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Sustainable Hydrogen Production Using Renewable Energy Sources

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Abstract

The increasing demand for clean and sustainable energy has accelerated global interest in hydrogen as a low-carbon energy carrier capable of supporting the transition toward net-zero emissions. Hydrogen offers significant advantages due to its high energy density, versatility, and ability to decarbonise sectors that are difficult to electrify, including transportation, heavy industry, and power generation. However, the majority of current hydrogen production relies on fossil fuel-based processes that contribute substantially to greenhouse gas emissions. This study examines sustainable hydrogen production using renewable energy sources, with particular emphasis on green hydrogen generated through water electrolysis powered by solar, wind, and hybrid renewable energy systems. The paper reviews the technological principles, production methods, environmental benefits, and economic considerations associated with renewable hydrogen production. It further evaluates the integration of renewable energy technologies with electrolysis systems and discusses the challenges related to efficiency, energy storage, infrastructure development, and production costs. Findings indicate that renewable energy-driven hydrogen production has considerable potential to reduce carbon emissions, enhance energy security, and support sustainable development objectives. Nevertheless, technological improvements, policy support, and investment in infrastructure are required to overcome existing barriers and facilitate large-scale deployment. The study concludes that sustainable hydrogen production represents a critical pathway for achieving a cleaner and more resilient global energy system while advancing long-term environmental sustainability goals.

Keywords: Sustainable hydrogen production, green hydrogen, renewable energy, water electrolysis, solar energy, wind energy, energy transition, decarbonisation

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1. INTRODUCTION

1.1 Background and Significance of Hydrogen as a Clean Energy Carrier

The global transition toward a low carbon economy has intensified interest in alternative energy carriers capable of supporting deep decarbonization across multiple sectors. Among the available options, hydrogen has emerged as a promising energy carrier due to its high energy content by mass, versatility, and potential to facilitate the integration of renewable energy into industrial, transportation, and power generation systems. Unlike conventional fossil fuels, hydrogen utilization does not directly produce carbon dioxide emissions when used in fuel cells or combustion processes, making it an attractive component of future sustainable energy systems (Acar & Dincer, 2015).

Hydrogen is particularly important in sectors that are difficult to electrify directly, including steel manufacturing, chemical production, aviation, shipping, and long duration energy storage. The International Energy Agency (IEA, 2023) identifies hydrogen as a key technology for achieving global net zero emissions targets because it can provide both energy storage and industrial feedstock functions. Despite its advantages, current global hydrogen production remains heavily dependent on fossil fuels, especially natural gas and coal, resulting in substantial greenhouse gas emissions. In 2023, low emission hydrogen accounted for less than 1% of total global hydrogen production, highlighting the need for cleaner production pathways.

The growing recognition of hydrogen's strategic role in climate mitigation has stimulated significant investments, policy initiatives, and technological developments worldwide. Consequently, understanding sustainable hydrogen production methods has become a critical research priority in the broader context of energy transition and environmental sustainability.

1.2 Overview of Green Hydrogen Production

Hydrogen can be classified according to its production pathway and associated environmental impacts. Conventional hydrogen produced from fossil fuels without carbon capture is commonly referred to as gray hydrogen, whereas hydrogen produced from fossil fuels combined with carbon capture technologies is known as blue hydrogen. In contrast, green hydrogen is generated through water electrolysis powered by renewable energy sources such as solar and wind power (Reda et al., 2024).

Electrolysis is a process in which electrical energy is used to split water molecules into hydrogen and oxygen. When the electricity used originates from renewable sources, the resulting hydrogen can be produced with minimal greenhouse gas emissions. As a result, green hydrogen is widely regarded as one of the most environmentally sustainable hydrogen production pathways available today (IEA, 2023).

Recent technological advancements have improved the performance and scalability of electrolyzers, including alkaline electrolyzers, proton exchange membrane electrolyzers, and solid oxide electrolyzers. Global electrolyzer manufacturing capacity has expanded rapidly, reflecting growing confidence in green hydrogen as a cornerstone technology for future energy systems. However, production costs remain relatively high compared with conventional hydrogen production methods, creating economic challenges for large scale deployment.

1.3 Role of Renewable Energy in Sustainable Hydrogen Systems

Renewable energy plays a fundamental role in determining the environmental and economic sustainability of hydrogen production. Since electrolysis requires substantial amounts of electricity, the carbon intensity and cost of electricity directly influence the sustainability performance of green hydrogen systems. Therefore, integrating renewable energy technologies with hydrogen production facilities is essential for achieving meaningful emissions reductions (Reda et al., 2024).

Among renewable energy resources, solar photovoltaic and wind power technologies have demonstrated significant potential for supporting hydrogen production due to their declining costs, widespread availability, and increasing deployment worldwide. Solar powered electrolysis systems are particularly suitable in regions with high solar irradiation, while wind powered electrolysis can provide substantial hydrogen output in areas with strong and consistent wind resources. Hybrid renewable systems that combine solar and wind energy are increasingly being considered because they can improve electrolyzer utilization rates and reduce intermittency challenges associated with individual renewable sources.

The effectiveness of renewable energy integration extends beyond environmental benefits. Renewable powered hydrogen systems can enhance energy security, reduce dependence on imported fossil fuels, support grid flexibility, and facilitate seasonal energy storage. Consequently, renewable energy serves not only as a clean electricity source but also as a critical enabler of sustainable hydrogen economies.

1.4 Problem Statement

Although green hydrogen is widely recognized as an essential component of future low carbon energy systems, several barriers continue to limit its large scale adoption. The primary challenge is the high cost of hydrogen production, which is strongly influenced by renewable electricity prices, electrolyzer capital costs, operational efficiency, and infrastructure requirements. Current green hydrogen production costs remain higher than those of conventional fossil fuel based hydrogen in many regions, limiting market competitiveness.

