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Solar-Energized Alkaline Electrolyzers: A Path to Sustainable and Efficient Hydrogen Production

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Abstract

The Present examines the design of an alkaline electrolyzer model powered by solar energy, in which different electrolytes, i.e., KOH, NaCl, and NaOH are dissolved in water to generate hydrogen gas, explicitly targeting the production of renewable green hydrogen as an HHO-gas most sustainably and least carbon emission. This method of hydrogen production aligns with the increasing emphasis on renewable energy sources and the need for scalable, clean energy systems that can meet future energy demands while minimizing environmental impact. As such, solar-powered electrolysis is poised to play a vital role in developing a hydrogen economy and the broader goals of achieving energy sustainability and security. This work focuses on uncovering the highest HHO gas yield with the least corrosion involved in an automated temperature and pressure-regulated alkaline electrolyzer. The experiment employs 316L stainless steel as the electrode material due to its significantly lower corrosion rates up to 10 to 100 times less corrosive than carbon steel. The experimental results, focusing on green hydrogen production, power efficiency, and material sustainability, show a remarkable agreement with the mathematical model, confirming that the gas generators consistently deliver the specified output across various operational conditions.

Keywords: Alkaline Electrolyzer; Electrolyte Efficiency; Green Hydrogen Production; Solar-Electrolysis

1. INTRODUCTION

The ever-increasing demand for clean and sustainable energy solutions has spurred significant research into innovative technologies to lower carbon emissions and solve the energy crisis. One of them is solar-powered hydrogen production, also known as Green Hydrogen. This paper presents the design and development of a solar-powered electrolyzer system aimed at producing green hydrogen gas, a clean-burning fuel with the potential to revolutionize the energy frameworks in use.

H_2 has the highest specific energy of any fuel now in use, at 33.31 kW h kg−1, making it one of the most efficient and eco-friendly achievable fuels. The primary objective of this study is to explore the feasibility of green hydrogen production using a sustainable and renewable energy source like solar power. This approach minimizes greenhouse gas emissions and promotes energy independence by reducing reliance on finite fossil fuels.

In aiming to produce the most low-emission hydrogen fuel, the research explores the integration of solar panels with the electrolyzer system as a zero-emission power source. In an interpretative study by M. A. Khan et al., the experimental work shows that a stable system with solar to hydrogen efficiency of 28% can be obtained upon optimizing the configuration of concentrator photovoltaic-electrolysis cells (40.7% efficient) and available alkaline electrolyzers (70% efficient).[1]

In addition to the energy sources, the electrodes are the crucial components of the electrolysis process. They are typically made of conductive materials like stainless steel or nickel. The choice of electrode material significantly impacts the electrolyzer's efficiency and durability. According to a study, various electrode designs were compared by Yilmaz et al. [2], who reported that the electrodes made of 316 L stainless steel plates were understood as the best material for a cathodic electrode in an alkaline electrolyte medium due to their high corrosion resistance characteristics. The electrolyte is the medium through which the electric current flows.

The different electrolytes are judged on their HHO gas production efficiency under similar and regulated temperatures and pressures and are found among the best and highest-yielding electrolytes. In an analysis of HHO gas generation, Balaji Subramanian et al. [3] describe the electrolytes solution of NaOH, NaCl, and KOH, which are widely used in alkaline electrolysis due to their highly reactive nature. A comparative study by A.K. El Soly et. al [4] reveals how various factors such as effects of different electrolytes and their concentration, plate connections, cell gap, electric current, operating temperature, time and voltage affect the yield of HHO gas production flow rate.

For analyzing and carrying on the finding-dependent research, an experimental model is set through which various measures can be examined, and among them, the best ones can be observed. We are evaluating the best practices to help us simulate the electrolyzer system's production of oxyhydrogen gas (HHO) as clean energy under various operating conditions like electrolyte concentration, current density, temperature, and pressure factors.

The experimental setup includes a Solar Panel Array, Electrolyzer Cell, and Gas Collection System. Toward the cessation of the study, the experimental results are studied and compared with the pre-existing methods to find the most suitable ones that produce highly efficient and clean green hydrogen gas through a solar-powered alkaline electrolyzer.

2. ELECTROLYSIS PROCESS

Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolysis driven by solar power has been proven to be the most promising option for carbon-free hydrogen production from renewable resources [5]. It is an increasingly promising approach for sustainable hydrogen production.

