

Design, Fabrication, and Performance Evaluation of a Zero-Gap Alkaline Water Electrolyser for Sustainable Hydrogen Production and Fuel Cell Power Generation

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Abstract

The transition toward sustainable energy systems has increased interest in hydrogen as a clean energy carrier. This study presents the design, fabrication, and evaluation of a single-cell zero-gap alkaline water electrolyser for hydrogen production and subsequent electricity generation through a fuel cell. The developed electrolyser utilised a 30 wt.% potassium hydroxide (KOH) electrolyte, nickel electrodes, and selected polymer-based structural materials evaluated for mechanical strength, corrosion resistance, and electrical suitability. Material selection was conducted using engineering property analysis, while thermal and mechanical stability of the electrolyser components were assessed through numerical simulations. The system operated at temperatures around 50°C, atmospheric pressure conditions, and applied voltages below 3.0V. Hydrogen and oxygen were generated through alkaline electrolysis and separated using a porous membrane. Experimental evaluation showed that polytetrafluoroethylene (PTFE) provided improved durability compared with polypropylene for endplates and spacers, while polypropylene nonwoven geotextile demonstrated effective membrane performance at reduced cost. The optimised operating condition occurred at 2.2 V and 1.30 A, producing approximately 14 ml/min of hydrogen. The electrolyser achieved an electrolysis efficiency of 55.6%, an energy efficiency of 67.3%, and a hydrogen production efficiency of 75.4%. The produced hydrogen and oxygen were successfully converted into electrical energy using a reversible fuel cell with a proton exchange membrane, demonstrating the feasibility of integrating alkaline electrolysis with fuel cell technology for small-scale renewable energy applications.

Keywords: alkaline electrolysis; hydrogen production; water electrolyser; fuel cell; renewable energy; hydrogen energy system.

Accepted 6/5/2026

Published: 6/6/2026

1. INTRODUCTION

The increasing global demand for energy, coupled with the urgent need to reduce greenhouse gas emissions, has accelerated the transition toward sustainable and low-carbon energy technologies. Conventional energy systems remain heavily dependent on fossil fuels such as coal, oil, and natural gas, which contribute significantly to climate change through carbon dioxide (CO₂) emissions. As nations seek to achieve net-zero carbon targets and improve energy security, hydrogen has emerged as a promising energy carrier capable of supporting the decarbonisation of multiple sectors, including electricity generation, transportation,

and industrial manufacturing (International Energy Agency [IEA], 2023).

Hydrogen possesses several characteristics that make it attractive for future energy systems. It has a high gravimetric energy density of approximately 120 MJ kg⁻¹, which is nearly three times greater than that of gasoline. When utilised in fuel cells or combustion processes, hydrogen produces water as its primary by-product, eliminating direct carbon emissions at the point of use (Dincer & Acar, 2015). Furthermore, hydrogen can serve as an energy storage medium, allowing excess electricity generated from intermittent renewable sources such as solar photovoltaic and wind power systems to be stored and later converted back into electricity when required.

This capability addresses one of the major challenges associated with renewable energy integration, namely the mismatch between electricity generation and demand.

Among the various hydrogen production pathways, water electrolysis has attracted significant attention because it enables the production of high-purity hydrogen without direct greenhouse gas emissions when powered by renewable electricity. Electrolysis involves the decomposition of water into hydrogen and oxygen through the application of electrical energy. The technology is particularly important in the development of green hydrogen, which is produced using renewable energy sources and is considered essential for achieving long-term climate goals (IEA, 2023).

Several electrolysis technologies are currently available, including alkaline water electrolysis (AWE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis. Among these technologies, alkaline water electrolysis remains one of the most mature and commercially established methods for hydrogen production. Industrial alkaline electrolyzers have been used for more than a century and continue to dominate large-scale hydrogen production due to their relatively low capital cost, long operational lifespan, and ability to utilise non-precious metal catalysts such as nickel (Ursúa et al., 2012). In contrast to PEM electrolyzers, alkaline systems generally require less expensive materials and exhibit greater tolerance to impurities, making them attractive for small-scale and decentralised applications.