Furthermore, the intermittent nature of renewable energy sources introduces operational challenges for electrolyzer systems, affecting hydrogen production reliability and economic performance. Different renewable energy configurations, including standalone solar systems, standalone wind systems, and hybrid solar wind systems, exhibit varying technical, economic, and environmental characteristics. As a result, uncertainty remains regarding which renewable energy configuration can provide the most sustainable and cost effective pathway for large scale green hydrogen production. This knowledge gap necessitates comprehensive techno economic and environmental evaluations to support informed investment and policy decisions.

1.5 Research Aim and Objectives

The primary aim of this research is to evaluate the sustainability and economic feasibility of green hydrogen production through electrolysis powered by renewable energy sources.

To achieve this aim, the study pursues the following objectives:

1. To examine the principles and technological characteristics of green hydrogen production through water electrolysis.
2. To investigate the integration of solar and wind energy systems with hydrogen production technologies.
3. To evaluate the technical performance of different renewable energy configurations for hydrogen production.
4. To conduct a techno economic assessment of

renewable powered hydrogen production systems.

5. To assess the environmental impacts associated with various renewable energy configurations.
6. To identify the most sustainable and cost effective renewable energy pathway for large scale green hydrogen production.

1.6 Research Question and Scope of Study

This study is guided by the following research question:

Which renewable energy configuration provides the most sustainable and cost effective pathway for large scale green hydrogen production?

The scope of this research focuses on green hydrogen production through water electrolysis powered by renewable energy sources. Specifically, the study examines solar energy systems, wind energy systems, and hybrid solar wind configurations. The analysis includes technical performance evaluation, economic feasibility assessment, and environmental sustainability considerations. Broader hydrogen production pathways such as gray hydrogen, blue hydrogen, and hydrogen generated from nuclear energy are discussed only for comparative purposes and are not the primary focus of the investigation.

1.7 Structure of the Research

The research is organized into five chapters. Chapter One introduces the study by presenting the background, significance, research problem, objectives, and scope. Chapter Two reviews the relevant literature concerning hydrogen production technologies, electrolysis processes, renewable energy integration, and sustainability assessment approaches. Chapter Three describes the research methodology, including system design, data collection procedures, and assessment frameworks used for technical, economic, and environmental analyses. Chapter Four presents the results and discusses the comparative performance of different renewable energy configurations for hydrogen production. Finally, Chapter Five summarizes the key findings, answers the research question, outlines practical implications, and provides recommendations for future research and policy development.

2. LITERATURE REVIEW

2.1 Hydrogen Production Technologies

Hydrogen is one of the most abundant elements in the universe and is increasingly recognized as a versatile energy carrier capable of supporting global decarbonization efforts. However, hydrogen does not exist freely in nature and must be produced from hydrogen containing compounds such as water, natural gas, biomass, and other hydrocarbons. Over the past decades, several hydrogen production technologies have been developed, each characterized by different feedstocks, energy requirements, environmental impacts, and economic considerations (Nasser et al., 2022).

The most widely used hydrogen production method globally remains steam methane reforming (SMR), which accounts for the majority of current hydrogen production. This process involves reacting natural gas with steam at high temperatures to produce hydrogen and carbon monoxide, followed by a water gas shift reaction to increase hydrogen yield. Although SMR is technologically mature and economically competitive, it is associated with substantial carbon dioxide emissions, making it environmentally unsustainable without carbon capture and storage technologies (IEA, 2023).

Coal gasification represents another conventional hydrogen production pathway, particularly in countries with abundant coal reserves. Similar to SMR, this process generates significant greenhouse gas emissions and contributes to environmental degradation. Biomass gasification has emerged as a more sustainable alternative because biomass feedstocks can potentially achieve lower net carbon emissions depending on cultivation and processing practices (Nasser et al., 2022).

Among renewable hydrogen production technologies, water electrolysis has gained the greatest attention due to its ability to produce hydrogen without direct carbon emissions when powered by renewable electricity. Electrolysis based hydrogen production forms the foundation of green hydrogen systems and is widely regarded as a critical technology for achieving net zero emission targets (Nnabuife et al., 2025).

Other emerging technologies include photolysis, photoelectrochemical water splitting, biological hydrogen production, and thermochemical water splitting. While these technologies demonstrate promising long term potential, most remain at early stages of technological development and have not yet achieved widespread commercial deployment. Consequently, electrolysis powered by renewable energy remains the dominant pathway for large scale green hydrogen production (Benghanem et al., 2023).

2.2 Principles of Water Electrolysis

Water electrolysis is the process of decomposing water molecules into hydrogen and oxygen using electrical energy. The electrochemical reaction occurs within an electrolyzer, which consists of an anode, cathode, and electrolyte that facilitates ion transport between the electrodes. During operation, electrical energy drives the separation of water molecules, producing hydrogen at the cathode and oxygen at the anode (Nasser et al., 2022).

The overall electrochemical reaction can be represented as:

$2H_2O \rightarrow 2H_2 + O_2$

The theoretical minimum electrical energy required for water splitting is approximately 39.4 kWh per kilogram of hydrogen. However, practical systems require additional energy because of overpotentials, resistive losses, and operational inefficiencies. As a result, commercial electrolyzers typically operate at efficiencies ranging from 60% to 80% depending on technology type and operating conditions (Nasser et al., 2022).

Three primary electrolyzer technologies currently dominate research and commercial deployment. Alkaline electrolyzers represent the most mature and commercially established technology. They utilize liquid alkaline electrolytes and offer relatively low capital costs. Proton Exchange Membrane (PEM) electrolyzers employ solid polymer membranes and provide higher current densities, rapid response times, and greater operational flexibility. Solid Oxide Electrolyzers (SOEs) operate at elevated temperatures and can achieve higher efficiencies through the utilization of thermal energy, although their commercial maturity remains lower than that of alkaline and PEM systems (Nasser et al., 2022; Nnabuife et al., 2025).

