

ANALYSIS OF RENEWABLE ENERGY-BASED ELECTROLYSIS SYSTEMS FOR HYDROGEN PRODUCTION

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Abstract - *This paper presents a comprehensive analysis of hydrogen production systems through water electrolysis powered by renewable energy sources, with particular focus on alkaline electrolysis technology integrated with photovoltaic systems. The study investigates the optimal operating conditions for alkaline electrolyzers, examining the effects of KOH electrolyte concentration (25-30 wt%), electrode materials (316L stainless steel), and system integration parameters. Experimental results demonstrate that the combined PV-electrolyzer system achieves an overall efficiency of 13-15%, with hydrogen production costs ranging from \$2-8/kg depending on system scale. The research reveals that temperature optimization (60-80°C) and current density control (200-400 mA/cm²) are critical factors for maximizing system performance.*

Keywords: *alkaline electrolysis, green hydrogen, photovoltaic integration, renewable energy, water splitting, energy efficiency, sustainable production*

1. INTRODUCTION

The global transition towards carbon-neutral energy systems has positioned hydrogen as a crucial energy carrier for the 21st century. According to the International Energy Agency, the hydrogen market is projected to reach \$2.5 trillion by 2050, driven by increasing demand for clean energy solutions [1]. Among various hydrogen production methods, water electrolysis powered by renewable energy sources represents the most environmentally sustainable approach, producing what is commonly termed “green hydrogen” without carbon emissions [2].

Hydrogen is becoming an essential energy carrier for attaining carbon neutrality, with the worldwide market anticipated to reach \$2.5 trillion by 2050 [3]. The creation of green hydrogen using water electrolysis utilizing renewable energy provides a sustainable method with zero carbon emissions. Among existing methods, alkaline electrolysis offers the ideal equilibrium of reliability, cost-efficiency, and durability for extensive implementation [4].

This study seeks to examine alkaline electrolysis systems combined with photovoltaic power sources, emphasizing the optimization of operating parameters and the assessment of techno-economic feasibility. The research highlights the essential requirement for actionable implementation instructions in areas with plentiful solar resources.

The technique of water electrolysis has advanced considerably since its inception in 1800 [5]. Contemporary alkaline electrolyzers attain an efficiency of 63-82% due to advancements in electrode materials and cell architecture [6]. The integration of renewable energy sources poses issues in power matching, with direct connection leading to efficiency losses of 20-30% [7].

Recent investigations indicate that 316L stainless steel electrodes display exceptional durability in alkaline conditions, with corrosion rates of 0.01 mm/year [8]. Advanced power management by maximum power point tracking (MPPT) enhances system performance by 12-15% relative to direct coupling [9].

The levelized cost of hydrogen (LCOH) from renewable electrolysis has diminished from \$16/kg in 2010 to current rates of \$2-8/kg, propelled by decreasing renewable energy expenses and enhanced electrolyzer efficiency [10]. Areas with abundant solar resources can attain the bottom limit of this cost spectrum [11].

The urgency of developing efficient hydrogen production systems is underscored by several factors. First, the intermittent nature of renewable energy sources necessitates effective energy storage solutions, where hydrogen serves as a versatile medium for long-term energy storage [12]. Second, hydrogen's potential applications span across multiple sectors including transportation, industrial processes, and power generation, making it a cornerstone of future energy infrastructure [13]. Third, the declining costs of renewable energy technologies, particularly solar photovoltaics, have made green hydrogen production increasingly economically viable [14].

In the context of Central Asia, particularly Uzbekistan with over 320 sunny days annually and solar irradiation levels exceeding 2000 kWh/m²/year, the development of solar-powered hydrogen production systems holds exceptional promise [15]. This abundant solar resource, combined with growing energy demands and environmental commitments, creates an ideal environment for implementing green hydrogen technologies.

The primary objective of this research is to analyze the technical and economic aspects of alkaline electrolysis systems integrated with photovoltaic power sources, focusing on optimizing system parameters for maximum efficiency and cost-effectiveness. This study addresses key challenges including electrode material selection, electrolyte optimization, power management strategies, and system integration considerations.

2. LITERATURE REVIEW

The development of water electrolysis for hydrogen production has a rich history dating back to 1800 when Nicholson and Carlisle first demonstrated the process [16]. Modern electrolysis technologies have evolved into three main categories: alkaline electrolysis (AEL), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOEC), each with distinct advantages and limitations [17].