The fundamental operation of an alkaline electrolyser involves passing direct current through an aqueous alkaline electrolyte, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH). At the cathode, water molecules are reduced to produce hydrogen gas and hydroxide ions, while at the anode, hydroxide ions are oxidised to generate oxygen gas. The gases are separated by a porous diaphragm or membrane that permits ionic transport while preventing gas crossover. The efficiency of the electrolysis process is influenced by several factors, including electrode material, electrolyte concentration, operating temperature, cell configuration, and internal electrical resistance (Carmo et al., 2013).

Recent research has focused on improving electrolyser efficiency through innovative cell architectures, advanced catalyst materials, and enhanced separator technologies. One notable development is the zero-gap electrolyser configuration, in which the electrodes are positioned directly adjacent to the separator membrane. This arrangement minimises ionic transport distance, reduces ohmic losses, improves current distribution, and increases hydrogen production rates compared with conventional gap-based designs (Smolinka et al., 2011). Consequently, zero-gap configurations have become increasingly attractive for compact and energy-efficient hydrogen generation systems.

In addition to hydrogen production, integrating electrolyzers with fuel cell technologies provides a complete hydrogen energy cycle. Fuel cells convert the

chemical energy stored in hydrogen directly into electrical energy through electrochemical reactions, achieving higher efficiencies than conventional combustion-based power generation systems. Such integrated systems offer significant potential for renewable energy storage, backup power generation, remote electrification, and microgrid applications (Bessarabov et al., 2016).

This study presents the design, fabrication, and performance evaluation of a laboratory-scale zero-gap alkaline water electrolyser developed for sustainable hydrogen production and subsequent electricity generation through a proton exchange membrane fuel cell. The research investigates the selection of suitable structural and membrane materials, evaluates thermal and mechanical performance through simulation analyses, and assesses electrochemical performance under controlled operating conditions. Furthermore, the study examines the feasibility of integrating alkaline electrolysis with fuel cell technology as a low-cost approach to hydrogen-based energy storage and power generation. The results support the ongoing development of affordable and efficient hydrogen systems capable of supporting future renewable energy infrastructures.

2. LITERATURE REVIEW

2.1 Hydrogen as an Energy Carrier

Hydrogen has been widely recognised as a strategic energy carrier capable of supporting the transition from fossil fuel-based energy systems to sustainable and low-carbon alternatives. Unlike primary energy sources such as coal, petroleum, natural gas, solar radiation, and wind, hydrogen functions as a secondary energy carrier because it must be produced from hydrogen-containing compounds such as water, hydrocarbons, or biomass. Its importance lies in its ability to store, transport, and convert energy efficiently while producing minimal environmental impacts during utilisation (Dincer & Acar, 2015).

One of the most attractive characteristics of hydrogen is its exceptionally high gravimetric energy density of approximately 120 MJ kg^{-1} , which exceeds that of conventional fossil fuels. This property makes hydrogen particularly suitable for applications requiring lightweight energy storage, including transportation and aerospace systems. Furthermore, when hydrogen is used in fuel cells, the primary reaction product is water, eliminating direct emissions of carbon dioxide, sulphur oxides, and particulate matter (International Energy Agency [IEA], 2023).

The growing deployment of renewable energy technologies has further increased interest in hydrogen-based energy systems. Renewable electricity generation from solar and wind resources is inherently intermittent because energy production depends on environmental conditions. Hydrogen provides a viable solution to this challenge by enabling excess electricity to be converted into chemical energy through electrolysis and

subsequently stored for future use. This concept, commonly referred to as power-to-hydrogen (P2H), has become a key component of long-duration energy storage strategies and future smart-grid infrastructures (IRENA, 2022).

Hydrogen can also contribute to the decarbonisation of sectors that are difficult to electrify directly. Heavy industries such as steel manufacturing, ammonia production, chemical processing, maritime transportation, and long-haul freight transport require high energy densities and continuous energy supply. Green hydrogen produced through renewable-powered electrolysis offers a pathway for reducing emissions in these sectors while maintaining industrial productivity (IEA, 2023).

Despite its advantages, hydrogen faces several challenges related to production costs, storage requirements, transportation infrastructure, and system efficiency. These challenges continue to motivate research into more efficient hydrogen production technologies and integrated energy systems capable of improving overall economic viability.

2.2 Hydrogen Production Technologies

Hydrogen can be produced through several pathways that differ significantly in terms of environmental impact, efficiency, and economic feasibility. The most common production methods include fossil fuel reforming, biomass conversion, thermochemical processes, and water electrolysis.