This process integrates photovoltaic (PV) solar panels with an electrolyzer to split water (H_2O) into hydrogen (H_2) and oxygen (O_2) as shown in Figure 1. The photovoltaic panels, typically composed of semiconductor materials like silicon, convert sunlight into direct current (DC) electricity through the photovoltaic effect. This electricity is then supplied to the electrolyzer, where it drives the electrochemical reactions necessary for water splitting.

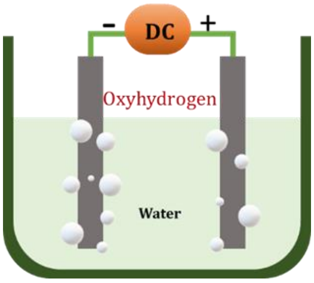

FIGURE 1. Oxyhydrogen production layout through the electrolysis process

The electrolyzer is composed of two electrodes a positively charged anode and a negatively charged cathode submerged in an electrolyte. Upon application of the DC electricity from the solar panels, water molecules at the anode undergo oxidation, producing oxygen gas, protons (H^+), and electrons. The reaction occurring at the anode is represented by:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

The generated protons migrate through the electrolyte towards the cathode, where they combine with the electrons supplied through the external circuit, resulting in the production of hydrogen gas. The cathodic reaction can be represented by:

$$4H^+ + 4e^- \rightarrow 2H^+$$

The hydrogen produced through electrolysis is utilized in fuel cells, industrial applications, and as a green fuel, while the oxygen, the byproduct, can be used industrially or released. The process's success hinges on solar panel performance, the choice of electrolytes, and the electrolyzer design. Efforts in research aim to boost efficiency and cut costs through improvements in solar technology, electrolyzer materials, and system integration, enhancing the feasibility of solar-powered hydrogen production.

3. CELL CONFIGURATION AND ELECTROLYSIS CELL DESIGN

The electrolyzer system design plays a crucial role in the electrolysis process. To conduct electrolysis there are many various types of electrolysers present like Alkaline Electrolyzer, PEM Electrolyzer, Solid Oxide Electrolyzer (SOE), and Anion Exchange Membranes (AEM). Through several studies, in a finding by A.K. El Soly et al. [6] concluded that Higher HHO gas is produced from wet cells compared to dry cells for the same design conditions because all the electrodes are immersed in the electrolyte solution and the active surface area of the electrodes is increased compared to the dry cell.

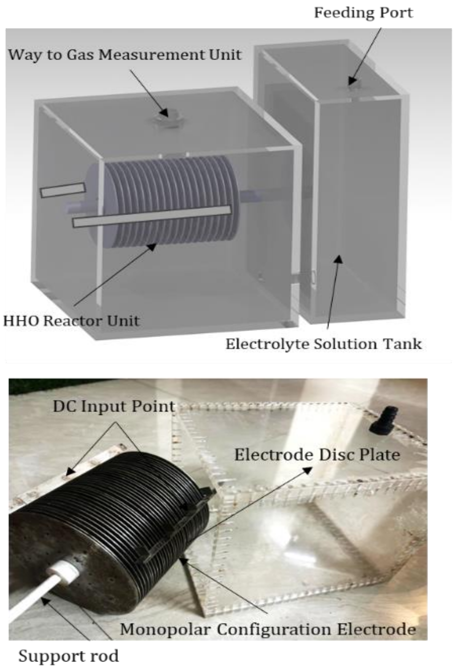

FIGURE 2.HHO generator setup details

In the presented experimental setup as shown in Figure 2. we employ a 316L stainless steel alkaline electrolyzer, which offers superior corrosion resistance and durability, essential for maintaining efficiency in highly alkaline environments, such as those containing KOH. The low carbon content of 316L stainless steel enhances its resistance to pitting and crevice corrosion, ensuring consistent electrolysis performance over time. Its smooth surface promotes better conductivity, reducing electrical resistance and facilitating higher hydrogen production.

Several studies highlight the high corrosion resistance of 316L stainless steel, showing up to 10 to 100 times less corrosion than other metals (Yilmaz et al., 2021) [7]. This makes it an excellent material for prolonged electrochemical reactions, yielding higher volumes of HHO gas at lower operational voltages. The high surface area of the wet cell configuration allows for more efficient reactions, further improving gas yield and reducing energy consumption.

