3+}/\text{Ni}^{4+}$ species and thereby reducing the OER onset potential [6]. The 100-hour endurance test revealed only a 1.2% drop in Faradaic efficiency for the Ni-Mo | NiFe cell. In stark contrast, 316L stainless steel lost 6.8%

of its initial efficiency over the same period owing to selective dissolution of chromium and iron from the steel matrix in concentrated alkali, a degradation pathway confirmed by inductively coupled plasma analysis of the spent electrolyte.

3.3 PV-coupled system performance (Keldiboyev I.I.)

Projected annual hydrogen outputs and system efficiencies for the configurations under study are reported in Table 3.

Table 3. Projected annual performance of PV-electrolyzer configurations (Andijan irradiance: $1,750 \text{ kWh m}^{-2} \text{ yr}^{-1}$)

Configuration	PV capacity (kW)	H ₂ output (kg/yr)	System eff. (%)	MPPT benefit
316L SS, no MPPT	5	110–120	58–62	—
Ni-Mo, no MPPT	5	130–145	68–72	—
Ni-Mo + MPPT	5	155–170	74–78	+19%
Ni-Mo NiFe + MPPT	5	160–180	78–82	+24%
Ni-Mo NiFe + MPPT	10	330–360	79–83	+24%

Direct coupling of the PV array to the electrolyzer (no MPPT) exposed the cell to large current swings as cloud cover caused irradiance to oscillate between 0.3 and 1.0 kW m^{-2} . Under such conditions gas bubble accumulation on electrode surfaces during low-irradiance intervals and the associated overpotential spikes during high-irradiance bursts collectively reduced the time-averaged hydrogen production rate. Inserting the P&O MPPT converter smoothed the delivered current and raised daily hydrogen yield by 19–24% relative to the direct-coupled baseline. For the fully optimised stack — 5 kW PV, 30 wt% KOH, Ni-Mo | NiFe electrodes, MPPT converter — annual output reached 160–180 kg H₂. Doubling the PV capacity to 10 kW scaled production to 330–360 kg yr⁻¹, sufficient to fuel a small fleet of hydrogen-powered vehicles or to cover the annual thermal-energy demand of roughly 20 households [7].

A cross-study observation deserves emphasis: the three parameters interact non-linearly. Replacing 316L steel with Ni-Mo | NiFe electrodes alone raised efficiency by 13–17 percentage points; adding MPPT control on top of that contributed a further 4–6 points. The combined gain of 17–24 points substantially exceeds a naive sum-of-parts estimate and underscores the value of holistic system optimisation rather than sequential, single-variable improvement.

4. Conclusions

1. Among all electrolyte candidates screened, 30 wt% KOH solution offers the best combination of ionic conductivity (620 mS cm^{-1}), low cell voltage (1.80 V), and long-term chemical stability. K₂CO₃-based electrolytes are contraindicated for sustained operation owing to progressive anode fouling.

2. The paired Ni-Mo cathode / NiFe-oxide anode configuration outperforms all single-material electrodes tested, achieving the lowest combined overpotential ($\sim 380\text{--}440 \text{ mV}$ at 300 mA cm^{-2}) and the smallest efficiency decay ($< 1.5\%$ over 100 hours), making it the preferred electrode system for alkaline water splitting.

3. MPPT power conditioning raises the hydrogen yield of a variable-irradiance PV-electrolyzer by 19–24% relative to direct coupling and should be treated as a mandatory component rather than an optional upgrade.



4. The fully integrated system — 5 kW PV array, 30 wt% KOH, Ni-Mo | NiFe electrodes, MPPT — generates 160–180 kg of emission-free hydrogen per year under Andijan climatic conditions, establishing a technically viable baseline for decentralised green hydrogen production in Uzbekistan.

5. Future work should address extended lifetime testing beyond 1,000 hours, outdoor weathering effects on electrode morphology, and techno-economic evaluation at pilot scale to validate commercial feasibility.

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