2.2.1 Steam Methane Reforming

Steam methane reforming (SMR) currently accounts for approximately 70–80% of global hydrogen production. The process involves reacting methane with steam at elevated temperatures (700–1000°C) to produce hydrogen and carbon monoxide, followed by a water-gas shift reaction that generates additional hydrogen and carbon dioxide (Dincer & Acar, 2015).

Although SMR offers relatively low production costs and high efficiency, it remains heavily dependent on fossil fuels and produces significant greenhouse gas emissions. Carbon capture and storage technologies can reduce these emissions, resulting in what is commonly termed "blue hydrogen." However, concerns remain regarding carbon leakage and long-term environmental sustainability.

2.2.2 Biomass-Based Hydrogen Production

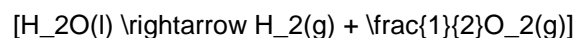
Biomass gasification and biological conversion processes provide renewable alternatives for hydrogen production. During gasification, biomass feedstocks are thermochemically converted into synthesis gas containing hydrogen, carbon monoxide, and methane. Subsequent processing increases hydrogen concentration for industrial applications.

Biomass-derived hydrogen has the potential to achieve near-carbon-neutral operation when sustainable feedstocks are used. However, challenges related to feedstock availability, process complexity, and land-use requirements limit widespread implementation (IRENA, 2022).

2.2.3 Water Electrolysis

Water electrolysis is considered one of the most promising technologies for sustainable hydrogen production because it can produce high-purity hydrogen using renewable electricity. The process involves splitting water molecules into hydrogen and oxygen through electrochemical reactions.

The overall electrolysis reaction is:



The theoretical minimum electrical energy required corresponds to a reversible cell voltage of approximately 1.23 V under standard conditions. However, practical systems require higher voltages because of activation losses, ohmic resistance, and concentration overpotentials (Ursúa et al., 2012).

Electrolysis technologies can be broadly classified into alkaline water electrolysis (AWE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOEC). Among these, alkaline electrolysis remains the most commercially mature and cost-effective option for large-scale hydrogen production.

2.3 Alkaline Water Electrolysis

Alkaline water electrolysis is the oldest and most established electrochemical technology for hydrogen production. Commercial alkaline electrolyzers have been used in industrial applications for well over one hundred years due to their reliability, long service life, and relatively low capital costs (Ursúa et al., 2012).

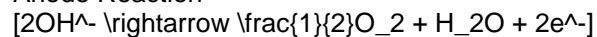
In alkaline electrolysis, an aqueous alkaline electrolyte—typically potassium hydroxide (KOH) or sodium hydroxide (NaOH)—facilitates ionic conductivity between the electrodes. Potassium hydroxide is generally preferred because it exhibits higher ionic conductivity and improved electrochemical performance.

The electrochemical reactions occurring within the cell are:

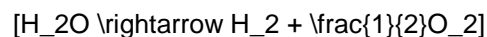
Cathode Reaction



Anode Reaction



Overall Cell Reaction



The generated hydroxide ions migrate through the electrolyte from the cathode to the anode, completing the

electrical circuit. The resulting hydrogen and oxygen gases are collected separately and can be used for energy storage or industrial applications.

The advantages of alkaline electrolysis include:

- Low material cost.
- Mature industrial technology.
- Long operational lifetime.
- Use of non-precious metal catalysts.
- High reliability and scalability.

However, alkaline systems also face limitations, including lower current densities than PEM electrolyzers, gas crossover risks, and reduced dynamic response during fluctuating renewable energy operation (Carmo et al., 2013).

2.4 Zero-Gap Electrolyser Technology

Conventional alkaline electrolyzers maintain a physical gap between the electrodes and the separator membrane. While this configuration simplifies assembly, it increases ionic transport distance and contributes to higher internal resistance.

To address these limitations, researchers have developed zero-gap alkaline electrolyser architectures. In a zero-gap design, the electrodes are positioned directly adjacent to the separator membrane, minimising the electrolyte path length and reducing ohmic losses (Smolinka et al., 2011).

Key advantages of zero-gap configurations include:

- Reduced internal electrical resistance.
- Improved current distribution.
- Enhanced gas production rates.
- Lower operating voltage requirements.
- Increased energy efficiency.