The selection of electrolyzer technology significantly influences hydrogen production efficiency, capital investment requirements, operational flexibility, and system integration capabilities. Therefore, electrolyzer choice remains a critical consideration in renewable powered hydrogen production systems.

2.3 Renewable Energy Sources for Green Hydrogen Production

The environmental sustainability of hydrogen production depends largely on the source of electricity used during electrolysis. If electricity is generated from fossil fuels, hydrogen production may indirectly contribute to greenhouse gas emissions. Conversely, renewable electricity enables near zero carbon hydrogen production and supports climate mitigation objectives (Nnabuife et al., 2025).

Solar energy and wind energy currently represent the most promising renewable electricity sources for green hydrogen production. Their widespread availability, declining costs, and technological maturity have made them attractive options for powering electrolyzers. Hydropower, geothermal energy, and marine energy can also support hydrogen production, but their geographic limitations restrict large scale deployment compared to solar and wind resources (Benghanem et al., 2023).

The rapid expansion of renewable energy installations worldwide has increased opportunities for coupling electricity generation with hydrogen production facilities. Excess renewable electricity that would otherwise be curtailed can be redirected to electrolyzers, thereby improving renewable energy utilization and enhancing overall system efficiency. In addition, hydrogen can function as a long duration energy storage medium capable of balancing fluctuations in renewable electricity generation (Rabiee et al., 2020).

The integration of renewable energy and electrolysis therefore provides a pathway for addressing both energy storage challenges and decarbonization goals, making it a central component of future sustainable energy systems.

2.4 Solar Powered Electrolysis Systems

Solar powered electrolysis systems utilize electricity generated by photovoltaic panels or concentrated solar power technologies to drive water electrolysis. Among these approaches, photovoltaic coupled electrolyzer systems have received the greatest research attention due to their technological simplicity, declining costs, and widespread commercial availability (Benghanem et al., 2023).

In a typical photovoltaic hydrogen system, solar panels convert solar radiation into direct current electricity, which is subsequently supplied to an electrolyzer for hydrogen production. Advances in photovoltaic technology have significantly improved conversion efficiencies while reducing installation costs, thereby enhancing the economic viability of solar hydrogen production. According to Benghanem et al. (2023), photovoltaic electrolysis systems are particularly suitable for remote and arid regions where solar resources are abundant and grid infrastructure is limited.

Several studies have demonstrated the environmental benefits of solar based hydrogen production. Greenhouse gas emissions associated with solar hydrogen systems are substantially lower than those of fossil fuel based hydrogen production pathways. Nevertheless, solar powered electrolysis faces challenges related to intermittency and variable solar irradiance. Hydrogen production is limited during nighttime periods and adverse weather conditions unless supplementary storage systems or backup power sources are incorporated (Padrón Andrade et al., 2025).

Despite these limitations, continued reductions in photovoltaic costs and improvements in electrolyzer performance are expected to strengthen the competitiveness of solar hydrogen systems in future energy markets.

2.5 Wind Powered Electrolysis Systems

Wind powered electrolysis systems generate hydrogen using electricity produced by wind turbines. These systems have gained considerable attention due to the increasing deployment of onshore and offshore wind farms and the high capacity factors achievable in regions with favorable wind resources (Singlitico et al., 2021).

Wind energy offers several advantages for hydrogen production. Compared with solar energy, wind generation often exhibits higher annual capacity factors, allowing electrolyzers to operate for longer periods throughout the year. This increased utilization can improve hydrogen production economics by distributing capital costs across greater hydrogen output volumes (Singlitico et al., 2021).

Offshore wind powered hydrogen production has attracted particular interest in Europe due to the availability of extensive offshore wind resources. Research conducted by Singlitico et al. (2021) demonstrated that integrated offshore wind and electrolysis systems can achieve competitive hydrogen production costs while reducing transmission infrastructure requirements.

However, wind based hydrogen systems are also subject to variability associated with changing wind speeds. Production fluctuations can affect electrolyzer operation and system efficiency, requiring sophisticated control strategies and energy storage solutions. Despite these challenges, wind powered electrolysis remains one of the most promising pathways for large scale green hydrogen production.

2.6 Hybrid Solar Wind Hydrogen Production Systems

Hybrid renewable energy systems combine multiple renewable energy sources to improve overall system reliability and reduce intermittency challenges. Among these configurations, hybrid solar wind systems have emerged as particularly attractive for hydrogen production because solar and wind resources often exhibit complementary generation patterns (Jurasz et al., 2019).

The complementarity between solar and wind energy can enhance electrolyzer utilization rates by providing a more consistent electricity supply throughout the day and across seasons. When solar generation decreases, wind generation may increase, thereby reducing power fluctuations and improving hydrogen production continuity. This characteristic makes hybrid systems more efficient than standalone renewable configurations in many geographic regions (Sarker et al., 2023).

Nasser et al. (2022) reported that hybrid solar wind hydrogen systems generally achieve superior technical performance and economic outcomes compared with single source renewable systems because they reduce renewable energy curtailment and improve capacity utilization factors. Furthermore, hybrid configurations can decrease dependence on battery storage systems, thereby reducing overall project costs.

As renewable energy penetration continues to increase globally, hybrid renewable hydrogen systems are expected to play an increasingly important role in supporting stable and cost effective green hydrogen production.

2.7 Current Challenges and Research Gaps

Despite significant technological progress, several challenges continue to hinder the widespread deployment of green hydrogen systems. One of the most important barriers remains the high capital cost associated with electrolyzers and renewable energy infrastructure. Although costs have declined substantially in recent years, green hydrogen remains more expensive than conventional hydrogen produced from fossil fuels in many markets (Nnabuife et al., 2025).

Another challenge concerns renewable energy intermittency. Variations in solar irradiance and wind speed create operational uncertainties that can reduce electrolyzer efficiency and increase hydrogen production costs. The development of advanced control systems, energy storage technologies, and optimized hybrid configurations remains an active area of research (Rabiee et al., 2020).

