COMPREHENSIVE STUDY OF ELECTROLYTE TYPE, ELECTRODE MATERIAL, AND SYSTEM EFFICIENCY IN SOLAR-POWERED ALKALINE WATER ELECTROLYSIS FOR HYDROGEN PRODUCTION

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Abstract

This paper presents the combined results of three interrelated studies: (1) the effect of electrolyte type — KOH, NaOH, and K_2CO_3 — on hydrogen production in an alkaline electrolyzer; (2) the effect of electrode material — 316L stainless steel, pure Ni, Ni-Mo alloy, NiFe oxide, and Ni-Mo/NiFe composite — on electrochemical efficiency; and (3) an overall system efficiency analysis of a photovoltaic (PV) array integrated with an alkaline electrolyzer via an MPPT controller. Experimental results show that 30% KOH provides the highest ionic conductivity (620 mS/cm), while the Ni-Mo/NiFe composite electrode achieves the lowest overpotential. Combined with an MPPT controller, a 5 kW PV system can produce 160–180 kg of green hydrogen per year under Andijan, Uzbekistan climatic conditions.

Keywords: *alkaline electrolysis, KOH, NaOH, electrode material, Ni-Mo alloy, NiFe oxide, MPPT, solar energy, hydrogen production, efficiency.*

Introduction

Hydrogen energy is increasingly recognised as a key enabler in the transition to a low-carbon economy. According to the International Energy Agency (IEA), hydrogen is expected to account for 18% of global final energy demand by 2050 [1]. Currently, however, over 96% of hydrogen is produced from natural gas via steam methane reforming, releasing substantial amounts of CO_2. Water electrolysis powered by renewable energy — particularly solar photovoltaics — offers a carbon-free alternative that produces only oxygen as a by-product [2].

Uzbekistan is actively positioning itself to exploit this opportunity. Presidential Decree No. PD-60 (18 April 2023) designates renewable energy deployment and hydrogen technology research as national priorities. The country's solar resources are exceptional: annual solar irradiation reaches 1,600–1,900 kWh/m^2 with more than 2,800 sunshine hours per year, providing a strong and reliable energy basis for electrolysis systems [3].

The performance of an alkaline electrolyzer depends on three tightly coupled factors: (a) electrolyte type and concentration, which govern ionic conductivity, corrosion behaviour, and long-term stability; (b) electrode material, which determines overpotential losses and durability; and (c) power management, which maximises energy extraction from a variable solar source. Studying these factors in isolation risks missing important interactions; a holistic, combined analysis is therefore essential [4].

This paper integrates findings from three coordinated student research projects — Ibrohimov O.B. (electrolyte effect), Yunusov Kh.F. (electrode material effect), and Keldiboyev I.I. (system-level efficiency) — into a unified analysis that covers the full chain from electrolyte selection to annual hydrogen yield.

Materials and methods

All experiments were conducted in the Renewable Energy Sources Laboratory of Andijan State Technical Institute. The test setup comprised 500 mL borosilicate glass electrolysis cells, a thermostat maintaining 80°C, 10×10 cm electrodes, and a current density of $j = 300$ mA/cm^2 for all comparative tests.

Study 1 (Ibrohimov O.B.) — Electrolyte screening: Five electrolyte solutions were tested — KOH (25% and 30%), NaOH (20% and 30%), and K_2CO_3 (25%) — using identical Ni-Mo electrodes. Ionic conductivity was measured with an LCR meter; cell voltage was monitored over 500 hours. Hydrogen volume was collected by water displacement.

Study 2 (Yunusov Kh.F.) — Electrode characterisation: Five electrode materials were evaluated in 30% KOH at 80°C — (i) 316L stainless steel (Fe-18Cr-8Ni-2Mo), (ii) pure Ni (99.9%), (iii) Ni-Mo alloy (80:20 wt%), (iv) NiFe oxide coating, and (v) Ni-Mo/NiFe composite (Ni-Mo cathode paired with NiFe oxide anode). Techniques: linear sweep voltammetry (LSV, 1 mV/s), electrochemical impedance spectroscopy (EIS, 0.1 Hz–100 kHz), and a 100-hour stability test.

Study 3 (Keldiboyev I.I.) — System efficiency modelling: A PV emulator (0–48 V, 0–10 A) reproduced the real solar irradiance profile of Andijan city. Hydrogen yield was compared with and without an MPPT controller (P&T100 algorithm). Annual H_2 output was calculated for 5 kW and 10 kW PV systems, benchmarked against the Faradaic efficiency.

Results and discussion

1. Effect of Electrolyte Type (Ibrohimov O.B.)

Table 1 summarises the key electrochemical parameters for each electrolyte at $j = 300$ mA/cm^2 and 80°C.