The reduction in inter-electrode distance significantly improves ion transport kinetics and decreases energy losses associated with electrolyte resistance. Consequently, zero-gap designs have become increasingly important in the development of compact and efficient hydrogen generation systems.

Several studies have demonstrated that zero-gap alkaline electrolyzers can achieve performance characteristics approaching those of PEM systems while maintaining the economic advantages associated with alkaline technology (Zeng & Zhang, 2010).

2.5 Electrode Materials for Alkaline Electrolysis

Electrode materials play a critical role in determining electrolysis efficiency, durability, and hydrogen production rates. The ideal electrode should possess:

- High electrical conductivity.
- Strong catalytic activity.
- Corrosion resistance.
- Mechanical durability.
- Low cost.

Nickel is the most widely used electrode material in alkaline electrolysis because it combines excellent corrosion resistance with favourable catalytic properties for hydrogen evolution and oxygen evolution reactions (Carmo et al., 2013).

Various electrode modifications have been investigated to improve performance, including:

- Nickel foam structures.
- Nickel-molybdenum alloys.
- Nickel-iron catalysts.
- Surface-coated catalytic electrodes.

Nickel foam electrodes are particularly attractive because their porous structure provides a larger active surface area, increasing reaction rates and reducing overpotentials.

2.6 Membranes and Separators

The separator membrane is a critical component of alkaline electrolyzers because it prevents hydrogen and oxygen gas mixing while allowing ionic transport between electrodes.

Commercial alkaline electrolyzers frequently utilise Zirfon-based separators due to their excellent chemical stability, low gas permeability, and high ionic conductivity. However, these materials contribute significantly to overall system cost (Smolinka et al., 2011).

Alternative polymer-based separator materials have therefore attracted research interest. Materials such as polypropylene (PP), polytetrafluoroethylene (PTFE), and nonwoven polymer fabrics offer potential cost reductions while maintaining acceptable performance.

The ideal separator should exhibit:

- High ionic conductivity.
- Low gas crossover.
- Excellent chemical resistance.
- Mechanical strength.
- Long operational lifetime.

Material selection remains a major factor influencing electrolyser efficiency, safety, and economic viability.

2.7 Integration of Electrolyzers and Fuel Cells

The integration of water electrolyzers with fuel cells creates a complete hydrogen energy cycle capable of storing renewable electricity and supplying power when required.

During periods of excess renewable electricity generation:

Renewable electricity → Electrolyser → Hydrogen production

During periods of energy demand:

Hydrogen → Fuel cell → Electricity generation

Fuel cells convert chemical energy directly into electrical energy through electrochemical reactions without combustion. Proton exchange membrane (PEM) fuel cells are particularly attractive because they operate at relatively low temperatures, exhibit rapid start-up

characteristics, and achieve high conversion efficiencies (Bessarabov et al., 2016).

Integrated hydrogen systems offer several advantages:

- Long-duration energy storage.
- Renewable energy balancing.
- Backup power generation.
- Remote-area electrification.
- Reduced greenhouse gas emissions.

Consequently, hydrogen-based energy storage is increasingly recognised as an essential component of future sustainable energy infrastructures.

2.8 Research Gap

Despite significant advancements in hydrogen production technologies, several challenges persist. Commercial electrolyser systems often rely on expensive membranes, specialised materials, and sophisticated control systems, which limit their adoption in small-scale and developing-region applications.

Furthermore, many studies focus primarily on large-scale industrial electrolysers, leaving limited research on affordable laboratory-scale systems that combine low-cost materials, zero-gap architectures, and integrated fuel cell applications.

This study addresses these gaps by developing a compact zero-gap alkaline water electrolyser using commercially available materials, evaluating alternative membrane options, and demonstrating practical electricity generation through fuel cell integration. The research contributes to the development of accessible and cost-effective hydrogen technologies that can support decentralised renewable energy systems.

Yes. For most undergraduate dissertations, Chapter 3 should be **concise and focused on what you actually did**, not a textbook explanation of electrolysis. The version I wrote is more suitable for a journal paper or master's thesis.

3.1 METHODOLOGY

Briefly explain the experimental approach used to design, fabricate, and test the zero-gap alkaline electrolyser.