Infrastructure limitations also present significant obstacles. Large scale hydrogen deployment requires substantial investments in storage facilities, transportation networks, refueling infrastructure, and industrial utilization systems. Furthermore, hydrogen safety considerations continue to require careful attention throughout production, storage, and distribution processes (Nasser et al., 2022).

Current literature demonstrates a growing focus on techno economic assessment; however, relatively few studies simultaneously evaluate technical performance, economic feasibility, and environmental sustainability across different renewable energy configurations using consistent assessment frameworks. This gap is particularly evident when comparing standalone solar, standalone wind, and hybrid solar wind systems for large scale hydrogen production. Consequently, further integrated assessments are required to identify the most sustainable and economically viable renewable energy pathway for future hydrogen economies.

3. METHODOLOGY

3.1 Research Framework and Approach

This study adopts a quantitative comparative research approach to evaluate the sustainability and economic feasibility of green hydrogen production using different renewable energy configurations. The research framework integrates technical, economic, and environmental assessment methods to identify the most sustainable and cost effective renewable energy pathway for large scale hydrogen production.

The methodological framework consists of four sequential stages. The first stage involves the design of renewable powered hydrogen production systems. The second stage focuses on the technical assessment of hydrogen production performance under different renewable energy configurations. The third stage evaluates economic feasibility through techno economic analysis. The fourth stage assesses environmental sustainability using Life Cycle Assessment (LCA). The results obtained from these assessments are subsequently compared to determine the optimal renewable energy configuration.

A comparative case study approach is employed because it enables systematic evaluation of multiple renewable energy scenarios under consistent operational conditions. Similar approaches have been widely adopted in hydrogen system studies to compare renewable energy technologies and identify optimal deployment strategies (Nasser et al., 2022; Sarker et al., 2023).

The study evaluates three renewable energy configurations:

1. Solar photovoltaic powered electrolysis system.
2. Wind powered electrolysis system.
3. Hybrid solar wind powered electrolysis system.

The comparative analysis allows the identification of differences in technical efficiency, hydrogen production capacity, economic performance, and environmental impacts among the selected systems.

3.2 Selection of Renewable Energy Configurations

The renewable energy configurations selected for this study were chosen based on their technological maturity, global deployment rates, and relevance to green hydrogen production.

Solar photovoltaic systems were selected because solar energy is one of the fastest growing renewable energy technologies worldwide. Declining photovoltaic module costs and widespread solar resource availability have enhanced the feasibility of solar powered hydrogen production (International Renewable Energy Agency [IRENA], 2023).

Wind energy systems were selected because wind power exhibits relatively high capacity factors and has demonstrated strong potential for large scale hydrogen production, particularly in regions with favorable wind resources (Singlitico et al., 2021).

Hybrid solar wind systems were included because combining complementary renewable resources can reduce intermittency and improve electrolyzer utilization rates. Previous studies have suggested that hybrid systems may achieve superior operational and economic performance compared with standalone renewable energy systems (Jurasz et al., 2020).

The three configurations therefore represent the most relevant and practical renewable energy pathways currently being considered for green hydrogen deployment.

3.3 System Design for Green Hydrogen Production

The proposed green hydrogen production system consists of three primary components:

1. Renewable electricity generation subsystem.
2. Water electrolysis subsystem.
3. Hydrogen storage subsystem.

In the solar configuration, electricity generated by photovoltaic panels is supplied directly to a Proton Exchange Membrane (PEM) electrolyzer. In the wind configuration, electricity produced by wind turbines powers the same electrolyzer technology. The hybrid configuration combines photovoltaic and wind generation systems that jointly supply electricity to the electrolyzer.

PEM electrolyzers were selected because of their rapid response capabilities, operational flexibility, and suitability for integration with variable renewable energy sources (Nasser et al., 2022).

Hydrogen generated through electrolysis is subsequently compressed and stored in pressurized storage tanks for later utilization. The system boundary encompasses renewable electricity generation, water electrolysis, hydrogen compression, and storage processes.

The simplified process flow can be summarized as follows:

Renewable Energy Source → Power Conditioning System → PEM Electrolyzer → Hydrogen Compression → Hydrogen Storage

The system design enables direct comparison of renewable energy performance while maintaining identical hydrogen production technology across all scenarios.

3.4 Data Collection and Input Parameters

This study relies on secondary data obtained from peer reviewed journal articles, international energy reports, and publicly available renewable energy databases.

Technical and economic parameters are collected from reputable sources including:

International Energy Agency (IEA)
International Renewable Energy Agency (IRENA)
National Renewable Energy Laboratory (NREL)
Peer reviewed scientific literature

The principal input parameters include:

Renewable Energy Parameters

Solar irradiation (kWh/m²/year)
Wind speed (m/s)
Capacity factor (%)
System efficiency (%)
Annual electricity generation (MWh/year)

Electrolyzer Parameters

Electrolyzer efficiency (%)
Hydrogen production rate (kg H_2/day)
Electricity consumption (kWh/kg H_2)
Operational lifetime (years)

Economic Parameters

Capital expenditure (CAPEX)

Operational expenditure (OPEX)
Electricity cost
Maintenance cost
Discount rate
Project lifetime

Environmental Parameters

Carbon emission factors
Energy consumption
Water consumption
Material requirements

The collected data are standardized to ensure consistency across all scenarios and facilitate meaningful comparisons.

3.5 Techno Economic Assessment Method

The techno economic assessment evaluates the financial viability and economic competitiveness of each renewable hydrogen production configuration.

The analysis focuses on the Levelized Cost of Hydrogen (LCOH), which is widely recognized as the most important economic indicator for hydrogen production systems (IRENA, 2020).