The choice of 316L stainless steel in our electrolyzer enhances not only the overall efficiency but also the economic feasibility of large-scale green hydrogen production. Given its resilience and performance in demanding electrolysis conditions, it stands out as a reliable option for maximizing HHO gas output while minimizing corrosion-related issues. This material selection directly contributes to the system's ability to sustain high production rates, supporting the goals of renewable energy development and energy sustainability.

3.1. Electrolyte Selection and Observation

Our research investigated the influence of electrolyte choice, concentration, temperature, and electrode gap on the efficiency of green hydrogen production through alkaline water electrolysis.

We found that Potassium Hydroxide (KOH) consistently outperforms other electrolytes, exhibiting the highest HHO (oxyhydrogen) production rates across a range of concentrations. As illustrated in Figure 3, the HHO production rate increases linearly with increasing electrolyte concentration for all electrolytes tested, with KOH achieving the highest production rates, reaching 1.0 L/min at a concentration of 1.4 M. [7] Sodium Hydroxide (NaOH) offers a cost-effective alternative with a production rate of 0.7 L/min at the same concentration, demonstrating its potential as a viable option for large-scale hydrogen production. In contrast, Sodium Chloride (NaCl) and Sodium Carbonate (Na_2CO_3) exhibit significantly lower production rates, indicating that they are less suitable for high-efficiency hydrogen generation.

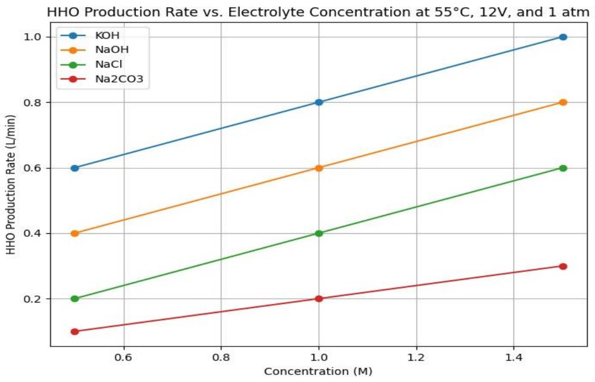

FIGURE 3.HHO production rate

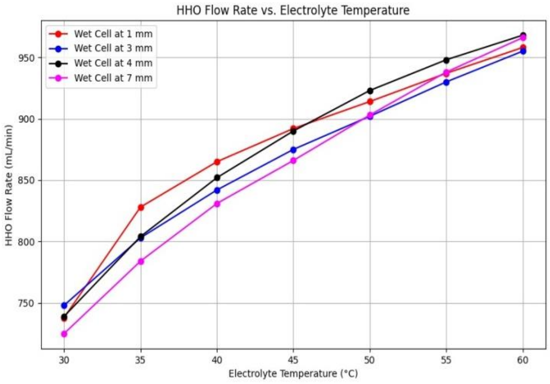

FIGURE 4.HHO Flow Rate

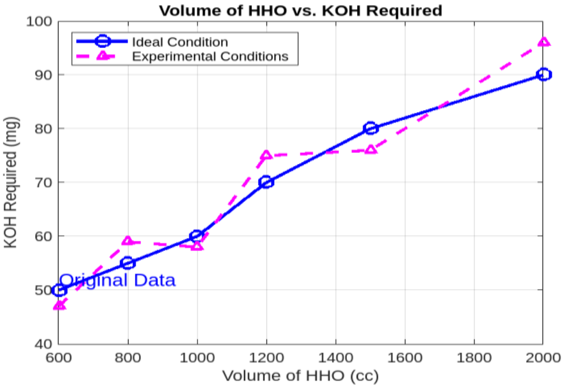

FIGURE 5. Ideal production v/s actual experimental production on KOH

We also investigated the impact of temperature and electrode gap on HHO production, as illustrated in Figure 3. Higher electrolyte temperatures and narrower electrode gaps further enhanced the production efficiency [7]. The data clearly shows that higher electrolyte temperatures enhance HHO production rates. For instance, when the electrolyte temperature increases from 30°C to 60°C, HHO flow rates for the 1 mm cell gap increase by approximately 30%. This suggests that narrower gaps between electrodes facilitate better ion transport and reduce resistance, thereby boosting electrolysis efficiency. The 7 mm cell gap, on the other hand, shows the lowest performance, emphasizing the importance of optimizing electrode configuration for efficient HHO production.