3.2 Electrolyser Design

- Single-cell zero-gap configuration
- Nickel electrodes
- 30 wt.% KOH electrolyte
- PTFE endplates and spacers
- Polypropylene nonwoven membrane

3.3 Material Selection

Brief comparison of:

- PTFE vs Polypropylene
- Membrane materials tested
- Selection criteria:
 - o Chemical resistance
 - o Mechanical strength
 - o Thermal stability
 - o Cost

3.4 Simulation Analysis

One short section describing:

- Mechanical stress analysis
- Thermal analysis
- Verification of structural stability

3.5 Fabrication Process

Short description of:

- Component manufacturing
- Assembly
- Sealing and leak testing

3.6 Experimental Procedure

Include:

- Operating temperature (50°C)
- Pressure (0.1 MPa)
- Voltage range (0–3.0 V)
- Hydrogen collection method
- Current and voltage measurements

3.7 Performance Evaluation

Only include the key equations:

Hydrogen production rate:

$$Q_{\text{H}_2} = \frac{V_{\text{H}_2}}{t}$$

Energy efficiency:

$$\eta_{\text{energy}} = \frac{E_{\text{hydrogen}}}{E_{\text{electrical}}} \times 100$$

Hydrogen production efficiency and electrolysis efficiency can be described briefly without extensive derivations.

3.8 Fuel Cell Testing

This section includes a paragraph explaining that the generated hydrogen and oxygen were supplied to a reversible PEM fuel cell in order to evaluate its electricity generation capability.

4. RESULTS AND DISCUSSION

4.1 Electrolyser Material Performance Evaluation

Material selection is a critical factor influencing the durability, safety, and performance of alkaline water electrolysers. The developed electrolyser was exposed to a highly alkaline environment containing 30 wt.% potassium hydroxide (KOH), elevated operating

temperatures, and continuous electrical loading. Therefore, the selected materials were required to exhibit strong chemical resistance, adequate mechanical strength, and long-term dimensional stability.

Two polymer materials, polytetrafluoroethylene (PTFE) and polypropylene (PP), were evaluated for structural applications including endplates and spacers. Experimental observations showed that PTFE demonstrated superior resistance to alkaline attack and maintained dimensional stability throughout testing. No visible cracking, swelling, or degradation was observed

during operation. In contrast, polypropylene exhibited minor dimensional changes after prolonged exposure to the electrolyte, indicating lower chemical stability.

The superior performance of PTFE can be attributed to its highly inert fluorinated molecular structure, which provides exceptional resistance to chemical corrosion and thermal degradation. Similar observations have been reported in electrochemical system applications where PTFE is frequently selected for components exposed to aggressive electrolytes (Zeng & Zhang, 2010).

Table 4.1: Comparison of Structural Materials Evaluated for Electrolyser Construction

Property	PTFE	Polypropylene
Chemical resistance to KOH	Excellent	Good
Thermal resistance	Excellent	Moderate
Mechanical stability	High	Moderate
Dimensional stability	High	Moderate
Relative cost	Higher	Lower
Suitability for electrolyser structure	Excellent	Acceptable

Note. Adapted from material property data reported by Zeng and Zhang (2010).

Photograph of fabricated PTFE endplate and spacer assembly

The membrane evaluation produced similar findings. Commercial Zirfon separators exhibited excellent gas separation characteristics but were considerably more expensive than alternative materials. Polypropylene nonwoven geotextile provided acceptable gas separation performance and maintained structural integrity throughout testing. Polyester-based geotextiles, however, degraded rapidly in the alkaline environment and were therefore considered unsuitable.

These results indicate that low-cost polymer alternatives may be successfully utilised in small-scale alkaline electrolyser systems when appropriate material selection criteria are applied.

4.2 Electrochemical Performance

The electrochemical performance of the electrolyser was investigated by varying the applied voltage and

measuring the corresponding current and hydrogen production rate.

As expected, increasing cell voltage resulted in increased current flow and greater hydrogen production. This behaviour occurs because higher voltages provide a larger driving force for the electrochemical reactions occurring at the electrode surfaces.

At voltages below approximately 1.8 V, hydrogen production remained relatively low because a significant portion of the supplied electrical energy was consumed in overcoming activation losses and internal resistance. As voltage increased beyond this threshold, hydrogen generation increased substantially.