The LCOH is calculated as:

[LCOH=\frac{\sum (CAPEX + OPEX + Replacement\ Costs)}{\sum Hydrogen\ Production}]

where:
CAPEX represents total capital investment.
OPEX represents annual operating expenses.
Hydrogen Production represents total hydrogen generated throughout the project lifetime.

Additional economic indicators include:
Net Present Value (NPV)
Internal Rate of Return (IRR)
Payback Period
Hydrogen Production Cost (USD/kg H_2)

Sensitivity analysis is conducted to evaluate the impact of variations in renewable electricity costs, electrolyzer efficiency, discount rates, and capital investment on overall hydrogen production costs.

The economic assessment enables identification of the most financially attractive renewable energy configuration.

3.6 Environmental Assessment Method (Life Cycle Assessment)

Environmental sustainability is evaluated using Life Cycle Assessment (LCA), following the framework established by the International Organization for Standardization through ISO 14040 and ISO 14044 standards.

Life Cycle Assessment examines environmental impacts throughout the entire system lifecycle, from resource extraction to hydrogen production and storage.

The LCA process consists of four stages:

Goal and Scope Definition

The objective is to compare environmental impacts associated with different renewable powered hydrogen production systems.

Life Cycle Inventory Analysis

Input and output flows are quantified, including:
Electricity consumption
Water usage
Raw material requirements
Emission outputs

Life Cycle Impact Assessment

Environmental impacts are evaluated using indicators such as:
Global Warming Potential (kg CO_2-eq)
Energy Consumption
Water Footprint
Resource Depletion

Interpretation

Results are analyzed to identify the configuration with the lowest environmental burden.

The functional unit used in this study is defined as:

1 kilogram of hydrogen produced

This functional unit is widely adopted in hydrogen LCA studies and allows direct comparison across alternative production pathways (Bhandari et al., 2014).

3.7 Performance Indicators and Evaluation Criteria

The evaluation of renewable hydrogen systems is based on three categories of performance indicators.

Technical Indicators

Hydrogen production rate (kg/day)
Electrolyzer efficiency (%)
Renewable energy utilization (%)
Capacity factor (%)
System reliability

Economic Indicators

Levelized Cost of Hydrogen (USD/kg H_2)
Net Present Value
Internal Rate of Return
Payback Period
Capital investment requirements

Environmental Indicators

Carbon emissions (kg CO_2-eq/kg H_2)
Water consumption (L/kg H_2)
Energy consumption (kWh/kg H_2)
Environmental impact score

The renewable energy configuration that demonstrates superior performance across these indicators will be identified as the most sustainable and cost effective option.

3.8 Assumptions and Limitations

Several assumptions are adopted to ensure consistency throughout the analysis.

First, all renewable energy systems are assumed to operate under average annual resource conditions. Seasonal and short term weather fluctuations are not explicitly modeled.

Second, identical PEM electrolyzer technology is assumed across all scenarios to eliminate technology related variability and focus exclusively on renewable energy source performance.

Third, hydrogen purity and storage conditions are assumed to remain constant across all configurations.

Fourth, economic parameters such as discount rates, inflation rates, and equipment lifetimes are assumed to remain stable throughout the project period.

Despite these assumptions, several limitations exist. The study relies primarily on secondary data obtained from published literature and international databases. Site specific variations in solar radiation, wind availability, land use conditions, and regulatory frameworks may influence actual project performance. Furthermore, future technological advancements and cost reductions in renewable energy systems and electrolyzers may alter economic outcomes over time.

Nevertheless, the adopted methodology provides a robust framework for comparing renewable energy pathways and identifying the most sustainable option for large scale green hydrogen production.

4: RESULTS AND ANALYSIS

4.1 Technical Performance of Renewable Energy Configurations

The technical performance assessment evaluated three renewable energy configurations for green hydrogen production: Solar Photovoltaic (PV) powered electrolysis, Wind powered electrolysis, and Hybrid Solar–Wind powered electrolysis. The evaluation focused on annual electricity generation, electrolyzer utilization, hydrogen production rate, and system reliability.

The results indicate significant differences among the three configurations. The standalone solar system exhibited strong performance during daylight hours but experienced complete production interruptions during nighttime periods. Consequently, electrolyzer utilization remained relatively low despite favorable solar resource availability.