These findings underscore the crucial role of optimizing both electrolyte choice and operating conditions for maximizing hydrogen production. KOH emerges as the preferred electrolyte for high-efficiency alkaline water electrolysis, particularly when combined with higher temperatures and narrower electrode gaps. Our research provides valuable insights for the design and development of more efficient and scalable green hydrogen production systems.

Explanation of Data Integration is shown in Figure 3. The added specific data points (KOH at 1.4 M producing 1.0 L/min, NaOH at 1.4 M producing 0.7 L/min) to provide a quantitative comparison of electrolyte performance. And also mentioned the linear trend observed in the graph. It included the 30% increase in HHO flow rate for the 1 mm gap between 30°C and 60°C to quantify the impact of temperature. The highlighted contrasting performance of the 1 mm and 7 mm gaps demonstrates the importance of electrode configuration as shown in Figure 4. And in Figure 5. describes the comparative study of ideal production v/s actual experimental production when using KOH as an electrolyte.

3.2. Inhibitor to Corrosion by Electrolyte

In this study, the effectiveness of imidazole derivatives as corrosion inhibitors was examined to mitigate electrode degradation in alkaline water electrolysis systems, particularly against the corrosive effects of electrolytes like KOH, NaOH, KCl and Na_2CO_3. Recognizing the corrosion challenge, which drastically impairs electrolyzer performance and durability, our investigation focused on applying synthesized imidazole derivatives to electrodes. These derivatives are noted for their capacity to establish protective films on surfaces, thereby reducing corrosion rates.

The experimental setup entailed the preparation of 25% concentrated electrolyte solutions, into which different concentrations of imidazole derivatives were introduced. The electrodes were then immersed in these solutions at controlled temperatures (25°C, 50°C) and humidity. Corrosion rates were quantitatively assessed through electrochemical impedance spectroscopy and cyclic voltammetry, providing insights into the efficacy of the inhibitors. Findings revealed a significant enhancement in the corrosion resistance of 316L stainless steel electrodes within alkaline environments, ascribed to the application of imidazole derivatives.

Moreover, the study highlights the impact of environmental conditions like temperature on corrosion rates, with elevated temperatures accelerating the degradation process. It can be found that leveraging imidazole derivatives as corrosion inhibitors emerges as a viable strategy to improve alkaline water electrolyzers' operational stability and efficiency, which is crucial for advancing green hydrogen production at a commercial scale.

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3.4. Solar-Powered Electrolysis and its Hybrid Energy Storage System

Solar-powered electrolyzers offer a renewable way to produce hydrogen, significantly cutting down on fossil fuel reliance and greenhouse gas emissions. Achieving energy independence and combating climate change are key benefits of this sustainable method.

One of the primary challenges we face in solar-powered electrolysis is the intermittent nature of solar power due to fluctuations in daylight and weather, which can be mitigated using a hybrid energy storage system that combines supercapacitors and lead-acid batteries. Supercapacitors provide rapid energy storage and release, making them ideal for short-term fluctuations, while lead-acid batteries offer long-term energy storage for periods of reduced solar availability. Figure 6. shows a Block diagram of a stand-alone PV system with a battery and charge controller.

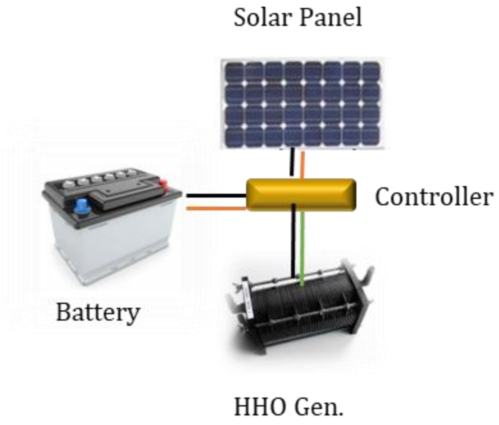

FIGURE 6. Block diagram for PV backup

The setup involves a supercapacitor bank, configured in parallel to achieve the desired capacitance (e.g., 100F), connected to the charge controller and the electrolysis system and a lead-acid battery bank, assembled in series to achieve the required voltage (e.g., 12V) and in parallel to increase capacity (e.g., 100Ah).