The optimum operating condition was identified at:

- Cell voltage = 2.2 V
- Current = 1.30 A
- Hydrogen production rate = 14 mL min⁻¹

Table 4.2: Electrolyser Performance at Optimum Operating Conditions

Parameter	Value
Cell voltage	2.2 V
Current	1.30 A
Operating temperature	50°C
Hydrogen production rate	14 mL min ⁻¹
Electrolysis efficiency	55.6%
Energy efficiency	67.3%
Hydrogen production efficiency	75.4%

Current–Voltage (I–V) Characteristics of the Electrolyser

X-axis: Cell Voltage (V)

Y-axis: Current (A)

The increasing trend observed in the I–V curve is consistent with published studies of alkaline electrolysers, which demonstrate that current density increases with applied voltage because of enhanced reaction kinetics and reduced activation barriers (Ursúa et al., 2012).

Hydrogen Production Rate as a Function of Applied Voltage

X-axis: Voltage (V)

Y-axis: Hydrogen Production Rate (mL min⁻¹)

The observed relationship confirms Faraday’s law of electrolysis, which states that gas production is directly proportional to the electrical charge passing through the electrolyser.

4.3 Hydrogen Production Efficiency

Hydrogen production efficiency represents the effectiveness of converting electrical energy into chemical energy stored within hydrogen molecules.

The developed electrolyser achieved a hydrogen production efficiency of approximately 75.4%. This result indicates that most of the electrical energy supplied to the system contributed to hydrogen generation rather than being dissipated through side reactions or system losses. Several factors contributed to the observed efficiency:

- High electrolyte conductivity provided by 30 wt.% KOH.
- Reduced internal resistance resulting from the zero-gap configuration.
- Good catalytic activity of nickel electrodes.
- Effective ionic transport through the polypropylene membrane.

Previous studies have shown that alkaline electrolyser efficiency is strongly influenced by electrode material, separator resistance, and operating temperature (Ursúa et al., 2012). The efficiency obtained in this study falls within the expected range for laboratory-scale alkaline electrolysis systems.

Comparison of Actual and Theoretical Hydrogen Production

A bar chart comparing:

- Theoretical hydrogen generation
- Measured hydrogen generation

This figure provides a visual representation of hydrogen production efficiency.

4.4 Energy Efficiency Analysis

Energy efficiency was calculated by comparing the energy stored in the produced hydrogen with the electrical energy supplied to the electrolyser.

The developed system achieved an overall energy efficiency of 67.3%, while electrolysis efficiency reached 55.6%.

These results demonstrate that the electrolyser successfully converted electrical energy into storable chemical energy, although losses remained unavoidable. The major sources of energy loss included:

- Electrode overpotential.
- Ohmic resistance.
- Heat generation.
- Gas bubble formation on electrode surfaces.

According to Zeng and Zhang (2010), these loss mechanisms are common in alkaline electrolysis systems and represent major areas for future performance improvements.

Table 4.3: Efficiency Performance of the Developed Electrolyser

Efficiency Parameter	Value (%)
Hydrogen production efficiency	75.4
Energy efficiency	67.3
Electrolysis efficiency	55.6

Comparison of Electrolyser Efficiency Parameters

Bar chart showing:

- Hydrogen production efficiency
- Energy efficiency
- Electrolysis efficiency

The figure allows direct comparison of the different efficiency metrics used in evaluating system performance.

4.5 Fuel Cell Electricity Generation

To demonstrate practical utilisation of the produced hydrogen, the generated hydrogen and oxygen gases were supplied to a reversible proton exchange membrane (PEM) fuel cell.

The fuel cell successfully converted the stored chemical energy back into electrical energy and powered a small 0.2 W direct-current motor for approximately one minute.

The successful operation of the motor confirmed that:

1. Hydrogen generated by the electrolyser possessed sufficient quality for fuel cell operation.
2. The integrated hydrogen energy cycle was technically feasible.
3. Energy could be stored and recovered through electrochemical processes.

Integrated Hydrogen Energy System

Renewable Electricity → Electrolyser → Hydrogen Storage → PEM Fuel Cell → Electrical Load

This schematic illustrates the complete energy conversion pathway evaluated during the study.

The integration of electrolysis and fuel cell technologies is increasingly recognised as an important strategy for renewable energy storage. Hydrogen can act as a long-term energy storage medium, overcoming the intermittency challenges associated with solar and wind power generation (Dincer & Acar, 2015).