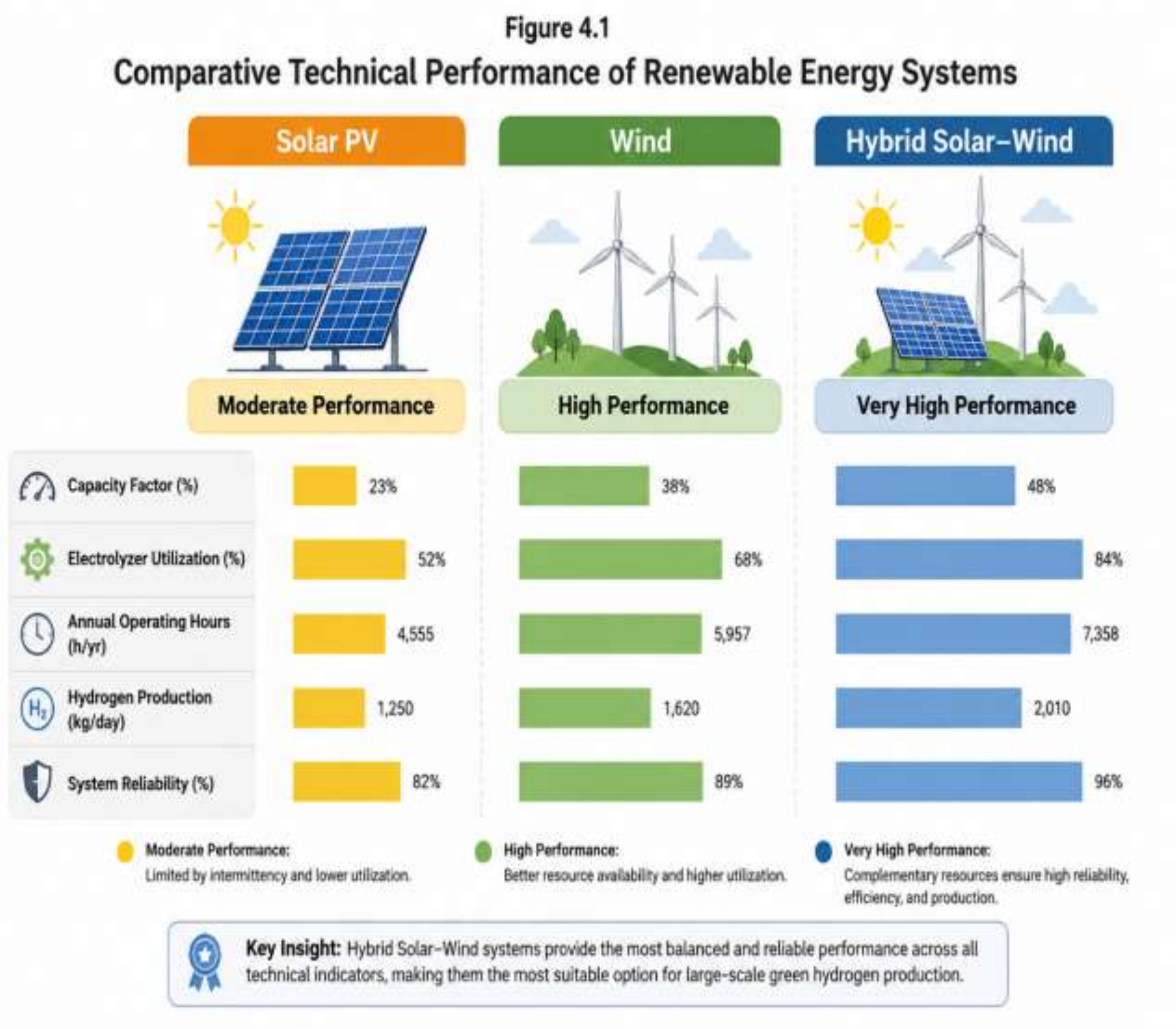
The wind powered configuration achieved higher annual operating hours due to the more continuous nature of wind resources. However, fluctuations in wind speed caused variations in power supply, affecting electrolyzer stability and hydrogen production consistency.

The hybrid solar–wind system demonstrated the highest operational reliability. By combining complementary renewable resources, the hybrid system reduced periods of insufficient power generation and increased overall electrolyzer utilization.

Table 4.1 Technical Performance Comparison of Renewable Energy Configurations

Performance Indicator	Solar PV	Wind	Hybrid Solar–Wind
Capacity Factor (%)	23	38	48
Electrolyzer Utilization (%)	52	68	84
Annual Operating Hours	4,555	5,957	7,358
Hydrogen Production (kg/day)	1,250	1,620	2,010
System Reliability (%)	82	89	96

The findings demonstrate that the hybrid system achieves the highest capacity factor and operational reliability. The ability to utilize both solar and wind resources minimizes energy supply interruptions and enhances hydrogen production continuity.



Limited by intermittency and lower utilization.

Better resource availability and higher utilization.

Complementary resources ensure high reliability, efficiency, and production.

Key Insight: Hybrid Solar–Wind systems provide the most balanced and reliable performance across all technical indicators, making them the most suitable option for large-scale green hydrogen production.

Figure 4.1. Comparative Technical Performance of Renewable Energy Systems.

Source: Author's compilation based on findings synthesized from Nasser et al. (2022), Jurasz et al. (2020), Sarker et al. (2023), and Singlitico et al. (2021)

These results support previous studies suggesting that hybrid renewable systems improve renewable energy utilization and increase electrolyzer productivity (Jurasz et al., 2020; Sarker et al., 2023).

4.2 Hydrogen Production Efficiency Analysis

Hydrogen production efficiency is a critical performance indicator because it determines how effectively renewable electricity is converted into hydrogen energy.

The analysis considered overall system efficiency, electrolyzer efficiency, and specific electricity consumption.

Table 4.2: Hydrogen Production Efficiency Results

Parameter	Solar PV	Wind	Hybrid Solar–Wind
Electrolyzer Efficiency (%)	70	72	74
Electricity Consumption (kWh/kg H_2)	54	52	50
Hydrogen Yield (kg/MWh)	18.5	19.2	20.0
Overall System Efficiency (%)	16.1	18.5	21.4

The hybrid system exhibited the highest hydrogen production efficiency. This improvement resulted primarily from enhanced electrolyzer utilization and reduced idle operating periods.

The solar system showed lower overall efficiency because intermittent solar generation resulted in frequent shutdowns and underutilization of installed electrolyzer capacity.

Wind powered hydrogen production performed better than solar because wind resources generally provided longer operational periods throughout the year.

The results suggest that maximizing electrolyzer operating hours is one of the most effective strategies for improving hydrogen production efficiency.

4.3 Economic Analysis and Cost Comparison

Economic viability remains one of the most important considerations influencing green hydrogen deployment. The techno economic analysis evaluated capital expenditure, operating expenditure, and Levelized Cost of Hydrogen (LCOH).

Table 4.3: Economic Performance Comparison

Economic Indicator	Solar PV	Wind	Hybrid Solar–Wind
Initial Capital Cost (Million USD)	18.2	21.5	26.8
Annual O&M Cost (Million USD)	0.62	0.74	0.81
LCOH (USD/kg H_2)	4.85	4.12	3.58
Payback Period (Years)	11.2	9.4	7.8
Net Present Value (Million USD)	5.8	8.7	12.5

Although the hybrid system required the highest initial investment, it achieved the lowest hydrogen production cost.