A dual charge controller is installed to manage the supercapacitor and battery banks, ensuring efficient energy flow from the solar panels to the storage devices while preventing overcharging. The charge controller prioritizes charging the supercapacitors due to their fast-charging capabilities and directs any surplus energy to the lead-acid batteries for storage. When solar energy is insufficient, the supercapacitors discharge first, offering short-term power support. Once depleted, the lead-acid batteries provide long-term backup power until solar irradiance is restored. The Energy Management System (EMS) further enhances system efficiency by actively monitoring energy flow and adjusting power distribution to ensure optimal performance.

3.5. Carbon Footprint Calculation

The carbon footprint and energy consumption associated with hydrogen production via renewable sources such as photovoltaic (PV) and concentrated solar power (CSP) systems are critical metrics in assessing the sustainability of green hydrogen. Regarding carbon emissions, the footprint of PV-driven hydrogen production processes is estimated to be between 1.03 and 1.87 kg CO_2 per kilogram of hydrogen. In contrast, CSP-driven processes generate approximately 1.05 to 1.67 kg CO_2 per kilogram of hydrogen.

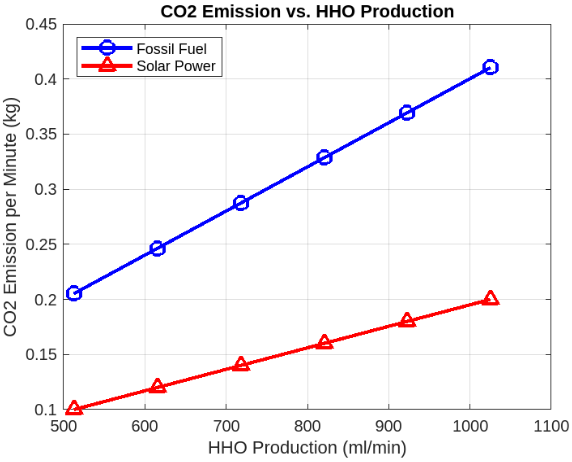

Figure 7 CO_2 Emission Vs. HHO production

The carbon footprint for solar-based alkaline electrolysis is estimated at 2 to 2.3 kg CO_2 per kilogram of hydrogen and can potentially emit as little as 1 kg of CO_2 per kilogram of hydrogen produced, depending on the efficiency of the system and the renewable electricity supply chain. The overall sustainability of solar-powered hydrogen production is influenced by the energy intensity involved in manufacturing solar equipment.

Moreover, manufacturing photovoltaic systems requires more energy, which slightly increases the carbon footprint of hydrogen production via solar energy. Figure 7. In the conducted experiment, it was analyzed and calculated how much carbon emission is cut with the help of CSP systems instead of traditional energy sources. Efforts to improve the manufacturing efficiency of solar technologies and optimize electrolysis processes are essential to further reduce the carbon emissions associated with solar-powered hydrogen generation.

4. DISCUSSION

In our experimental setup, the performance of the 316L stainless steel alkaline electrolyzer was evaluated across different electrolytes (KOH, NaOH, and NaCl) and varying operating conditions. The data demonstrate that KOH produced the highest yield of HHO gas, reaching 1.0 L/min at 1.4 M concentration, significantly outperforming NaOH and NaCl. The results also showed that the increase in temperature from 30°C to 60°C, along with the reduction of the electrode gap, led to an approximate 30% increase in gas production, particularly for narrower gaps, which facilitated better ion transport.

The high corrosion resistance of 316L stainless steel, especially in KOH environments, ensured minimal degradation and contributed to long-term system stability, with 10 to 100 times lower corrosion rates than other materials (Yilmaz et al., 2021). Additionally, integrating a hybrid energy storage system combining supercapacitors and lead-acid batteries mitigated the issue of solar intermittency, ensuring continuous electrolyzer operation even during low irradiance periods.

CONCLUSION

This research demonstrates that combining 316L stainless steel and KOH as the electrolyte in a solar-powered alkaline electrolyzer offers high efficiency in producing green hydrogen. The system's design maximized HHO gas yield, while the hybrid energy storage system addressed solar power variability. The results align with the mathematical model predictions, confirming that the proposed setup can sustain efficient hydrogen production with minimal carbon emissions. The findings support the scalability of this approach for renewable energy applications, contributing to the global transition towards a hydrogen economy.

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