Table 1. Comparative performance of electrolyte solutions ($j = 300$ mA/cm^2, 80°C)

Electrolyte	Conc.	σ (mS/cm)	Cell voltage (V)	Efficiency (%)
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_2CO_3	25%	310	2.10	65–68

30% KOH delivered the highest ionic conductivity (620 mS/cm) and the lowest cell voltage (1.80 V), yielding an efficiency of 78–82%. NaOH at the same concentration provided lower conductivity (490 mS/cm), resulting in 5–7 percentage points lower efficiency. K_2CO_3 performed worst: within 500 hours, carbonate precipitates accumulated on the anode surface, raising cell voltage and degrading efficiency to 65–68%. These results confirm that 30% KOH is the optimal electrolyte for alkaline hydrogen electrolysis under the tested conditions, consistent with the established literature [5].

2. Effect of Electrode Material (Yunusov Kh.F.)

Table 2 reports cathode and anode overpotentials (η) and overall efficiency for each electrode in 30% KOH at 80°C.

Table 2. Electrochemical performance of electrode materials (30% KOH, 80°C, j = 300 mA/cm²)

Electrode	Cathode η (mV)	Anode η (mV)	Efficiency (%)	Stability
316L steel	380–420	420–460	62–65	Low
Pure Ni	260–300	380–430	67–70	Moderate
Ni-Mo	110–150	350–390	74–78	High
NiFe oxide	230–270	270–320	72–76	Mod.–High
Ni-Mo/NiFe	100–140	260–300	78–82	High

The Ni-Mo/NiFe composite electrode simultaneously minimised both cathode and anode overpotentials (100–140 mV and 260–300 mV, respectively), achieving an overall efficiency of 78–82%. Over the 100-hour stability test its efficiency declined by only 1.2%, compared with 6.8% for 316L steel, which underwent surface corrosion in the alkaline environment. The superior HER activity of Ni-Mo is explained by the Volcano principle: Mo atoms shift the hydrogen adsorption energy of Ni towards the optimal Sabatier value. The enhanced OER activity of NiFe oxide arises from Fe incorporation raising the valence of Ni and promoting oxygen-evolving surface species [6].

3. System Efficiency Analysis (Keldiboyev I.I.)

Table 3 presents annual hydrogen yields and system efficiencies for different PV-electrolyzer configurations under Andijan irradiance conditions (1,750 kWh/m²/yr).

Table 3. Annual performance of PV-electrolyzer configurations (Andijan, 1,750 kWh/m²/yr)

System configuration	PV power (kW)	H_2 yield (kg/yr)	System eff. (%)	MPPT gain
PV + 316L (no MPPT)	5	110–120	58–62	—
PV + Ni-Mo (no MPPT)	5	130–145	68–72	—
PV + Ni-Mo (MPPT)	5	155–170	74–78	+19%
PV + Ni-Mo/NiFe (MPPT)	5	160–180	78–82	+24%
PV 10 kW + Ni-Mo/NiFe	10	330–360	79–83	+24%

The MPPT controller stabilised the average current density as solar irradiance varied between 0.3 and 1.0 kW/m² throughout the day, increasing daily H_2 yield by 19–24% compared with direct-coupled configurations. The optimal combination — 5 kW PV array, 30% KOH electrolyte, Ni-Mo/NiFe electrodes, and MPPT control — produced 160–180 kg H_2 per year, sufficient to meet the annual energy needs of approximately 10 households. Scaling to a 10 kW PV system raised annual production to 330–360 kg [7].

Taken together, the three studies demonstrate that optimising each subsystem independently is insufficient: when all three factors — electrolyte, electrode, and power management — are jointly optimised, overall system efficiency rises from a baseline of 58–65% (316L steel, no MPPT) to 78–82% (Ni-Mo/NiFe, MPPT), an absolute improvement of 13–24 percentage points.

Conclusions

1. Among the electrolytes tested, 30% KOH solution provides the highest ionic conductivity (620 mS/cm) and the best efficiency (78–82%); K_2CO_3 is unsuitable for long-term operation due to anode fouling.

2. The Ni-Mo/NiFe composite electrode (Ni-Mo cathode + NiFe oxide anode) delivers the lowest combined overpotential (~380–440 mV) and the highest stability (efficiency loss < 1.5% per 100 hours) among all electrode configurations studied.

3. An MPPT controller increases daily hydrogen yield by 19–24% in a variable-irradiance solar environment, making it an essential component of any PV-coupled electrolyzer.

4. Under Andijan, Uzbekistan climatic conditions, the combination of a 5 kW PV array, 30% KOH electrolyte, Ni-Mo/NiFe electrodes, and MPPT control can produce 160–180 kg of green hydrogen per year, representing a viable decentralised energy solution.

5. Further research should focus on scaling these findings to pilot-plant level and assessing long-term durability (> 1,000 hours) under real outdoor operating conditions in Central Asia.

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