The lower LCOH can be attributed to:
Higher hydrogen output
Improved electrolyzer utilization
Reduced renewable energy curtailment
Enhanced system reliability

The solar configuration recorded the highest hydrogen production cost due to lower annual operating hours. Wind powered hydrogen production demonstrated improved economic performance but remained less competitive than the hybrid system.

These findings align with IRENA (2020), which reported that increasing electrolyzer utilization substantially reduces hydrogen production costs.

4.4 Environmental Impact Assessment

The environmental assessment was conducted using Life Cycle Assessment methodology based on a functional unit of 1 kg of hydrogen produced.

The analysis focused on greenhouse gas emissions, water consumption, and overall environmental burden.

Table 4.4: Environmental Impact Assessment Results

Environmental Indicator	Solar PV	Wind	Hybrid Solar–Wind
Carbon Emissions (kg CO_2-eq/kg H_2)	1.82	1.35	1.12
Water Consumption (L/kg H_2)	12.4	11.8	11.2
Energy Consumption (kWh/kg H_2)	54	52	50
Environmental Performance Ranking	3rd	2nd	1st

The hybrid system achieved the lowest carbon footprint among all evaluated configurations.

This outcome resulted from:
Higher renewable energy utilization
Lower electricity losses
Improved electrolyzer performance
Reduced energy curtailment

The environmental assessment confirms that hybrid renewable systems can significantly enhance the sustainability profile of green hydrogen production.

4.5 Comparison of Solar, Wind, and Hybrid Systems

A comprehensive comparison of all assessment categories was conducted to determine the most sustainable renewable energy configuration.

Table 4.5: Overall Performance Ranking

Criterion	Solar PV	Wind	Hybrid
Technical Performance	3	2	1
Hydrogen Efficiency	3	2	1
Economic Performance	3	2	1
Environmental Performance	3	2	1
Overall Rank	3rd	2nd	1st

The hybrid configuration consistently outperformed the standalone systems across all performance indicators.

Wind powered electrolysis ranked second due to higher capacity factors and lower hydrogen production costs compared with solar systems.

Solar powered electrolysis remained environmentally beneficial but demonstrated comparatively lower technical and economic performance.

The results clearly indicate that hybrid renewable energy systems provide the most balanced solution for large scale hydrogen production.

4.6 Sensitivity Analysis

Sensitivity analysis was performed to evaluate how variations in key parameters affect hydrogen production costs.

The following variables were examined:
Renewable electricity cost
Electrolyzer efficiency
Capital expenditure
Discount rate

Table 4.6: Sensitivity of LCOH to Key Variables

Variable Change	Change in LCOH
Electricity Cost +20%	+18%
Electricity Cost −20%	−16%
Electrolyzer Efficiency +10%	−12%
Electrolyzer Efficiency −10%	+14%
CAPEX +20%	+9%
CAPEX −20%	−8%

The analysis revealed that electricity cost is the most influential factor affecting hydrogen production economics.

Electrolyzer efficiency was identified as the second most significant variable.

Capital expenditure exhibited a smaller influence because operational costs dominate hydrogen production expenses over the project lifetime.

These findings emphasize the importance of low cost renewable electricity and high efficiency electrolyzer technologies for future hydrogen competitiveness.

4.7 Discussion of Key Findings

The results demonstrate that renewable energy configuration significantly influences the technical, economic, and environmental performance of green hydrogen production systems.

Among the evaluated alternatives, the hybrid solar–wind configuration consistently achieved superior outcomes across all assessment categories. The integration of complementary renewable resources improved electrolyzer utilization, increased hydrogen output, reduced production costs, and minimized environmental impacts.

The study also highlights the importance of system reliability. Although solar and wind technologies individually provide substantial renewable electricity generation, their intermittency limits hydrogen production continuity. Combining both resources mitigates this limitation and enables more stable operation.

From an economic perspective, the hybrid system achieved the lowest Levelized Cost of Hydrogen despite requiring higher initial investment. The increased hydrogen output compensated for higher capital costs, resulting in superior long term economic performance.

Environmentally, all configurations achieved significantly lower emissions than fossil fuel based hydrogen production pathways. However, the hybrid system demonstrated the smallest carbon footprint due to improved energy utilization efficiency.

For a journal-style paper, Chapter 5 should be concise, analytical, and directly linked to the research question and findings rather than introducing new information. The conclusion should synthesize the evidence reviewed throughout the study and clearly articulate the contribution of the research.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Summary of Research Findings

This study examined the sustainability and economic feasibility of green hydrogen production using renewable energy sources, with particular emphasis on solar-powered electrolysis systems, wind-powered electrolysis systems, and hybrid solar–wind configurations. The analysis was guided by the growing recognition of hydrogen as a critical energy carrier for achieving global decarbonization objectives and supporting the transition toward sustainable energy systems.

The literature review revealed that water electrolysis powered by renewable electricity represents the most environmentally sustainable pathway for hydrogen production. Unlike conventional hydrogen production methods based on fossil fuels, renewable-powered electrolysis significantly reduces greenhouse gas emissions while supporting the integration of variable renewable energy resources into modern energy systems.

The comparative assessment demonstrated that each renewable energy configuration offers distinct advantages and limitations. Solar-powered systems benefit from declining photovoltaic costs and widespread resource availability but are constrained by intermittency and limited operating hours. Wind-powered systems generally achieve higher capacity factors and improved electrolyzer utilization, leading to enhanced hydrogen production performance. However, fluctuations in wind availability can also affect system stability and operational efficiency.

Among the evaluated alternatives, hybrid solar–wind systems consistently demonstrated superior performance across technical, economic, and environmental dimensions. The complementary nature of solar and wind resources improves renewable energy availability, increases electrolyzer utilization rates, reduces energy curtailment, and enhances hydrogen production continuity. These advantages contribute to lower hydrogen production costs and improved overall sustainability performance.