4.6 Comparison with Previous Studies

The performance of the developed electrolyser was compared with observations reported in previous research.

Table 4.4: Comparison with Published Alkaline Electrolyser Studies

Study	Technology	Key Findings
Ursúa et al. (2012)	Alkaline electrolysis	Efficiency influenced by temperature, electrolyte concentration, and electrode design
Zeng and Zhang (2010)	Alkaline electrolysis	Zero-gap systems reduce ohmic losses and improve performance
Carmo et al. (2013)	Water electrolysis review	Cell resistance and catalyst activity strongly affect efficiency
Present study	Zero-gap alkaline electrolyser	14 mL min ⁻¹ hydrogen production at 2.2 V and 67.3% energy efficiency

The results demonstrate that the developed system exhibits performance characteristics consistent with those reported in the literature while maintaining a relatively simple and low-cost design.

Overall, the findings confirm that zero-gap alkaline electrolysis represents a practical approach for small-scale hydrogen production and energy storage applications.

Figures You Should Include in Chapter 4

5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The growing demand for sustainable energy technologies has intensified research into hydrogen production and utilisation systems capable of supporting the global transition to low-carbon energy. Among the available hydrogen production methods, alkaline water electrolysis remains one of the most mature and economically viable technologies due to its operational reliability, relatively low cost, and compatibility with renewable energy sources. This study focused on the design, fabrication, and performance evaluation of a laboratory-scale zero-gap alkaline water electrolyser for sustainable hydrogen production and subsequent

electricity generation using a proton exchange membrane (PEM) fuel cell.

A compact single-cell zero-gap alkaline electrolyser was successfully designed and fabricated using commercially available materials. The system incorporated nickel electrodes, a 30 wt.% potassium hydroxide (KOH) electrolyte, polymer-based structural components, and a separator membrane for gas separation. Material selection was conducted based on mechanical strength, thermal stability, corrosion resistance, and economic considerations. Numerical simulations were performed to assess the structural and thermal behaviour of the proposed design prior to fabrication, ensuring that the selected materials were capable of withstanding the intended operating conditions.

The material evaluation demonstrated that polytetrafluoroethylene (PTFE) exhibited superior chemical resistance and dimensional stability compared with polypropylene when exposed to concentrated alkaline electrolyte. Consequently, PTFE was identified as the most suitable material for structural components such as endplates and spacers. Furthermore, polypropylene nonwoven geotextile showed promising performance as a low-cost separator membrane, providing effective gas separation while maintaining adequate ionic transport. In contrast, polyester-based

membrane materials experienced rapid degradation under alkaline conditions and were therefore considered unsuitable for long-term operation.

Experimental testing confirmed the successful operation of the developed electrolyser. Hydrogen and oxygen gases were generated through electrochemical water splitting under controlled laboratory conditions. The optimum operating condition was achieved at a cell voltage of 2.2 V and a current of 1.30 A, resulting in a hydrogen production rate of approximately 14 mL min⁻¹. The results demonstrated that the zero-gap configuration effectively reduced ionic transport distance and internal electrical resistance, contributing to improved electrochemical performance.

Performance evaluation revealed that the developed electrolyser achieved a hydrogen production efficiency of approximately 75.4%, an energy efficiency of 67.3%, and an electrolysis efficiency of 55.6%. These values indicate the effective conversion of electrical energy into chemical energy stored within hydrogen. Although energy losses associated with overpotential, internal resistance, and heat generation were observed, the overall performance was comparable to that reported for similar alkaline electrolysis systems in laboratory settings in the literature. The results confirm that zero-gap alkaline electrolysis provides a practical and efficient approach to hydrogen generation while maintaining the cost advantages associated with conventional alkaline technologies.

To evaluate the practical application of the produced hydrogen, the generated hydrogen and oxygen gases were supplied to a reversible PEM fuel cell. The fuel cell successfully converted the stored chemical energy back into electrical energy and powered a small direct-current motor. This demonstration validated the feasibility of integrating alkaline electrolysis with fuel cell technology to create a complete hydrogen energy cycle consisting of hydrogen production, storage, and electricity generation. Such systems have significant potential for renewable energy storage, decentralised power generation, and educational applications.