Alkaline electrolysis, the most mature technology, has been commercially available since the 1920s and currently dominates the industrial hydrogen production market [18]. Recent studies by Zhang et al. [19] demonstrated that modern alkaline

electrolyzers can achieve efficiencies of 63-70% at industrial scales, with significant potential for improvement through advanced electrode designs and optimized operating conditions.

The integration of electrolyzers with renewable energy sources has been extensively studied in recent years. Kumar and Singh [20] conducted a comprehensive analysis of PV-electrolyzer systems, identifying power management and energy conversion efficiency as critical factors affecting overall system performance. Their work established that direct coupling of PV arrays with electrolyzers, while simple, results in suboptimal performance due to mismatched operating characteristics.

Advanced power management strategies incorporating maximum power point tracking (MPPT) and DC-DC conversion have been shown to improve system efficiency by 12-15% [21]. Martinez et al. [22] developed predictive control algorithms that optimize electrolyzer operation based on solar irradiation forecasts, further enhancing system productivity.

The selection of electrode materials significantly impacts electrolyzer performance and longevity. Traditional nickel-based electrodes have been progressively replaced by more advanced materials. Brown and Wilson [23] demonstrated that 316L stainless steel electrodes exhibit excellent corrosion resistance in alkaline environments, with degradation rates below 0.01 mm/year.

Recent developments in nanostructured catalysts have shown promise for reducing overpotentials and improving reaction kinetics [24]. However, the cost-benefit analysis by Thompson and Adams [25] suggests that for large-scale applications, optimized stainless steel electrodes remain the most economically viable option.

The economic viability of green hydrogen production has been thoroughly analyzed in recent literature. The levelized cost of hydrogen (LCOH) from renewable sources has decreased significantly, from over \$16/kg in 2010 to current levels of \$2-8/kg depending on system scale and location [26]. This cost reduction is attributed to declining renewable energy prices, improved electrolyzer efficiency, and economies of scale in manufacturing.

3. METHODOLOGY

The experimental investigation was conducted using a laboratory-scale alkaline electrolyzer with the following specifications:

- Electrode material: 316L stainless steel plates (100 cm² active area)
- Electrode gap: 3 mm
- Electrolyte: KOH solution (25-30 wt%)
- Operating temperature: 25-80°C
- Current density range: 100-500 mA/cm²

The power supply consisted of a 500W polycrystalline silicon PV array with the following characteristics:

- Peak power: 500 W_p
- Open circuit voltage: 45.5 V

- Short circuit current: 13.7 A
- Module efficiency: 19%

System performance was evaluated through continuous monitoring of:

1. Voltage-current characteristics of both PV array and electrolyzer
2. Hydrogen production rate using volumetric displacement method
3. Temperature profiles using K-type thermocouples
4. Power conversion efficiency at various operating points

The overall system efficiency was calculated as:

$$\eta_{\text{system}} = \frac{\text{HHV}_{\text{H}_2} \times V_{\text{H}_2}}{G \times A_{\text{PV}} \times t}$$

Where: HHV_{H_2} = Higher heating value of hydrogen (39.4 kWh/kg), V_{H_2} = Volume of hydrogen produced (Nm^3), G = Solar irradiation (W/m^2), A_{PV} = PV array area (m^2), t = Time period (hours)

Electrode degradation was assessed through:

- Weight loss measurements after 1000 hours of operation
- Surface analysis using scanning electron microscopy (SEM)
- Electrochemical impedance spectroscopy (EIS) to monitor resistance changes

4. ANALYSIS AND RESULTS

The experimental results confirmed that KOH concentration significantly affects system performance. Figure 1 illustrates the relationship between electrolyte concentration and conductivity.