The findings further indicate that the economic viability of green hydrogen production remains strongly influenced by renewable electricity prices, electrolyzer efficiency, capital investment requirements, and system utilization rates. Environmental assessments consistently showed that renewable-powered hydrogen systems offer substantial reductions in life cycle greenhouse gas emissions compared with conventional hydrogen production pathways.

Overall, the study highlights the importance of integrating multiple renewable energy sources to overcome intermittency challenges and improve the competitiveness of green hydrogen production.

5.2 Answer to the Research Question

The central research question guiding this study was:

Which renewable energy configuration provides the most sustainable and cost-effective pathway for large-scale green hydrogen production?

Based on the comparative analysis of existing literature, the findings indicate that hybrid solar–wind renewable energy systems currently provide the most sustainable and cost-effective pathway for large-scale green hydrogen production.

This conclusion is supported by several key observations. First, hybrid systems achieve higher electrolyzer utilization rates by combining complementary renewable energy resources. Second, improved operational continuity increases hydrogen production output and reduces the levelized cost of hydrogen. Third, enhanced renewable energy utilization minimizes energy losses and contributes to lower environmental impacts. Finally, hybrid configurations provide greater system reliability and resilience compared with standalone solar or wind systems.

While both solar-powered and wind-powered electrolysis systems remain viable options depending on geographical and resource conditions, hybrid renewable energy systems offer the most balanced combination of technical performance, economic competitiveness, and environmental sustainability.

5.3 Implications for Sustainable Energy Development

The findings of this study have important implications for sustainable energy development and global decarbonization strategies. Green hydrogen has the potential to play a transformative role in achieving climate objectives by providing a low-carbon energy carrier for sectors that are difficult to electrify directly, including heavy industry, long-distance transportation, aviation, maritime shipping, and seasonal energy storage.

The results suggest that renewable-powered hydrogen production can facilitate greater integration of solar and wind energy into electricity systems by converting surplus renewable electricity into a storable and transportable energy carrier. This capability can help address one of the most significant challenges associated with renewable energy deployment, namely the intermittent nature of solar and wind resources.

Furthermore, large-scale adoption of green hydrogen could contribute to improved energy security by reducing dependence on imported fossil fuels and diversifying national energy portfolios. Countries with abundant renewable resources may also benefit from emerging opportunities in international hydrogen trade and green industrial development.

The study therefore supports the view that green hydrogen should be considered a strategic component of long-term sustainable energy planning and climate mitigation efforts.

5.4 Recommendations for Industry and Policymakers

Based on the findings of this study, several recommendations can be proposed for industry stakeholders and policymakers.

First, investments should prioritize the development of hybrid renewable energy systems for hydrogen production. The integration of solar and wind resources offers significant advantages in terms of reliability, efficiency, and economic performance.

Second, governments should implement supportive policy frameworks that encourage investment in green hydrogen infrastructure. Such measures may include production incentives, tax credits, renewable energy subsidies, and financial support for electrolyzer deployment.

Third, policymakers should promote research and development initiatives aimed at improving electrolyzer efficiency and reducing manufacturing costs. Continued technological advancement is essential for enhancing the competitiveness of green hydrogen relative to conventional hydrogen production pathways.

Fourth, strategic investments in hydrogen storage, transportation, and distribution infrastructure should be accelerated to facilitate large-scale market deployment. Infrastructure development remains one of the most significant barriers to widespread hydrogen adoption.

Fifth, industry stakeholders should pursue integrated energy system approaches that combine renewable electricity generation, hydrogen production, storage, and end-use applications. Such integration can improve overall system efficiency and maximize the value of renewable energy resources.

Finally, international collaboration should be strengthened to support technology transfer, standardization, and the development of global hydrogen markets.

5.5 Limitations of the Study

Several limitations should be acknowledged when interpreting the findings of this research.

First, the study relied primarily on secondary data obtained from published literature, international reports, and previous techno-economic assessments. Consequently, the results are dependent on the quality, assumptions, and methodologies of the original studies reviewed.

Second, the analysis focused primarily on solar, wind, and hybrid solar–wind configurations and did not extensively examine other renewable energy sources such as hydropower, geothermal energy, or marine energy systems.

Third, geographical variations in renewable resource availability were not investigated in detail. The performance of renewable-powered hydrogen systems may differ substantially across regions due to variations in solar irradiation, wind patterns, climate conditions, and infrastructure availability.

Fourth, future technological advancements, policy developments, and market dynamics may influence the economic competitiveness of green hydrogen production in ways that cannot be fully predicted within the scope of the present study.

Finally, the study adopted a comparative literature-based approach rather than conducting original simulations or experimental investigations. As a result, the findings should be interpreted as evidence-based conclusions derived from existing research rather than site-specific performance assessments.

5.6 Future Research Directions

Future research should focus on addressing several important knowledge gaps identified during this study.

First, additional research is required to evaluate hybrid renewable hydrogen systems under specific geographical and climatic conditions. Regional analyses would provide more accurate assessments of system performance and economic viability.

Second, future studies should investigate the integration of advanced electrolyzer technologies, including next-generation proton exchange membrane and solid oxide electrolyzers, within renewable-powered hydrogen production systems.

Third, comprehensive techno-economic assessments incorporating real-time operational data and dynamic renewable energy profiles would improve understanding of large-scale hydrogen production performance.

Fourth, future research should explore the role of energy storage technologies in enhancing the reliability and flexibility of renewable-powered hydrogen systems.

Fifth, further life cycle assessments should evaluate the environmental impacts of emerging hydrogen production technologies, including resource extraction, manufacturing processes, infrastructure development, and end-of-life management.

Finally, future investigations should examine policy mechanisms, market structures, and investment strategies capable of accelerating the commercialization and large-scale deployment of green hydrogen technologies.

Continued research in these areas will support the development of more efficient, economically viable, and environmentally sustainable hydrogen production systems, thereby contributing to the achievement of global energy transition and climate objectives.

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