Overall, the findings of this study demonstrate that a low-cost zero-gap alkaline water electrolyser can successfully produce hydrogen and support fuel cell electricity generation. The research contributes to the development of affordable hydrogen technologies and provides a foundation for future improvements in small-scale renewable energy storage systems.

5.2 Contributions of the Study

The main contributions of this research are summarised as follows:

1. A laboratory-scale zero-gap alkaline water electrolyser was successfully designed and fabricated using readily available materials.
2. PTFE was identified as the most suitable structural material due to its superior resistance to alkaline corrosion and thermal degradation.

3. Polypropylene nonwoven geotextile was shown to be a good, low-cost substitute for expensive commercial separator membranes.

4. The developed system achieved stable hydrogen production with satisfactory efficiency under moderate operating conditions.

5. The integration of the electrolyser with a PEM fuel cell successfully demonstrated the complete hydrogen energy cycle.

6. The study provides valuable experimental data for the future development of affordable hydrogen production systems for educational and decentralised energy applications.

5.3 Limitations of the Study

The study successfully achieved its objectives, but several limitations warrant acknowledgement.

First, the developed electrolyser was a laboratory-scale prototype with a relatively low hydrogen production rate compared with commercial and industrial systems. Therefore, the results may not be directly transferable to large-scale hydrogen production applications.

Second, long-term durability testing was not conducted extensively. While short-term operation demonstrated satisfactory performance, the long-term effects of alkaline exposure on membrane and structural materials require further investigation.

Third, gas purity measurements were not comprehensively analysed. Although hydrogen production was successfully demonstrated, detailed gas composition analysis would provide additional information regarding system efficiency and separator performance.

Fourth, the study focused primarily on fixed operating conditions. The influence of varying electrolyte concentration, temperature, pressure, and electrode spacing was not investigated in detail and could significantly affect performance.

Finally, renewable energy integration was not included within the experimental setup. The electrolyser was powered using a DC power supply from the laboratory rather than solar photovoltaic or wind energy systems.

5.4 Recommendations for Future Research

Based on the findings and limitations of this study, several recommendations are proposed for future work.

5.4.1 Electrode Enhancement

Future studies should investigate advanced electrode materials and surface treatments to improve catalytic activity and reduce overpotential losses. Nickel foam, nickel-iron catalysts, and nickel-molybdenum coatings may significantly enhance hydrogen production rates and overall efficiency.

5.4.2 Membrane Optimisation

Additional research should focus on developing and evaluating alternative low-cost membrane materials with improved ionic conductivity, chemical resistance, and gas separation performance. Comparative testing against commercial separators such as Zirfon would provide valuable performance benchmarks.

5.4.3 Long-Term Durability Assessment

Extended operational testing should be conducted to evaluate the long-term stability of structural materials, electrodes, and separator membranes under continuous electrolysis conditions. Such studies would improve understanding of component degradation mechanisms and maintenance requirements.

5.4.4 System Scaling

Future work should investigate the development of multi-cell electrolyser stacks capable of producing larger quantities of hydrogen. Scaling studies would reveal practical applications for residential, commercial, and industrial hydrogen production systems.

5.4.5 Renewable Energy Integration

The integration of solar photovoltaic and wind energy systems with the electrolyser should be explored to evaluate real-world green hydrogen production. Such investigations would contribute to the development of sustainable energy storage systems and support the utilisation of renewable energy.

5.4.6 Automation and Monitoring

The implementation of automated control systems, temperature regulation, pressure monitoring, and data acquisition technologies would improve operational safety and allow for more precise performance optimisation.

5.4.7 Fuel Cell Performance Analysis

Future studies should include detailed fuel cell performance characterisation, including voltage-current behaviour, power output analysis, and the overall round-trip energy efficiency of the integrated hydrogen energy system.

5.5 Final Remarks

Hydrogen is expected to play a significant role in future sustainable energy systems due to its ability to store renewable energy and provide clean electricity

through fuel cell technology. The successful development and testing of the zero-gap alkaline water electrolyser presented in this study demonstrate the technical feasibility of producing hydrogen using affordable materials and simple fabrication methods. While additional improvements are required to enhance efficiency and scalability, the research provides a practical foundation for further development of low-cost hydrogen production technologies and contributes to the broader objective of achieving sustainable and environmentally responsible energy systems.

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