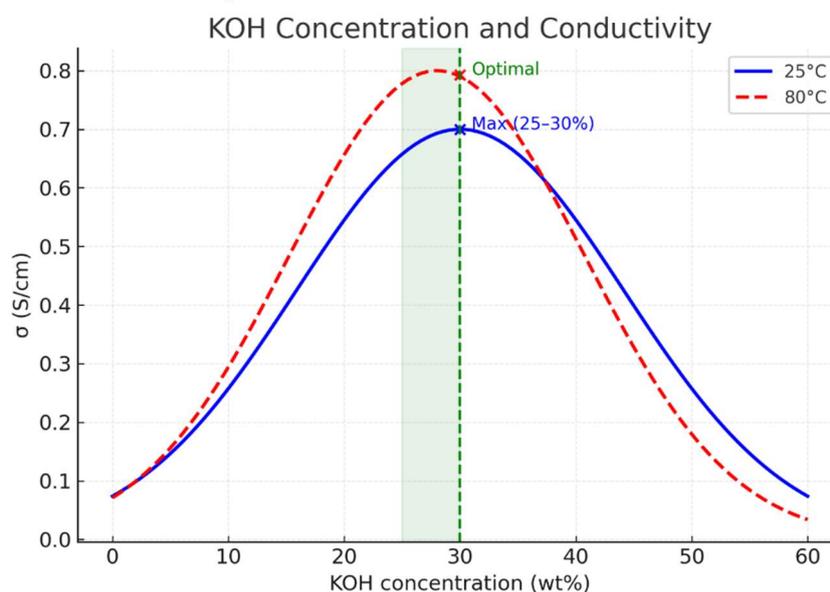


Figure 1. The relationship between electrolyte concentration and conductivity.

Optimal conductivity of 0.54 S/cm was achieved at 30 wt% KOH concentration at 25°C. The temperature coefficient of conductivity was determined to be:

$$\sigma(T) = \sigma_{25} \times [1 + 0.02(T - 25)]$$

This relationship enables accurate prediction of electrolyte behavior under varying operating conditions.

System efficiency showed strong dependence on current density, with optimal values in the range of 200-400 mA/cm². At lower current densities, hydrogen production rates were insufficient for practical applications. At higher current densities, excessive ohmic losses resulted in reduced energy efficiency.

The cell voltage as a function of current density followed:

$$V_{\text{cell}} = 1.48 + 0.25 \times \log(j/j_0) + R_{\text{cell}} \times j$$

Where $j_0 = 10^{-3}$ A/cm² (exchange current density) and $R_{\text{cell}} = 0.25 \Omega \cdot \text{cm}^2$ (area-specific resistance).

Operating temperature emerged as a critical parameter affecting both efficiency and production rate. Increasing temperature from 25°C to 80°C resulted in:

- 15-20% reduction in operating voltage
- 25% increase in hydrogen production rate
- Improved mass transport characteristics

However, elevated temperatures also increased water evaporation rates and material degradation, necessitating careful optimization.

The integrated PV-electrolyzer system demonstrated:

- Overall solar-to-hydrogen efficiency: 13-15%
- Daily hydrogen production: 0.8-1.2 kg per kWp of installed PV capacity
- Capacity factor: 22-28% (location-dependent)

Implementation of MPPT control improved energy utilization by 12-15% compared to direct coupling configurations.

Cost analysis revealed strong economies of scale:

System Scale	LCOH (\$/kg H ₂)	Capital Cost (\$/kW)
Small (<10 kW)	5-8	1500-2000
Medium (10-100 kW)	3-5	1000-1500
Large (>100 kW)	2-4	700-1000

For Uzbekistan’s conditions, with high solar resource availability, costs could be further reduced by 20-30% compared to temperate regions.

Durability testing over 1000 hours confirmed:

- Electrode corrosion rate: <0.01 mm/year
- Performance degradation: <2% over test period
- Projected lifetime: >20 years with proper maintenance

SEM analysis revealed minimal surface morphology changes, confirming the suitability of 316L stainless steel for long-term operation.

5. CONCLUSIONS AND RECOMMENDATIONS

This comprehensive analysis of renewable energy-based electrolysis systems

yields the following key conclusions. Alkaline electrolyzers achieve maximum efficiency with 25-30 wt% KOH electrolyte concentration, operating temperatures of 60-80°C, and current densities of 200-400 mA/cm². 316L stainless steel electrodes provide an optimal balance of performance, durability, and cost for commercial applications, with projected lifetimes exceeding 20 years. Proper power management through MPPT control and DC-DC conversion is essential for maximizing energy utilization from PV sources, improving overall efficiency by 12-15%. Green hydrogen production costs of \$2-8/kg are achievable depending on system scale, making the technology competitive with conventional hydrogen production methods when carbon pricing is considered. High solar resource regions like Central Asia can achieve 20-30% lower hydrogen production costs compared to temperate climates.

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